M.L. 2016 Project Abstract
For the Period Ending June 30, 2019

PROJECT TITLE: Sentinel Lakes Monitoring and Data Synthesis – Phase III
PROJECT MANAGER: Melissa K. Treml, Fisheries Research and Policy Manager
AFFILIATION: Minnesota Dept. Natural Resources, Division of Fish and Wildlife, Fisheries Research & Policy Unit
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2016, Chp. 186, Sec. 2, Subd. 03g

APPROPRIATION AMOUNT: $401,000
AMOUNT SPENT: $348,102
AMOUNT REMAINING: $52,898

Sound bite of Project Outcomes and Results

The Sentinel Lakes Program has described large ecological changes such as changing water temperatures, impacts from zebra mussels and spiny water flea, and impacts due to land use and will continue to benefit Minnesota's natural resource managers and constituents by identifying changes and understanding their impacts.

Overall Project Outcome and Results

We are grateful for the ENRTF's support, which has been instrumental for the development and success of the Sentinel Lakes Program. DNR and PCA have ensured the continuation of the program including DNR fisheries support for 3 permanent Sentinel Lakes staff positions who will direct program activities and lead remote monitoring and pelagic and juvenile fish sampling, area fisheries staff and IBI Program support through continued fish sampling and remote monitoring and PCA and EWR support through continued water quality, zooplankton, macroinvertebrate and aquatic plant collection and analysis. These monitoring activities will foster the continuation of the long-term monitoring framework and help collaborators utilize the existing framework to investigate specific questions.

Phase 3 of the Sentinel Lakes Long-Term Monitoring Program comprised a wide variety of data management, monitoring and research activities on the 25 Sentinel Lakes. During 2016-2019, Highlights include:

- The Sentinel Lakes datasets have been gathered, assembled, standardized, undergone QA/QC, and metadata have been created for each dataset with all data and metadata available upon request.
- We have outfitted all 25 Sentinel Lakes with continuous water temperature loggers for a total of 180 currently active recording loggers.
- We have summarized and analyzed trends in water quality, water temperature, water level, zooplankton, pelagic fish and game fish trends over time.
- We have established new sampling activities targeting juvenile fish with an emphasis on growth, and new aging protocols for pelagic fish to better track year class strength, growth, and mortality.
- We have identified dissolved oxygen monitoring as a data gap and we have already made progress to fill this gap.
- We have prioritized the dissemination of Sentinel Lakes data and information which has resulted in an updated public website (https://www.dnr.state.mn.us/fisheries/slice/index.html), data sharing with numerous collaborators, 30+ presentations, public media coverage, and research proposals and funded projects with collaborators.

Project Results Use and Dissemination

We have prioritized the dissemination of Sentinel Lakes data and information over the last 3 years which has resulted in an updated public website (https://www.dnr.state.mn.us/fisheries/slice/index.html), data sharing with numerous collaborators, 30+ presentations, public media coverage, and research proposals and funded projects with collaborators. Specifics are provided in the date specific updates with highlights below.

The updated Sentinel Lakes section of the DNR website includes new information and a smart phone friendly design. In addition to the program description and contacts list we have also included detailed lake descriptions, methodology, and updated research project descriptions.

The Sentinel Lakes datasets have been gathered, assembled, standardized, undergone QA/QC, and metadata have been created for each dataset with all data and metadata available upon request. We are working with MNiT staff to ensure compatibility with existing DNR database architecture, branding and ADA requirements. Details located under Activity 1 Outcome 1.

We have fostered a data sharing philosophy that has encouraged outside researchers to request Sentinel Lakes data. Now that data are reviewed for QA/QC and metadata have been created, data requests can be filled quickly and are complemented by trophic level specific metadata. As noted, data sharing is an important part of the Sentinel Lakes Program and one that we will continue to promote. In the past 3 years we have shared data with collaborators who include: Universities (University of Minnesota Twin Cities, University of Minnesota Duluth and Large Lakes Observatory, Bemidji State University, University of North Carolina, Kalamazoo College), Federal scientists (Environmental Protection Agency, USGS, USFWS, NPS), Tribal Biologists (1834 Treaty Authority, Lac du Flambeau Band of Lake Superior Chippewa Indians, Red Lake Department of Natural Resources), state agencies (Wisconsin DNR, MN PCA, and MN DNR) and private industry (TetraTech).

Data sharing has resulted in numerous submitted research proposals including several funded grants and projects including $46,500 from Midwest Glacial Lakes Fish Habitat Partnership to support dissolved oxygen monitoring, 2 funded Sport Fish Restoration projects lead by DNR, and LCCMR support for Kathryn Schreiner (UMD and Large Lakes Observatory) and colleagues for the project “A Survey of Microplastics in Minnesota’s Inland Aquatic Food Webs”.

We have given 30+ presentations to groups like The Association for the Sciences of Limnology and Oceanography; Midwest Fish and Wildlife Conference; Annual Meeting of the Minnesota Chapter of the American Fisheries Society; Bemidji State University; the Fish and Wildlife Division’s Climate and Renewable Energy Steering Team; Section, Region, and Unit specific DNR meetings; Interagency research meeting with the Minnesota Department of Agriculture; Board of Water and Soil Resources; Minnesota Pollution Control Agency; University of Minnesota; the St. Croix Watershed Research Station; and the Department of Natural Resources. Also several webinars were given to EPA’s regional lake monitoring network and we presented and instructed participants at the Remote Sensing Workshop.

Several public media outlets have featured Sentinel Lakes stories including Minnesota Public Radio, The Star Tribune, The Echo Press, and the Outdoor News.

Manuscript “Stable isotopes indicate that zebra mussels increase dependence of lake food webs on littoral energy sources” by Brian Herwig and colleagues was published in 2018 in the journal of Freshwater Biology documenting energy flow change pre and post zebra mussels infestation in Lake Carlos.

The Second Sentinel Lakes Summit brought 70 collaborators from DNR, PCA, university faculty and federal researchers together to learn, discuss, and advance the science related to long term monitoring and changes in Minnesota lakes.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2016 Work Plan Final Report

Date of Report: August 15, 2019

Final Report

Date of Work Plan Approval: June 7, 2016

Project Completion Date: June 30, 2019

PROJECT TITLE: Sentinel Lakes Monitoring and Data Synthesis – Phase III

Project Manager: Melissa K. Treml, Fisheries Research and Policy Manager

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Location: Statewide. See map in Section IX.

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$401,000**
	Amount Spent:	**$348,102**
	Balance:	**$52,898**

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 03g

Appropriation Language:
$401,000 the second year is from the trust fund to the commissioner of natural resources for the third and final phase of a monitoring and multidisciplinary research effort on 25 sentinel lakes in Minnesota, which will integrate and synthesize previously collected data to enhance understanding of how lakes respond to large-scale environmental stressors and provide for improved ability to predict and respond to lake changes for water and fisheries management. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Sentinel Lakes Monitoring and Data Synthesis – Phase 3

II. PROJECT STATEMENT: Continued monitoring of 25 Sentinel Lakes and the integration of data collected since the onset of the Sentinel Lakes Long-term Monitoring Program (previously funded by ENRTF as SLICE) will enable a fuller understanding of the key mechanistic and emergent properties of lakes affected by environmental stressors such as land use modification, invasive species, and climate change. Since 2008 DNR's Section of Fisheries, with funding from LCCMR, has coordinated the monitoring of biological, physical, and chemical attributes of 25 lakes and their watersheds. Our intent with the Sentinel Lakes Program is to continue monitoring these lakes and their watersheds, including water temperature, clarity, chemistry as well as biological monitoring to include fish, zooplankton and other invertebrates, and aquatic plants. We also propose the development of a state-wide water temperature monitoring network on Minnesota lakes that will complement our ongoing efforts on Sentinel Lakes and also enhance our understanding of the thermal dynamics on a wider variety of lakes. Integrating the vast amount of data collected in the last 8 years is now needed to allow managers, researchers, and policy makers a deeper understanding of the synergistic mechanisms within these systems and allow for the development of management strategies thereby ensuring the resiliency of desirable lake conditions. Our overall goal is to bridge baseline and future work on Sentinel Lakes by providing data integration and data synthesis to understand more fully mechanisms that promote healthy and resilient lakes (e.g., which factors promote high water quality, healthy aquatic plants and balanced fish communities). Ultimately we envision a better understanding of how and why lakes change due to environmental stressors and a better ability to predict and respond to lake changes, (e.g., what restoration efforts will work, and how predictable lake responses will be to management). Finally, these efforts will help the Sentinel Lakes Program identify knowledge gaps that will be considered in designing future monitoring and research efforts, thereby continuing Minnesota's reputation as a leader in the research, monitoring, and management of lakes.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of 11/30/2016:

Three interns and a LTM biologist (funded through this project) have been hired in support of the Sentinel Lakes Program. Sampling efforts throughout the summer and fall have been completed including water chemistry, zooplankton, and fisheries assessments. Water samples have been collected by the Minnesota Pollution Control Agency (MPCA) and processed by the Minnesota Department of Health (MDH) and data have subsequently been entered into the EQuIS database by MPCA staff. In concert with water chemistry sampling, zooplankton tows were collected monthly from May through October and will be processed and entered this winter by DNR staff. Fisheries assessments included standardized population, littoral fish community, pelagic fish community, as well as juvenile fish sampling. In addition, remote sensing equipment (weather stations, pressure transducers, dissolved oxygen, and temperature loggers) have been downloaded and removed for the winter. Water temperature data are housed on a shared network drive. We are currently organizing the water temperature data by lake and year to make the data easier to use.

Volunteers from various cooperating agencies (Minnesota Pollution Control Agency, University of Minnesota, the St. Croix Watershed Research Station, and the Department of Natural Resources) were asked to participate in one of two guiding committees for the Sentinel Lakes Program. The internal oversight committee was assembled (consisting of 3 representatives from fisheries management, a biometrician, 3 representatives from fisheries research, and the Program Coordinator) on November 3rd in Cloquet, MN and featured Program updates and feedback on Program direction from committee members. The Program will continue to work with area supervisors, cooperators, and the advisory committees to create a sustainable sampling schedule that will allow the Program to continue to be a valuable tool to detect meaningful trends in lake conditions.

We noticed that the project length and completion date on the budget did not match the work plan so we have updated the length and date on the project budget.

Amendment Request (11/30/2016)

This amendment request is to change from using the 1 NR Specialist Data Manager described in Activity 1 to a contract with Assistant Professor Paul Venturelli at the University of Minnesota. Professor Venturelli possesses a unique skill set and has shown the ability to work on large data sets and elucidate biological trends. To reflect this change, $129,375 in Activity 1 has been moved from Personnel to Professional/Technical/Service Contracts, the Direct and Necessary services have been recalculated and adjusted from $28,187 to $16,836, and that difference, $11,351, has been reallocated to personnel under Activity 2 to extend the support of the LTM Biologist. Amendment Approved by LCCMR 1/10/2017

Project Status as of 3/31/2017:

We are currently in the process of hiring three summer interns and a LTM biologist (former LTM biologist Derek Bahr accepted a permanent position with MN DNR) to support Sentinel Lake sampling and analysis efforts. In addition, the service agreement between the State of Minnesota and Dr. Venturelli is currently getting signatures so we expect work to begin soon.

In support of Activity 1 to expand temperature monitoring of Sentinel Lakes we have purchased over 100 continuous temperature loggers and have distributed a portion of those loggers to area representatives to replace existing loggers with expired batteries. Beginning this year temperature loggers will be placed in the Sentinel lakes that currently do not have loggers (South Center, St. Olaf, Peltier, and St. James). Hereafter, all 25 Sentinel Lakes will have continuous temperature monitoring data.

We are working with area fisheries representatives (DNR) and collaborators (PCA, EWR) to complete the 2017 sampling schedule and we have begun to transition the Sentinel Lakes Program to these cooperating agencies to ensure the long term viability of the Program.

Amendment Request (4/27/2017)

This amendment request is to change from using a contract with Assistant Professor Paul Venturelli at the University of Minnesota described in Activity 1 back to the NR Specialist Data Manager because Professor Venturelli will be leaving the University. To reflect this change, $129,375 in Activity 1 has been moved from Professional/Technical/Service Contracts back to Personnel and $11,351 from Personnel in Activity 2 has been moved back to Direct and Necessary services in Activity 1 (now $28,187). Amendment Approved by LCCMR 5/15/2017

Project Status as of 9/30/2017:

Will French was hired as the LTM Biologist, Tim Martin as the Fisheries Data Specialist, and 3 summer internships were hired in support of the Sentinel Lakes Program. Sampling efforts from 2017 included water chemistry, continuous water temperature and water level monitoring, phytoplankton, zooplankton, and fisheries assessments. Water quality samples have been collected by MPCA and processed by the Minnesota Department of Health (MDH) and data have subsequently been entered into the database by MPCA staff. In concert with water chemistry sampling, zooplankton tows were collected monthly from May through October. Fisheries assessments included the nearshore fish community and we expanded the pelagic fish community sampling in 2017.

In the summer of 2017 temperature loggers were placed in 4 Sentinel lakes that did not have loggers so that all 25 Sentinel Lakes now have continuous water temperature monitoring. In addition, a temperature logger chain was deployed on Ten Mile Lake to replace a single logger unit. We developed standard operating procedures for continuous water temperature and water level monitoring for the Sentinel Lakes Program and we delivered a webinar and workshop describing these procedures. We increased the number of lakes receiving pressure transducers that continuously measure changes in water elevation to include all 9 tier 1 lakes and Will French made improvements on the housings to make these meters more efficient to deploy and retrieve.

Tim Martin has become acquainted with the various datasets that are a part of the Sentinel Lake program and began inventory of the data. He has also begun to develop scripts and processes for the continuous water temperature data which include data standardization and QC.

Project Status as of 3/31/2018:

Large advances in data management have been achieved since the previous update and we are on track to achieve Outcome 1 for Activity 1 by the June 30, 2018 deadline. Multiple data sets have been gathered and centralized into Access databases and metadata have been created. Water quality (PCA), water level (EWR), and zooplankton (EWR) data are housed in existing databases and we are working with these groups to develop metadata. Other datasets are not housed in formal databases such as aquatic macrophytes, macroinvertebrates, and vertical gillnet data but instead are housed and maintained on individual computers by programs (EWR and DNR's lake IBI program) and we are working with these groups to create metadata. Improvements in data management have allowed us to better share data including metadata with collaborators. The number of requests for Sentinel Lakes data continuous to increase and we have provided data to numerous groups since the last update. We have also developed A Sentinel Lakes Water Temperature application to aid in data visualization and trend analysis. We are using the application to investigate thermal properties of the Sentinel Lakes and how these values have changed over time.

We sampled juvenile fish via October boat electrofishing in Elk, Carlos and Ten Mile Lakes and have processed those samples. Interestingly, bimodal length distributions were noted for age-0 largemouth bass (2017 year class) in all 3 lakes. Corresponding water temperature data suggest these bimodal distributions may have been caused by a sharp drop in water temperature during mid to late May, which likely interrupted largemouth bass spawning activity in these lakes resulting in two discrete groups of hatch dates.

We submitted a proposal to Midwest Glacial Lakes National Fish Habitat Partnership requesting funds to support the purchase of continuous dissolved oxygen sensors on several Sentinel Lakes to complement existing meters. In addition, USFWS and MN DNR have also contributed funds toward the purchase of continuous dissolved oxygen meters which will be deployed in three Sentinel Lakes spring 2018.

Sentinel Lakes Program staff gave 10 professional presentations at 3 conferences focused on the duration of lake stratification, early life history, and the impacts of zebra mussels.

We worked with area fisheries representatives (DNR) and collaborators (PCA, EWR) to complete the 2018 sampling schedule. We have also updated the Sentinel Lakes Committees and discussed potential changes to the fish sampling protocol. We are meeting with DNR Fisheries leadership in April to discuss the long term future of the Sentinel Lakes Program.

Project Status as of 9/30/2018:

Since the Sentinel Lakes data sets have been gathered and centralized, we are now working on a data portal to make the data available to managers, researchers, and other interested parties. Though these datasets are coming from a variety of different agencies and divisions, this portal allows us to put the data into compatible, standardized formats that will allow users to easily combine and compare the data for analysis. Additionally, this portal can provide various calculations based upon the raw data that are available for download. For those interested in comparing Sentinel Lake data to other lakes in the state, we have included a lake similarity tool in the data portal which allows the user to choose a lake in Minnesota and select a number of relevant parameters related to the physical morphology and biological community of the lake. The similarity analysis tool will then rank the Sentinel Lakes based upon how similar they are to the chosen lake so that users can identify the most representative Sentinel Lakes for their investigation.

Water quality, remote sensing, and biological field sampling were successfully completed over the spring, summer and fall of 2018. Of particular note, the Sentinel Lakes Program completed the first full year of intensive (fall and spring) juvenile fish sampling on several lakes in May of 2018 and found multiple instances of size-selective overwinter mortality. Sampling targeted juvenile Bluegill, Largemouth Bass, Rock Bass, and Yellow Perch and resulted in 497 juvenile fish in the fall of 2017 and an additional 724 juvenile fish were sampled in the spring of 2018 to examine overwinter survival. Quantile quantile plots of age-0 length distributions were compared between fall and spring electrofishing and we found multiple instances of length-dependent overwinter mortality. Size selective mortality favoring larger age-0 Yellow Perch occurred in all three lakes during the winter of 2017/18. Size selective mortality also occurred in all 3 lakes as the second cohort (late hatch) of Bluegill did not survive the winter. No age-0 Largemouth Bass were sampled in Ten Mile Lake and only a single age-0 Largemouth Bass was sampled in Elk Lake and Lak Carlos in the spring of 2018. Largemouth Bass appeared to have poor overwinter survival in all three sampled lakes during 2017/18, potentially indicating a weak 2017 year class in central and north central Minnesota.

Interest in Sentinel Lakes data has continued to increase providing multiple collaborative opportunities to use the Sentinel Lakes framework to better understand Minnesota lakes. For example, we are collaborating with partners at the University of Minnesota, USFWS and MN DNR to purchase and deploy continuous dissolved oxygen chains in multiple Sentinel Lakes to complement the continuous water temperature data already collected as part of this program. These data will help elucidate seasonal and long-term trends in oxygen and allow us to document impacts to lake function (nutrient cycling) and fish community (cisco).

Project Status as of 3/31/2019:

The most impactful update to report is that DNR Fisheries has created two permanent full-time positions to be a part of the Sentinel Lakes Program. This will make the Sentinel Lakes Program biologist and data management positions, currently supported by this ENTRF grant, fully funded by DNR Fisheries. As phase III of the ENRTF support comes to an end, these positions will ensure the continuity and long-term sustainability of this high priority Program. These two positions, along with the existing DNR Fisheries supported Sentinel Lakes Coordinator, will allow DNR Fisheries to continue the long-term monitoring framework and help its collaborators with grant supported research. We are grateful for the ENRTF's support, which has been instrumental for the development and success of the Sentinel Lakes Program.

By reviewing our datasets and collaborating with other researchers, we identified continuous dissolved oxygen monitoring as an important need (Activity 1, Outcome 3) in the long-term monitoring of these aquatic systems. To close this gap, we have collaborated with US Fish and Wildlife Service and the MNDNR Fisheries Habitat program to purchase 43 continuous dissolved oxygen (DO) sensors and Sentinel Lakes staff created and deployed chains of DO sensors in lakes Carlos, Greenwood, and South Center. Working with collaborators at the University of Minnesota, we have also been awarded funding from the Midwest Glacial Lakes Fish Habitat Partnership that allowed us to purchase additional DO sensors that Sentinel Lakes staff will deploy this spring in a minimum of 2 additional Sentinel Lakes, Madison and Ten Mile.

The Sentinel Lakes Program completed intensive juvenile fish sampling in October of 2018. We sampled 1,107 juvenile fish and collected length, weight, maturity and structures for age and growth analyses. Maturity results from Yellow Perch were interesting as male Perch sampled from Elk Lake and Pearl Lake were mature at age-0. The early age and small size at maturity observed in the male Yellow Perch is similar to observations made by MN DNR fisheries staff in other central Minnesota lakes and ties in to the upcoming DNR Yellow Perch project which will incorporate several Sentinel Lakes.

In addition to the many new and current projects utilizing the Sentinel Lakes framework and detailed below in the dissemination section, two large efforts, a Sentinel Lakes Summit and an updated website, will both help communicate project findings and generate discussion. The Second Sentinel Lakes Summit will occur on March 27 and 28 in Alexandria, MN. This event will bring people working on the Sentinel Lakes together to learn, discuss, and advance the science related to long-term monitoring and changes in Minnesota lakes using a combination of clustered presentations and moderated discussions. We are excited for the quality and scope of topics covered which spans every trophic level from water quality to fisheries. This is a great opportunity to not only communicate project findings to a broad audience (expecting 60-70 people from DNR, PCA, university faculty and federal researchers, as well as some LCCMR staff and committee members) but will also advance the science in general. We have also been working with the DNR Outreach group to update the Sentinel Lakes section of the DNR website including new information and smart-phone compatible design. In addition to the program description and contacts list we have also included detailed lake descriptions, methodology, and updated research project descriptions.

Overall Project Outcomes and Results:

We are grateful for the ENRTF's support, which has been instrumental for the development and success of the Sentinel Lakes Program. DNR and PCA have ensured the continuation of the program including DNR fisheries support for 3 permanent Sentinel Lakes staff positions who will direct program activities and lead remote monitoring and pelagic and juvenile fish sampling, area fisheries staff and IBI Program support through continued fish sampling and remote monitoring and PCA and EWR support through continued water quality, zooplankton, macroinvertebrate and aquatic plant collection and analysis. These monitoring activities will foster the continuation of the long-term monitoring framework and help collaborators utilize the existing framework to investigate specific questions.

Phase 3 of the Sentinel Lakes Long-Term Monitoring Program comprised a wide variety of data management, monitoring and research activities on the 25 Sentinel Lakes. During 2016-2019, Highlights include:

- The Sentinel Lakes datasets have been gathered, assembled, standardized, undergone QA/QC, and metadata have been created for each dataset with all data and metadata available upon request.
- We have outfitted all 25 Sentinel Lakes with continuous water temperature loggers for a total of 180 currently active recording loggers.
- We have summarized and analyzed trends in water quality, water temperature, water level, zooplankton, pelagic fish and game fish trends over time.
- We have established new sampling activities targeting juvenile fish with an emphasis on growth, and new aging protocols for pelagic fish to better track year class strength, growth, and mortality.
- We have identified dissolved oxygen monitoring as a data gap and we have already made progress to fill this gap.
- We have prioritized the dissemination of Sentinel Lakes data and information which has resulted in an updated public website (https://www.dnr.state.mn.us/fisheries/slice/index.html), data sharing with numerous collaborators, 30+ presentations, public media coverage, and research proposals and funded projects with collaborators.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Sentinel Lakes Data Integration and Synthesis.

Description: By July of 2016 nearly 9 years of monitoring data will have been collected on the 25 Sentinel Lakes. While these efforts have produced tangible results for the management of fisheries and lakes in Minnesota (e.g., Cisco biology, sampling, and habitat needs) a great deal more can be done with proper integration of the wide range of data sets that have been established. We propose to hire a data expert who will assemble these data in a manner which will allow us to make comparisons between trophic levels, different taxa, and responses to experimental design factors such as ecoregion, nutrient levels, mixing status, land use and other features being inventoried in the Sentinel Lakes Program. These investigations will allow for the continued development of strategies which will allow managers to plan and adjust to the ecological changes occurring in our lakes. Finally, this will help us identify data gaps, which will be integrated into future monitoring and research efforts.

Summary Budget Information for Activity 1: **ENRTF Budget: $157,562**
Amount Spent: $ 127,083
Balance: $ 30,479

Outcome	**Completion Date**
1. *Gather and assemble data sets*	30 June 2018
2. *Comprehensive analysis of data, identification of trends and empirical and mechanistic relationships*	30 June 2019
3. *Identification of data gaps and recommendations for future monitoring efforts when fully funded by Section of Fisheries*	30 June 2019

Activity Status as of 11/30/2016:

It was determined the skills needed to achieve the 3 outcomes for Activity 1 are best accomplished with an amendment request contract with a data management and analyst expert at the University of Minnesota. The contract would begin 1/1/2017.

Activity Status as of 3/31/2017:

The contract describing the service agreement between the State of Minnesota and Dr. Venturelli at the University of Minnesota was improved by comments from several collaborating agencies and is currently being encumbered. Work can begin once signatures are complete. This contract will combine and organize existing Sentinel Lake Program data into a single, centralized Access database to facilitate broad scale data analysis. Dr. Venturelli and Tim Martin (student under the advisement of Dr. Venturelli) will work closely with MNIT (DNR Fisheries staff) during the database design and development to ensure compatibility with existing DNR database architecture. This will help ensure the database is useable, sustainable and will be maintained in perpetuity. The contractor will also standardize existing data, including water quality (EQUIS) and phytoplankton data from MPCA databases and zooplankton data from the DNR EWR database. The contractor will work with area biologists to fill in missing data and complete descriptions of collected data whenever possible which will result in a “how to” manual for the data detailing fisheries and other sampling and processing methods used to collect and process the data. The contractor will design QA/QC protocols to ensure that existing data are biologically meaningful and accurate and will work with DNR representatives on data-related questions including temporal and spatial trends and variations thereof.

Activity Status as of 9/30/2017:

Tim Martin recently began (August 23, 2017) as the Fisheries Data Specialist and thus far has worked to gather and assemble the continuous water temperature and weather station data into a single spreadsheet on the shared DNR drive. Tim has also been running quality control measures on these data to look for data anomalies. We will work with the advisory committee to prioritize data efforts.

Activity Status as of 3/31/2018:

Large advances in data management have been achieved since the previous update and we are on track to achieve Outcome 1 for Activity 1 by the June 30, 2018 deadline. Specifically, continuous water temperature (> 900), dissolved oxygen profiles (> 400), ice cover (> 700), and weather data have been gathered and centralized into Access databases. Metadata have also been created for these data sets and adapted R scripts have been used to QAQC the continuous water temperature data. Water quality (PCA), water level (EWR), and zooplankton (EWR) data are housed in existing databases and we are working with these groups to develop metadata. Other datasets are not housed in formal databases such as aquatic macrophytes, macroinvertebrates, and vertical gillnet data but instead are housed and maintained on individual computers by programs (EWR and DNR's lake IBI program) and we are working with these groups to create metadata. We met with Fisheries MNiT staff and are currently identifying database options for those datasets that are currently not database supported.

We have also developed tools to aid in data visualization and trend analysis (Outcome 2). A Sentinel Lakes Water Temperature application was developed to visualize the continuous water temperature data collected as a part of the Sentinel Lakes Program, compare it to variables such as air temperature and ice cover, provide a platform for conducting thermal lake stratification calculations, and allow the user to compare how these values have changed over time. The application consists of three separate sections. The first section allows the user to visualize the water temperature at a single depth in the water column along with air temperature highs, lows, and means and ice in and out dates. The user can also change the date range of the data displayed. The second section allows the user to visualize the water temperatures throughout the water column in two different ways. First the data can be viewed in a profile view; wherein a line representing each depth shows how the temperature at that depth changes over time. Second, the data can be viewed as a heatmap, which shows a vertical perspective of how the water temperature changes throughout the water column over time. Additionally, stratification start and end dates with some user supplied definitions and ice in and out dates can be added. The heatmap visualization also allows for the calculation and display of the location of both the thermocline and metalimnion depths within the water column. Finally, the third section allows the user to visualize the temperature curve in the water column for an individual date and compare how that curve compares to the means of the other years on that date. Additionally, the thermocline and metalimnion depths can also be compared among years. We have expressed our interest to MNiT to host this water temperature application on the Sentinel Lake webpage so that it is accessible to the public and other external collaborators.

We have been analyzing thermal stratification duration and strength in the Sentinel Lakes and found that stratification duration varies greatly not only among lakes across the state (up to 2 months), but also among years within individual lakes (one month). We compared these stratification metrics against several different lake processes including hypolimnetic oxygen and phosphorus, epilimnetic chlorophyll, percentage of phytoplankton that are cyanobacteria, and the water temperature and depth. Stratification metrics did not significantly explain lake processes across all of the lakes however stronger relationships existed on individual lakes. For example, TDO3 (water temperature at the depth dissolved oxygen falls below 3 ppm) was inversely related to stratification duration and the strength of stratification.

Activity Status as of 9/30/2018:

In order to make the data collected by the Sentinel Lakes program available to managers, researchers, and other interested parties, we are developing a data portal to provide easy access to the majority of the program datasets. Though these datasets are coming from a variety of different agencies and divisions, this portal allows us to put the data into compatible, standardized formats that allow users to easily combine and compare the data for analysis. Additionally, this portal can provide various calculations based upon the raw data that are available for download. For example, it allows the user to calculate and download thermal layer depths based upon the raw temperature data. As additional standard calculations are identified, they will be added to the data portal. For those interested in comparing Sentinel Lake data to other lakes in the state, we have included a lake similarity tool in the data portal which allows the user to choose a lake in Minnesota and select a number of relevant parameters related to the physical morphology and biological community of the lake. The similarity analysis tool will then rank the Sentinel Lakes based upon how similar they are to the chosen lake so that users can identify representative Sentinel Lakes.

We are continuing to update the data portal in order to make sure that it is easy to use and provides the best data and information possible. We are adding instructions that will help the users understand the data better as well as understand how to best use the portal. Also, we are developing automatic metadata reports to provide as much information as possible about the specific data of interest. These reports will be customized to the data being processed.

Because of the volume of continuous data we are collecting from both the new DO sensors (details of new DO loggers described under dissemination) and the temperature sensors deployed in all of the Sentinel Lakes, we have developed a data logger processing tool that allows us to process these data in a quick, efficient, and accurate manner. Using the Shiny web app package for R, this tool provides a graphical interface for inputting the data, organizing them into a standardized format, and performing both automated and visual quality control tasks. This tool then provides the user with several options for exporting the data. In the future, this tool will be updated to include processing tools for other types of collected continuous data, as needed.

Activity Status as of 3/31/2019:

While the Sentinel Lakes datasets have been gathered and assembled (9-30-2018, Activity 1, Outcome 1) we continue to strive for ways to go beyond Outcome 1 to maximize the use of these data through the development of user-driven data tools. In the interest of centralizing the Sentinel Lakes data visualization and retrieval tools (described in previous updates) and relaying program information to the public, we have been developing a prototype for a Research Portal web interface. Ultimately, this web app will allow the user to learn about the Sentinel Lakes program, its lakes, and the research that is occurring on them as well as interact and retrieve Sentinel Lakes data through an interactive graphical user interface. We have begun collaborating with MNiT staff to develop this prototype into a fully compliant and workable reality which provides the functionality above while following the necessary security, accessibility, and branding requirements. Part of this process involves finding enterprise level solutions, either new or existing, to host the Sentinel Lakes data that have been organized during previous efforts. Additionally, we are planning to develop a Management Portal which will be used to plan and record field work trips, track equipment inventory, process data, and provide a centralized location for standard operating procedures. We are also collaborating with MNiT on the details of the underlying database which ensures all datasets will be supported and accessible.

We are on track to complete Activity 1, Outcome 2 by the final report. Trends of fish species analyses have been completed and a draft of the interpretation is in its 2nd in-house revision. The analysis of water quality trends is currently underway. Once the analysis is complete, PCA will assist in the interpretation of trends and in drafting the document. Analyses and interpretations will be included with the final report.

Pursuant to Activity 1, Outcome 3, we have identified dissolved oxygen monitoring as a data gap for long-term monitoring of aquatic systems. We received continuous dissolved oxygen (DO) sensors through funds from the US Fish and Wildlife Service and the MNDNR Fisheries Habitat program (approximately $43,000) and deployed them as sensor chains, much like the temperature sensor chains, in Carlos, Greenwood, and South Center lakes. In order to maintain consistency amongst lakes, we developed methods to determine which depths the sensors should be placed along the chains. To start, we calculated the maximum depth of the metalimnion using the continuous temperature dataset. Using this as a guide, we placed a sensor every two meters in the epilimnion and metalimnion. Below the metalimnion, we placed a sensor every five meters with one sensor placed at the bottom of the chain, regardless of distance from the nearest sensor above. When we deployed the sensor chain, we made sure the shallowest sensor was approximately one meter below the water's surface to keep it safe from boat propellers and ice.

In the fall of 2018, we retrieved these sensors to verify they were functioning correctly and downloaded the data that had been collected over the summer. These data revealed that there are stark differences between the DO concentrations among these lakes. Both Carlos and Greenwood lakes had sufficient levels of DO throughout the monitoring period, with only the deepest parts of Carlos moving towards low DO levels. In contrast, South Center was anoxic below ~5 m for most of the summer. At times, this anoxic layer reached depths as shallow as ~3 m. Given that South Center has a maximum depth of ~32 m, the vast majority of the water appears to be uninhabitable to aerobic organisms during the summer. After retrieving the data from the sensors, we redeployed them and they are continuing to record data during the winter. We will retrieve the data again this spring to see how DO dynamics progress during periods of ice cover and we will evaluate if the sensors need to be rearranged in order to maximize the quality of data collection.

In 2019, through funds received from the Midwest Glacial Lakes National Fish Habitat Partnership and additional funds from the MN DNR Habitat program, we will be purchasing and deploying additional DO logger chains on lakes Madison and Ten Mile with the potential of also adding them to Trout, South Twin and White Iron lakes. Additionally, a potential three more Sentinel Lakes will have DO sensors deployed on them by Fisheries Areas or outside organizations. The Ortonville Fisheries Area is working towards deploying three sensors on Artichoke Lake and the Windom Fisheries Area is looking into deploying sensors on Shaokotan Lake. The University of Minnesota Itasca Biological Research Station will deploy a sensor buoy on Elk Lake which will collect continuous DO data as well as a variety of other lake metrics.

Final Report Summary:

Outcome 1 - The Sentinel Lakes datasets have been gathered, assembled, standardized, QAQCed, and metadata have been created for each dataset with all data and metadata available upon request. Several web apps were created to allow us to process these data in a quick, efficient, and accurate manner and those tools will continue to be used by the Sentinel Lakes Program and are also being shared with and adapted by other state programs as well as national partnerships such as the Lake Monitoring Network with cooperators in more than 12 states. We are working with MNiT staff to ensure compatibility with existing DNR database architecture, branding and ADA requirements.

We have fostered a data sharing philosophy that has encouraged outside researchers to request Sentinel Lakes data. Now that data are QAQCed and metadata have been created, data requests can be filled quickly and are complemented by trophic level specific metadata. As noted, data sharing is an important part of the Sentinel lakes Program and one that we will continue to promote. In the past 3 years we have shared data with collaborators who include: Universities (University of Minnesota Twin Cities, University of Minnesota Duluth and Large Lakes Observatory, Bemidji State University, University of North Carolina, Kalamazoo College), Federal scientists (Environmental Protection Agency, USGS, USFWS, NPS), Tribal Biologists (1834 Treaty Authority, Lac du Flambeau Band of Lake Superior Chippewa Indians, Red Lake Department of Natural Resources), state agencies (Wisconsin DNR, MN PCA, and MN DNR) and private industry (TetraTech). Data sharing has resulted in numerous submitted research proposals including several funded grants and projects.

Outcome 2 - We have also developed tools to aid in data visualization and trend analysis. A Sentinel Lakes Water Temperature application was developed to visualize and analyze the continuous water temperature data collected as a part of the Sentinel Lakes Program, compare it to variables such as air temperature and ice cover, calculate thermal lake stratification, and allow the user to compare how these values have changed over time.
We have been analyzing thermal stratification duration and strength in the Sentinel Lakes and found that stratification duration varies greatly not only among lakes across the state (up to 2 months), but also among years within individual lakes (one month). We compared these stratification metrics against several different lake processes including hypolimnetic oxygen and phosphorus, epilimnetic chlorophyll, percentage of phytoplankton that are cyanobacteria, and the water temperature and depth. Stratification metrics did not significantly explain lake processes across all of the lakes however stronger relationships existed on individual lakes. For example, TDO3 (water temperature at the depth dissolved oxygen falls below 3 ppm) was inversely related to stratification duration and the strength of stratification.

Data management activities outlined in Outcome 1 allowed us to summarize and analyze the data.

Water Temperature

Water temperature is an important metric for the long-term monitoring of lake ecosystems as it can affect most lake biological, chemical, and physical processes (Mazumder et al 1990; Haase et al 2017; Skowron 2017). Oftentimes these processes are not linearly affected by temperature and can be further complicated by other lake processes; therefore, even minimal changes in temperature can have disproportionately large impacts, i.e. Cisco temperature and dissolved oxygen thresholds (Fang et al 2012; Missaghi et al 2017). As such, it is important to monitor for changes that may be occurring in lake temperature regimes and the Sentinel Lakes Program, with the help of MNDNR Fisheries Areas, have invested a considerable amount of resources towards collecting these data.

Sentinel Lakes water temperature data are collected using Onset HOBO Pro V2 continuous water temperature loggers placed either singly or as a logger chain in the pelagic zone on all 25 Sentinel Lakes. Current protocols suggest that these loggers be set to record water temperature at one hour intervals, though the interval has ranged from 15 to 60 minutes throughout the history of the program. In general the data from these loggers are retrieved annually by either MNDNR Fisheries Areas or the Sentinel Lakes Staff. Historically, there have been data gaps that have occurred due to missing loggers/logger chains, human error, and corrupted data. This has also lead to the depths of these loggers changing on many of the lakes, with the shallowest logger depth ranging between just below the surface to 5.1 m deep depending on the lake and time period. Once the water temperature data are collected, they go through an automatic QC process using the ContDataQC R package as well as a visual QC process to flag and remove any erroneous data points (Leppo 2019). We used this cleaned dataset to perform the analyses using R.

We explored long-term trends in water temperature using 3 analyses. The first analysis looked at the monthly means for the shallowest available depth for each time period on each lake to explore if monthly means have changed across years. We did this by selecting all months that had data collected on every day of that month, taking the means of those data, and running linear regression models for each month on each lake across the years data had been collected (2008 – 2019). Additionally, we ran a mixed effects model (mean temperature ~ Year + (1|Lake) + (1|Year)) for the month of June, taking into account the effects that individual lakes and the overall statewide yearly trend had on the water temperature.

The second analysis looked at how annual growing degree days (GDD) patterns have changed across years for each lake. In order to be included in the analysis, each year for each lake had to have temperature data for at least 90% of the days of the year and therefore not all Sentinel Lakes had sufficient amounts of data to be included in this analysis. This resulted in a dataset ranging from the years 2009 – 2018 and included 22 lakes. We determined the annual GDD (base 5 C°) by calculating the daily mean for the shallowest available depth on each lake, subtracted 5 from the daily mean, and summed up these results for each year (Uphoff et al. 2013). We created individual linear models for each lake to determine the amount of change occurring. We also conducted a linear mixed model for the GDD on all lakes using the formula: GDD ~ Year + (1|Lake) + (1|Year), taking into account the effects that individual lakes and the overall statewide yearly trend had on the GDD.

The third analysis looked at how the duration of thermal lake stratification has changed across the years. Historically, the Sentinel Lakes Program has deployed logger chains consisting of multiple temperature sensors vertically through the water column in six dimictic lakes (through recent efforts, the number of lakes with these chains has increased), with at least one lake in each of the four ecoregions. The data from these lakes ranged from 2008 – 2019. Using daily mean temperatures, we calculated the duration of stratification, defined as a temperature difference of at least 1°C over one vertical meter, anywhere in the water column. Because there are often early onset stratification events in the spring that eventually re-mix, we set a requirement of 14 consecutive stratified days for the lake to be considered stratified for the season. Using these criteria, we determined the number of days the lake was stratified by determining the first and last dates during these periods and counted the number of days between them. If there were multiple stratification periods during a year (n = 4), we simply added up the total number of days the lake was stratified.

In order to explore any trends that may be occurring, we ran linear regression models on the number of annual stratification days across the years for each lake.

Results

Monthly Means

Trends in water temperature over time in the Sentinel Lakes differed by month. Most months had variable temperature trends across the Sentinel Lakes, with the notable exception of June (Figure 1). June was the only month with increasing temperature trends for all 25 lakes during the monitoring period (Figure 2 and 3). Increasing water temperature trends were stronger in June than the other months based on model fit (nine lakes having R^2 values above 0.5; Figure 4) and significance (14 lakes have significant positive slopes at the 0.1 level; Figures 5). Across all of the Sentinel Lakes, the average June increase in water temperature was 2.3° C over a 10-year period or 0.23° C per year. Ten Mile Lake demonstrated the highest rate of change in June with an average temperature change of 0.38° C per year (R^2= 0.58, p = 0.018). There was also a difference in the June rate of change between ecoregions, with the Northern Lakes and Forests ecoregion showing the highest rate of change and the Western Cornbelt Plains the lowest (Table 1).

Growing Degree Days

Overall, there has been a slight increase in GDD across the years 2009 to 2018, though it is not significant. Due to the variability in the data, nine years is probably too short of a time span to detect any strong trends but on average, there was an increase of 9.148 GDD per year across all lakes during the measured time period (Figure 6). There does not appear to be any ecoregion effect on the rate of increase for GDD; however, the mean annual GDD does follow expected patterns when separated by ecoregion (Table 2). In general, lakes in the Canadian Shield have the lowest annual GDD, while the lakes in the Western Cornbelt Plains have the most.

Stratification Duration

There was a large amount of variability in in the number thermally stratified days, both across lakes and years (Table 3). All lakes, with the exception of Greenwood, showed an increasing number of thermally stratified days over time (Table 3). The only lake with a significant trend was Madison (R squared = 0.944, p = 0.028), although the Madison sample size was limited to four years so in general this analyses should be revisited to give more time to elucidate any possible trends.

Discussion

There is high degree of natural, annual variability in water temperature data making it difficult to elucidate trends with a limited number of years. While the general intra-annual patterns of heating and cooling are consistent, most of the data were too varied to describe specific trends across the years. The strongest trend was the consistent increase in June mean monthly temperatures in all Sentinel Lakes which could have an effect on a number of lake processes such as the strength of lake stratification, life-history of organisms, autochthonous production, and dissolved oxygen depletion rates.

This amount of variability highlights the importance of long-term datasets when studying trends. Though the Sentinel Lakes Program has collected a large amount of water temperature data over the last ten years, it will require consistent data collection over even longer timespans to discern the difference between meaningful trends and natural annual variability. As the amount of data increases, so too will our ability to gain a greater understanding of these processes. Just as important as the long-term data collection will be ensuring the long-term integrity of the data. Throughout the life of the Sentinel Lakes Program we are learning and adopting new techniques to continually improve the quality of these data, minimizing the possibility of data gaps and errors.

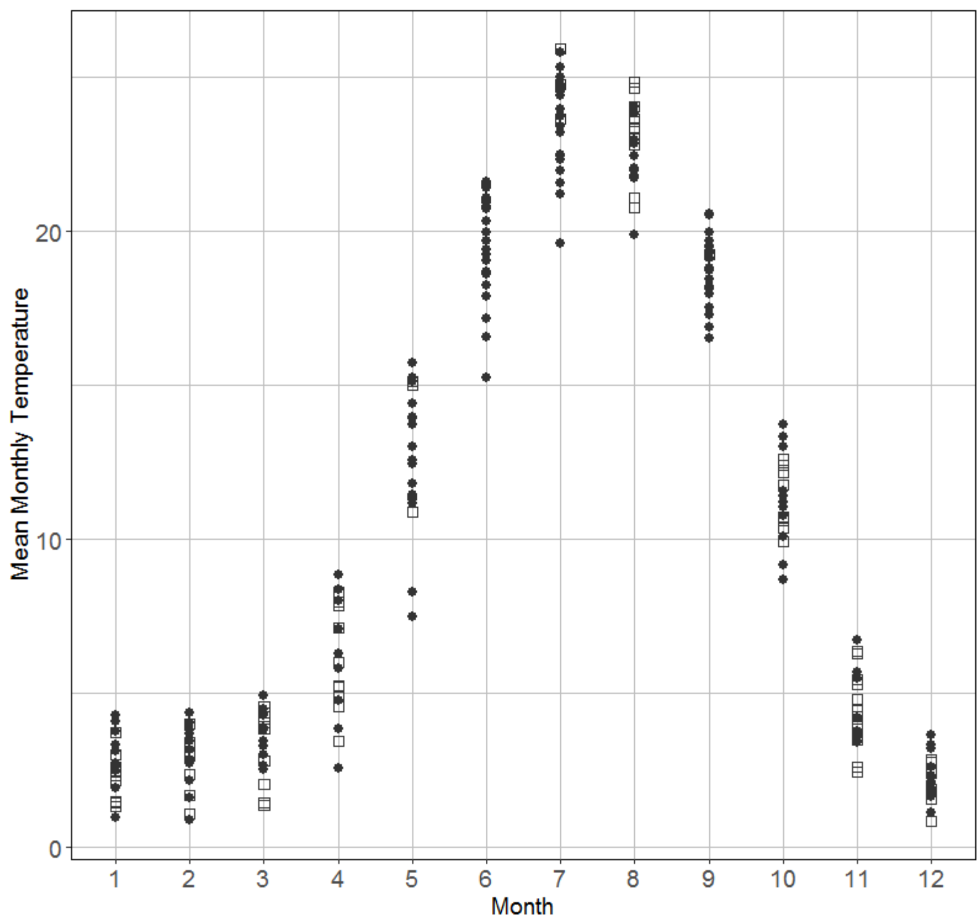

Figure 1. Mean monthly temperature across all years for each Sentinel Lake. Filled circles indicate lake months with positive slopes and open squares indicate negative slopes.

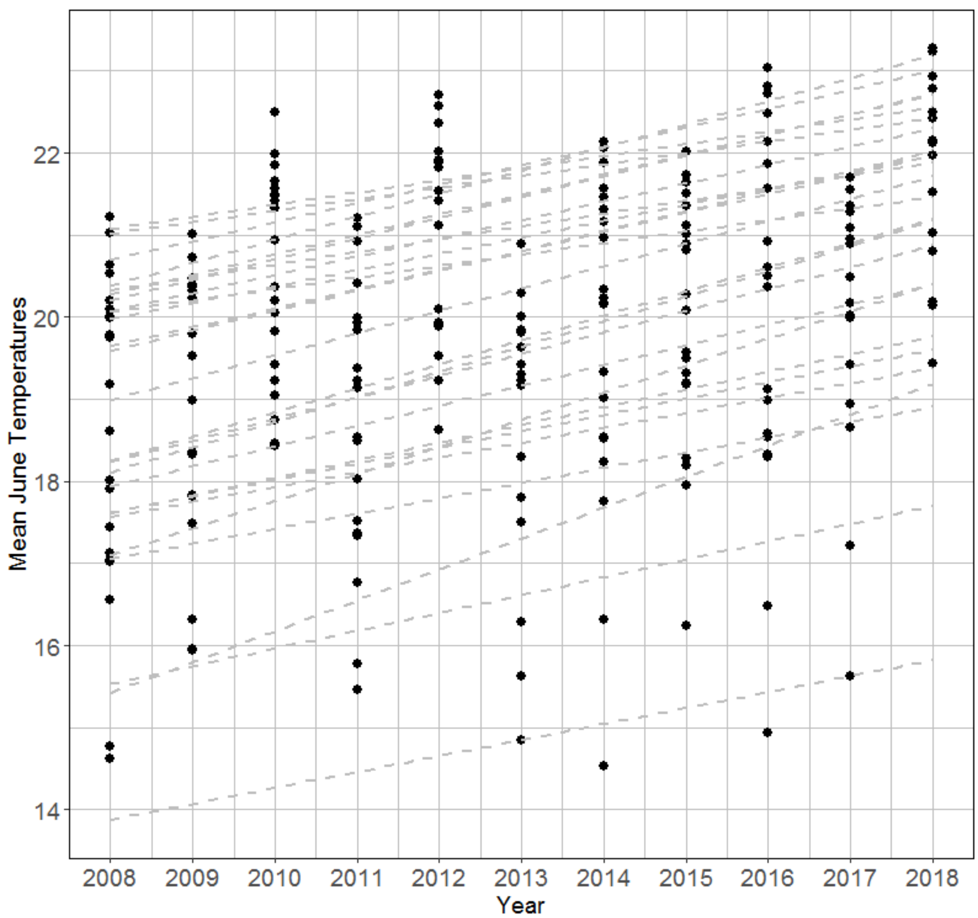

Figure 2. Mean June temperatures plotted across the years. The filled circles indicate the mean June temperature for each lake. The dashed lines are the linear regression lines for each lake across the years.

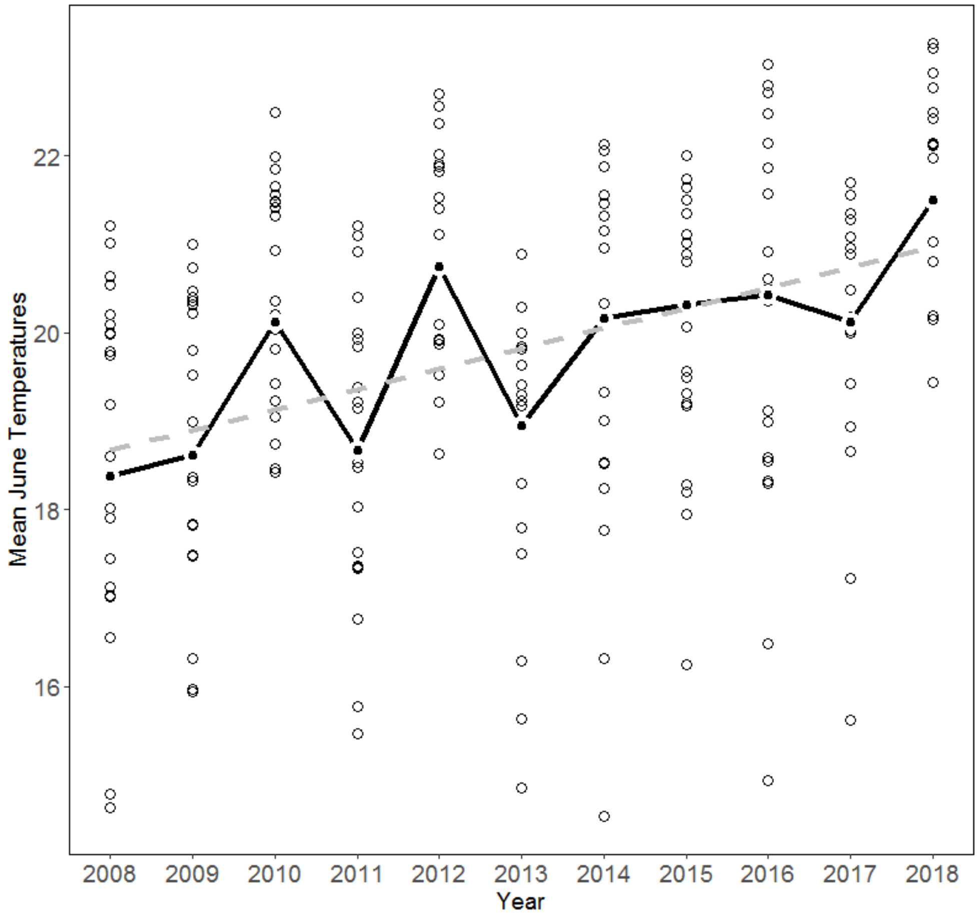

Figure 3. Plot of the linear mixed effects model for mean June temperatures across years. The open circles indicate the mean June temperature for each lake, the dashed gray line indicates the annual temperature linear trend (slope: 0.23), and the solid line indicates the annual year effect.

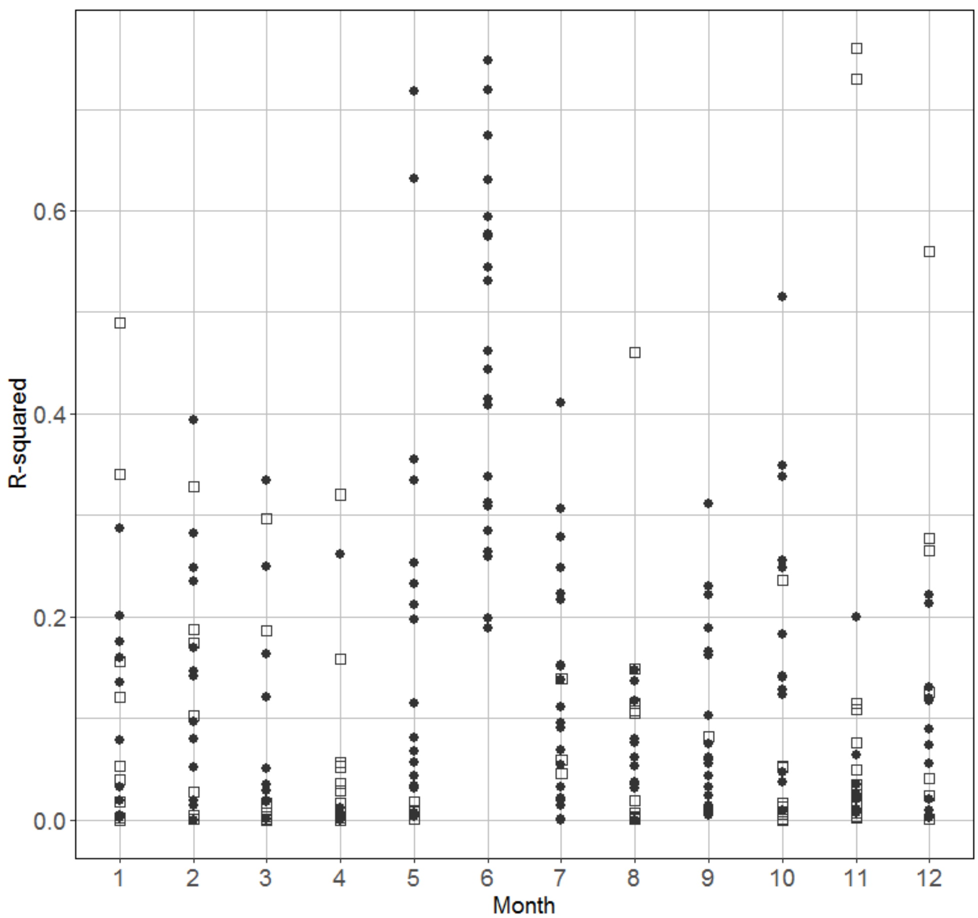

Figure 4. R-squared values for the mean monthly temperature linear regression models conducted on each lake. Filled circles indicate lake months with positive slopes and open squares indicate negative slopes.

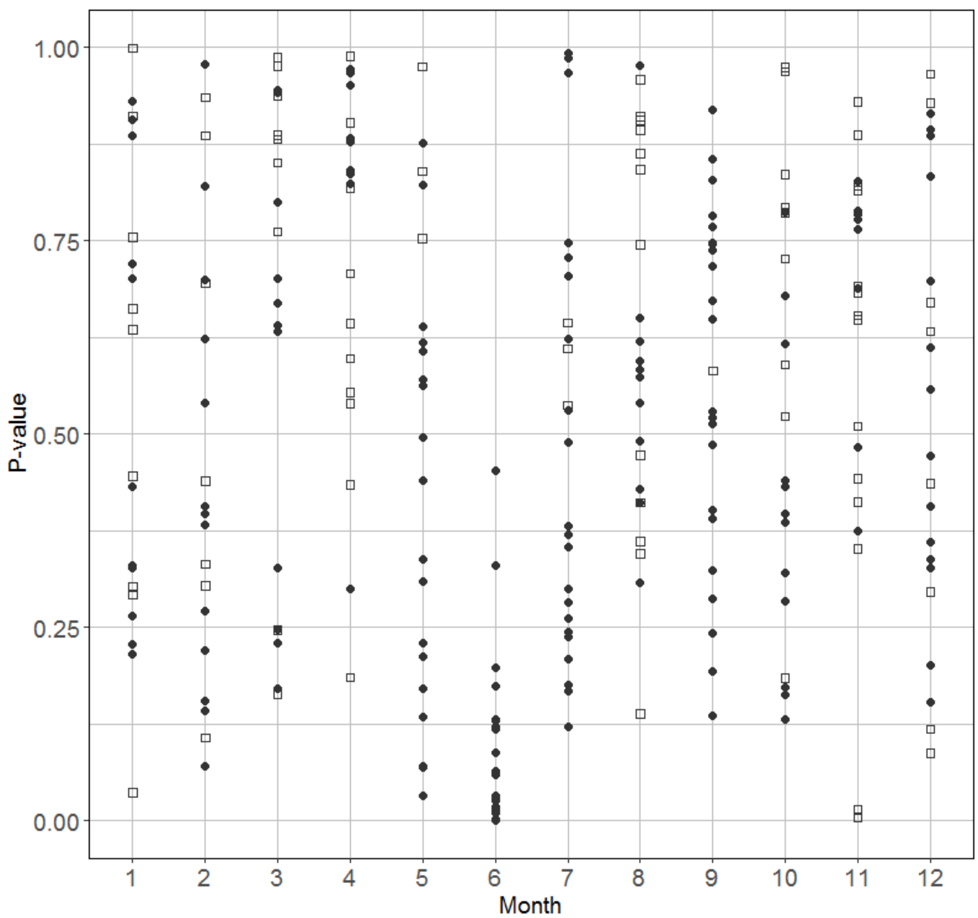

Figure 5. P-values for the mean monthly temperature linear regression models conducted on each lake. Filled circles indicate lake months with positive slopes and open squares indicate negative slopes.

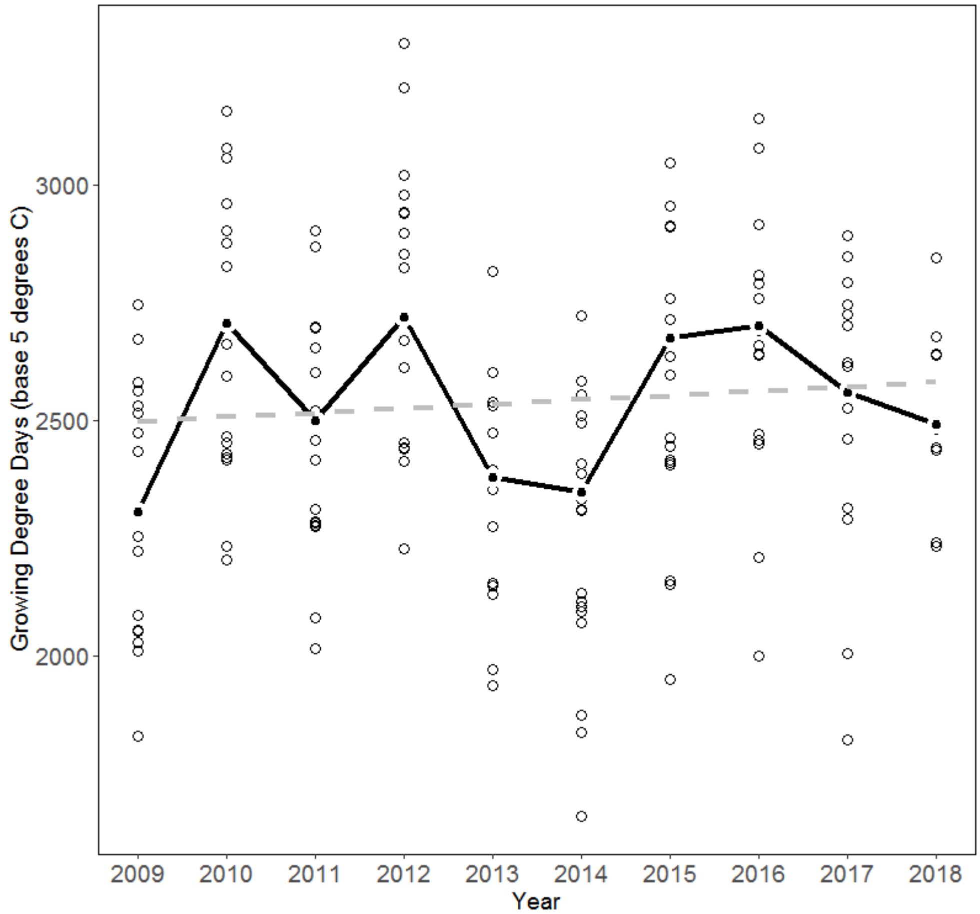

Figure 6. Annual GDD for each lake plotted across the years. The open circles indicate the total annual GDD for each lake. The dashed gray line indicates the annual GDD linear trend (slope: 9.15) and the solid line indicates the annual year effect.

Table 1. Mean slope values for June linear regression models separated by ecoregion.

Ecoregion	Mean Slope
Northern Lakes and Forests	0.27
North Central Hardwood Forests	0.23
Canadian Shield	0.20
Western Cornbelt Plains	0.20

Table 2. Lakes and ecoregions (shaded in gray) ordered by increasing mean GDD along with change in GDD per year.

Lake	Ecoregion	# of Years	Mean GDD	Change in GDD/Year
Greenwood	Canadian Shield	4	1857.28	53.20
Trout	Canadian Shield	9	2056.59	6.33
Tait	Canadian Shield	6	2074.78	-26.06
Echo	Canadian Shield	7	2255.91	15.96
Ten Mile	Northern Lakes and Forests	7	2256.17	26.33
White Iron	Canadian Shield	6	2281.15	14.39
Elephant	Canadian Shield	9	2300.04	17.85
Bear Head	Northern Lakes and Forests	9	2304.78	5.86
Hill	Northern Lakes and Forests	8	2477.52	10.07
South Twin	Northern Lakes and Forests	8	2502.34	5.51
Portage	Northern Lakes and Forests	9	2545.24	27.44
Elk	Northern Lakes and Forests	5	2569.03	-0.16
Artichoke	Western Corn Belt Plains	6	2611.10	9.36
Carlos	North Central Hardwood Forests	4	2636.83	64.65
Pearl	North Central Hardwood Forests	5	2673.59	33.10
Red Sand	Northern Lakes and Forests	4	2704.35	24.98
Belle	North Central Hardwood Forests	4	2704.36	-2.80
Cedar	North Central Hardwood Forests	10	2733.72	9.32
Carrie	Western Corn Belt Plains	9	2838.44	9.04
St. Olaf	Western Corn Belt Plains	5	2968.72	36.02
Madison	Western Corn Belt Plains	6	2979.81	0.13

Table 3. Lake, sample size, mean, maximum and minimum number of days lakes were thermally stratified.

Lake	# of Years	Mean	Max	Min	Slope	Ecoregion
Bear Head	5	104.60	88	122	4.20	Northern Lakes and Forests
Carlos	6	134.50	94	158	6.44	North Central Hardwood Forests
Elk	7	155.71	122	172	3.18	Northern Lakes and Forests
Greenwood	5	81.40	70	96	-3.30	Canadian Shield
Madison	4	94.50	65	115	16.60	Western Corn Belt Plains
Trout	9	129.78	91	150	2.78	Canadian Shield

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Water Level

Changes in lake water level can impact abiotic and biotic processes and be driven by large-scale stressors, such as climate change and extreme precipitation events. Therefore, monitoring lake levels is an important part of the Sentinel Lakes Long Term Monitoring Program. Several of the Sentinel Lakes include historical data collected before the inception of the program. These historical data were collected by taking readings from staff gauges placed at known elevations within the lake, and this method is currently used for the Tier 2 Sentinel Lakes. Over the past 10 years, the Sentinel Lakes Program has also deployed and maintained pressure transducer sensors (OTT Orpheus Mini) in up to 9 Tier 1 lakes to record hourly lake level data, which are then averaged into daily means. The Sentinel Lakes Water Level dataset is maintained by the MNDNR Ecological and Water Resources Unit and is available to the public on the MNDNR Lake Finder website (www.dnr.state.mn.us/lakefind/index.html).

We compiled the data for each lake from the Lake Finder website using the mnsentinellakes R package to summarize the mean lake levels of the Sentinel Lakes and describe the annual variability and trends in lake level (Table 1). We split the data into two time periods, first between the earliest records for the lake up to the most recent (grey) and second, during the 2008-2019 Sentinel Lakes Era (white). The number of years included for each lake are included in the table and collection began as early as 1925. The data were originally recorded in hundredths of feet (0.01 feet), but have been converted to meters for this analysis. All metrics are reported in meters. Additionally, the datum used to rectify the elevations varies from lake to lake. Mean Water Level is the mean value of all water level elevations collected for a particular lake. Max and Min Water Levels are the maximum and minimum values from those records, and Overall Range is the difference between those two values. Ten Year Trend is the slope of the trend line of mean annual water level for the most recent 10 years of data. In order for a particular year to be considered in the annual statistics, we required a minimum of 2 data points to be present within that year. We calculated Mean Annual Max, Min, and Range statistics by retrieving the maximum and minimum values, along with the difference between those values, for each year and averaging the yearly results. Max and Min Annual Ranges were calculated by determining the range for each year and retrieving the maximum and minimum of those ranges.

The mean overall range for all of the lakes in the Sentinel Lakes Era is 0.83 m; whereas, the mean annual range for all lakes is 0.33 m. Specific metrics for each Sentinel Lakes are located in Table 1. It is important to note that the number of samples varies among years. Some years have just a few recorded samples, and other years had samples recorded nearly daily. Additionally, the intra-annual seasonality may be different among years.

Table 1. Lake specific summary of two time periods (historical and recent) for mean water level, maximum water level, minimum water level, range in water level, mean annual maximum water level, mean annual minimum water level, mean annual range in water level, maximum annual range in water level, minimum annual range in water level and the ten year trend in water level.

Lake	Year Range	# of Years with Records	Mean Water Level (m)	Max Water Level (m)	Min Water Level (m)	Overall Range (m)	Mean Annual Max (m)	Mean Annual Min (m)	Mean Annual Range (m)	Max Annual Range (m)	Min Annual Range (m)	Ten Year Trend
Artichoke	1957 - 2019	26	329.87	330.37	328.85	1.52	330.04	329.73	0.17	0.27	0.04	-0.00442
	2008 - 2019	12	329.95	330.37	329.66	0.72	330.04	329.73	0.17	0.27	0.04	
Bear Head	2008 - 2018	11	458.87	459.05	458.59	0.46	458.96	458.59	0.20	0.32	0.10	0.01101
	2008 - 2018	11	458.87	459.05	458.59	0.46	458.96	458.59	0.20	0.32	0.10	
Belle	1943 - 2019	38	328.33	329.09	325.42	3.67	328.46	325.87	0.36	0.70	0.02	
	2008 - 2019	12	328.37	329.09	327.82	1.27	328.58	327.82	0.35	0.70	0.17	0.03432
Carlos	1925 - 2019	67	413.43	413.92	412.01	1.91	413.45	412.01	0.25	0.73	0.00	
	2008 - 2019	12	413.60	413.88	413.30	0.58	413.70	413.30	0.26	0.43	0.13	0.00917
Carrie	1980 - 2019	40	343.27	343.71	342.75	0.96	343.41	342.75	0.23	0.58	0.02	
	2008 - 2019	12	343.25	343.55	342.95	0.60	343.41	342.95	0.29	0.45	0.17	0.01576
Cedar	1959 - 2019	35	368.58	368.86	368.28	0.59	368.71	368.28	0.26	0.40	0.08	
	2008 - 2019	12	368.57	368.82	368.28	0.55	368.70	368.28	0.27	0.40	0.11	0.00347
Echo	2008 - 2018	11	370.32	370.85	369.58	1.26	370.64	369.58	0.63	1.11	0.20	
	2008 - 2018	11	370.32	370.85	369.58	1.26	370.64	369.58	0.63	1.11	0.20	0.01974
Elephant	2002 - 2018	12	397.12	397.50	396.83	0.68	397.33	396.83	0.33	0.63	0.24	
	2008 - 2018	11	397.12	397.50	396.83	0.68	397.33	396.83	0.33	0.63	0.24	0.02762
Elk	1938 - 2019	29	447.98	448.24	447.31	0.94	447.96	447.31	0.18	0.49	0.00	
	2008 - 2019	12	448.02	448.24	447.95	0.29	448.13	447.95	0.16	0.28	0.00	0.01061
Greenwood	2014 - 2018	5	29.25	29.60	28.80	0.80	29.45	28.80	0.42	0.59	0.30	
	2014 - 2018	5	29.25	29.60	28.80	0.80	29.45	28.80	0.42	0.59	0.30	-0.03984
Hill	1937 - 2019	60	387.34	388.20	386.75	1.44	387.49	386.75	0.46	1.27	0.00	
	2008 - 2019	12	387.07	388.08	386.75	1.32	387.41	386.75	0.53	1.27	0.00	-0.0004
Madison	1939 - 2019	71	309.61	310.59	305.71	4.87	309.78	305.71	0.50	1.53	0.01	
	2008 - 2019	12	309.99	310.59	309.27	1.31	310.15	309.27	0.43	0.81	0.20	0.02644
Pearl	1946 - 2019	40	340.21	341.07	339.94	1.13	340.38	339.94	0.20	0.80	0.04	
	2008 - 2019	12	340.20	340.74	340.09	0.65	340.37	340.09	0.20	0.43	0.09	-0.00511
Peltier	1951 - 2018	66	269.38	270.24	267.30	2.94	269.77	267.30	0.78	2.47	0.12	
	2008 - 2018	10	269.62	269.79	269.51	0.29	269.72	269.51	0.17	0.23	0.12	0.0078
Portage	1958 - 2019	36	437.13	437.32	436.71	0.61	437.19	436.96	0.11	0.24	0.00	
	2008 - 2019	12	437.14	437.32	436.97	0.35	437.22	436.97	0.13	0.20	0.04	-0.00284
Red Sand	1972 - 2019	23	365.16	365.73	364.62	1.11	365.23	364.67	0.20	0.36	0.05	
	2008 - 2019	12	365.20	365.73	364.69	1.04	365.32	364.69	0.23	0.36	0.13	0.05067
Shaokotan	1961 - 2019	33	541.25	541.73	540.43	1.30	541.36	540.67	0.36	0.71	0.05	
	2008 - 2019	12	541.32	541.65	540.76	0.89	541.42	540.76	0.39	0.56	0.26	0.01868
South Center	1968 - 2018	37	273.76	274.83	272.62	2.21	273.88	272.62	0.45	1.03	0.15	
	2018	1	273.35	NA	NA	NA	NA	NA	NA	NA	NA	-0.00791
South Twin	1937 - 2019	46	440.23	440.71	439.90	0.81	440.36	439.90	0.23	0.42	0.04	
	2008 - 2019	12	440.28	440.51	440.06	0.45	440.37	440.06	0.17	0.23	0.09	-0.00376
St. James	1984 - 2019	33	328.77	329.85	327.20	2.65	329.06	327.20	0.55	1.94	0.18	
	2008 - 2019	12	328.83	329.68	327.20	2.48	329.23	327.20	0.70	1.94	0.25	0.02391
St. Olaf	1942 - 2019	31	365.92	366.27	365.13	1.13	366.10	365.62	0.33	0.65	0.12	
	2008 - 2019	12	365.96	366.22	365.62	0.60	366.11	365.62	0.29	0.41	0.12	0.00057
Tait	2009 - 2018	10	539.61	539.87	539.39	0.48	539.76	539.39	0.25	0.34	0.16	
	2009 - 2018	10	539.61	539.87	539.39	0.48	539.76	539.39	0.25	0.34	0.16	0.0095
Ten Mile	1973 - 2019	47	420.44	420.69	419.86	0.84	420.55	419.86	0.20	0.45	0.01	
	2008 - 2019	12	420.46	420.69	420.29	0.41	420.57	420.29	0.16	0.29	0.01	0.00112
Trout	2008 - 2018	11	505.67	506.05	505.30	0.75	505.91	505.30	0.39	0.57	0.14	
	2008 - 2018	11	505.67	506.05	505.30	0.75	505.91	505.30	0.39	0.57	0.14	-0.01312
White Iron	1995 - 2018	24	422.34	423.16	421.46	1.70	422.77	421.46	0.65	1.60	0.14	
	2008 -2018	10	422.34	423.16	421.46	1.70	422.76	421.46	0.75	1.60	0.29	0.01475

Water Chemistry

Summary of Water Chemistry Status and Trends in Minnesota's Sentinel Lakes
May, 2019; Jesse Anderson and Lee Engel, MPCA

This report summarizes 10 years of water quality sampling as part of the Sentinel Lakes Program, reporting both spatial and temporal changes of principle water quality indices. In addition, this report provides details of several unique case studies of water quality changes as well as baseline averages of water quality parameters for all 25 lakes.

Sentinel Lakes Background

The value of lakes as indicators of environmental health, and the importance of long-term data collection in these resources are well established (Williamson et. al., 2009; Hampton and Stanley, 2013). In 2008 the Minnesota Department of Natural Resources and Minnesota Pollution Control Agency initiated a collaborative long-term program to monitor 25 representative lakes across Minnesota's diverse ecoregions, stratified by depth and trophic state / nutrient levels. Lakes in the Sentinel Lakes Program range from oligotrophic lake trout lakes in northern Minnesota's boreal forest, to shallow hypereutrophic lakes in the agricultural southwest. The three primary goals of the Sentinel Lakes Program are 1- to identify important biological, physical, and chemical trends in Minnesota lakes; 2 - identify the mechanisms behind these trends; and 3- identify management solutions to ensure long-term sustainability of Minnesota's lakes - given the presence of disturbances such as lakeshore development, climate change, and aquatic invasive species.

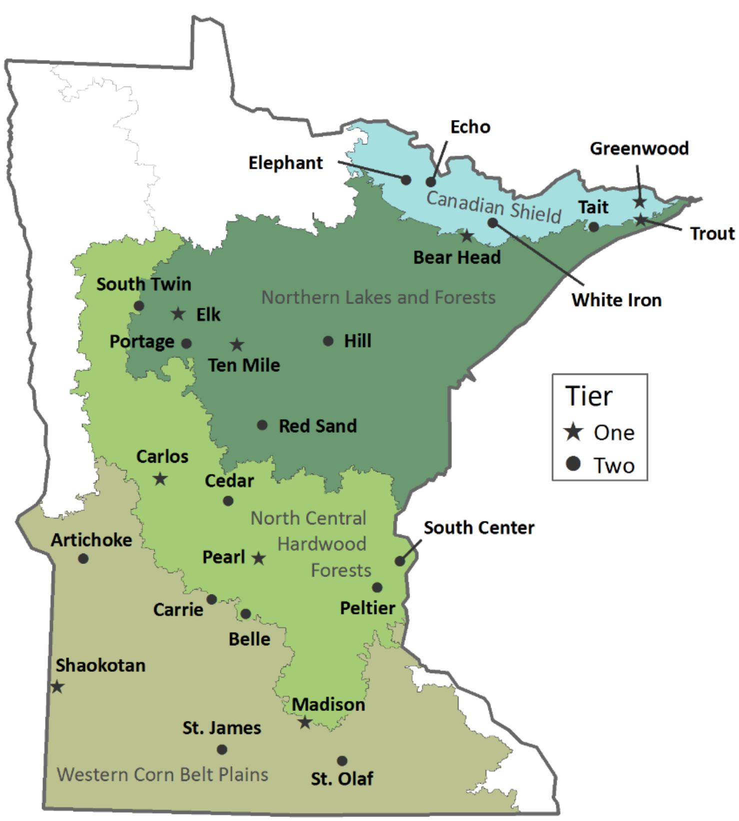


Figure 1. Minnesota's Sentinel Lakes and Ecoregions (MN DNR)

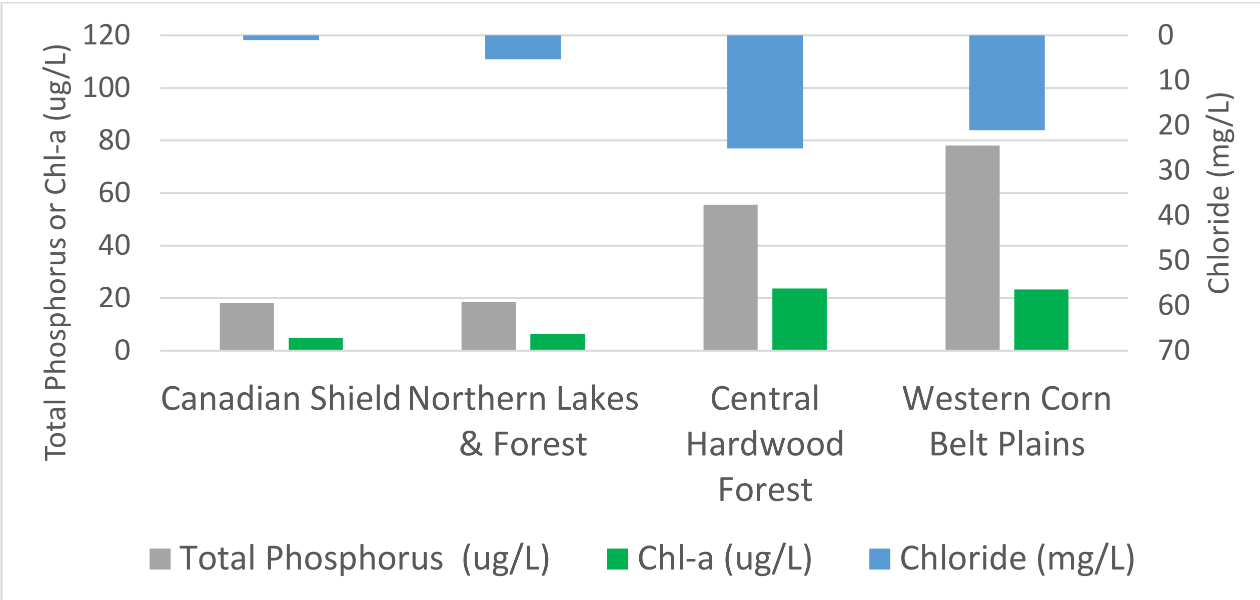
MPCA staff monitored the Sentinel Lakes monthly from May – October in 2008-2009 to gather a baseline dataset in each lake. Subsequently, the lakes were divided into two tiers, with Tier 1 lakes as a priority - monitored annually, and Tier 2 lakes monitored less frequently, following the MPCA's Intensive Watershed Monitoring Schedule (two years per decade). MPCA and DNR staff have developed detailed lake assessment reports for all 25 lakes (https://www.dnr.state.mn.us/fisheries/slice/index.html). The 2008-2018 average concentrations of principal water chemistry parameters collected for the Sentinel Lakes Program are summarized in Table 1. These data are limited to the site visits by MPCA staff, to make the datasets as comparable as possible for the purposes of this report. Many lakes in the network have been monitored by other organizations before the origination of the Sentinel Lakes Program, or since the MPCA's baseline monitoring period; these data will be the subject of future updates to the lake-specific assessment reports.

Regional nature of Minnesota lake water quality

Previous MPCA studies have documented the regional nature of Minnesota's lake water quality, the natural gradient of trophic status across Minnesota's diverse ecoregions (Figure 1), and how these conditions were used to derive nutrient criteria (Heiskary and Wilson, 1989; Heiskary and Wilson, 2008). In summary, lakes in the Northern Lakes and Forests ecoregions are moderately deep with watersheds dominated by forest and wetland land uses, and trophic status is typically oligotrophic to mesotrophic. Lakes in the Central Hardwood Forest (CHF) ecoregion are also moderately deep with watersheds characterized by a mosaic of land uses, and trophic status is typically mesotrophic to mildly eutrophic. Lakes in the Western Corn Belt Plains ecoregion are predominately shallow with dominant agricultural land use, and typical trophic status ranges from eutrophic to hypereutrophic. Most of the Sentinel Lakes which are declared Impaired are due to exceedances of the MCPA's nutrient criteria in central and southern MN (Table 1); exceptions include Portage Lake (which is close to the CHF Ecoregion boundary and has significant agricultural landuse in the vicinity), and Echo Lake in Superior National Forest (which is exceeding standards due to natural conditions).

The robust Sentinel Lakes datasets confirmed these regional patterns. To visually represent this, Figure 2 shows the mean total phosphorus, chlorophyll-a, and chloride concentration by ecoregion (sorted northeast to southwest across the state). Lake productivity increases along this ecoregion gradient; with the lowest phosphorus concentrations in the north, moderate in the central region, and highest in the agricultural south and southwest. Chloride concentrations in surface water are often used as a proxy for human disturbance. Main sources of chloride in Minnesota waters include road salt, water softeners, and agricultural sources (https://www.pca.state.mn.us/water/chloride-101). In the Sentinel Lakes, chloride concentrations are low (often below detection) in the Canadian Shield and increase from north to south (chloride concentrations do not exceed water quality standards in any Sentinel Lake). Conductivity and alkalinity show similar trends (Table 1), as water "hardness" generally increases across the same gradient.

Figure 2. Sentinel Lakes average water quality conditions by ecoregion, 2008-2018



Sentinel Lakes Water Quality Status and Trends; Case Studies from Sentinel Lakes

We now have a decade of annual sampling on the Tier 1 lakes allowing us to evaluate water quality trends in key parameters over time. MPCA and other studies (Smeltzer et al., 1989; Heiskary, et al., 1993) have determined that at least 8 consecutive years of monthly sampling are necessary to detect subtle changes of 10-20 percent in water quality trends. Only some Tier 1 lakes and parameters meet this criteria since 2008 (Table 2) due to budgetary and logistical circumstances with monitoring efforts. A few lakes have statistically significant trends from 2008-2018 in key water quality parameters, as shown in Table 2 ($p < 0.05$). In two of these cases the statistically significant trends are minor; such as a decline in total Kjeldahl nitrogen in Trout Lake of approximately 0.1 mg/L, and an increase in Secchi transparency in Ten Mile Lake of about 1 meter (the long term dataset from 1974-2018 indicates no trend). The trends identified in Carlos are ecologically substantial and are discussed in more detail as a case study later in this report.

In a few years, all Tier 1 lakes will have met the 8 year minimum threshold for trend detection; future reports will describe these results.

Table 2. Water Quality Trends in Tier 1 Sentinel Lakes, 2008-2018. Lakes and parameters with sufficient data (at least 8 years of monthly samples) are displayed; statistical test is parametric F test for linear trends from R (https://www.r-project.org/). Data analysis by Tim Martin, MN DNR

Tier 1 Lake	Parameter	Years of data, 2008-2018	Statistically Significant Trend (Y/N)	Trend Direction
Trout	Chloride	8	**N**	
Trout	Chlorophyll a	9	**N**	
Trout	Depth, Secchi disk depth	9	**N**	
Trout	Kjeldahl nitrogen	8	**Y**	**Declining**
Trout	Phosphorus	8	**N**	
Ten Mile	Chlorophyll a	10	**N**	
Ten Mile	Phosphorus	9	**N**	
Ten Mile	Depth, Secchi disk depth	9	**Y**	**Increasing**
Ten Mile	Kjeldahl nitrogen	9	**N**	
Elk	Chlorophyll a	9	**N**	
Elk	Kjeldahl nitrogen	8	**N**	
Elk	Phosphorus	8	**N**	
Carlos	Chlorophyll a	10	**Y**	**Declining**
Carlos	Phosphorus	9	**N**	
Carlos	Depth, Secchi disk depth	9	**Y**	**Increasing**
Carlos	Kjeldahl nitrogen	9	**N**	

Lake water clarity (or transparency) measured by a Secchi disk, is a common, principal water quality metric. Most Sentinel Lakes have longer historical Secchi datasets that predate the Sentinel Lake monitoring program. A few lakes have Secchi transparency data dating back decades (such as Carlos, to 1948). Six Sentinel Lakes were selected as MPCA Ecoregion Reference Lakes, and have data since in the early 1980's (Trout, Greenwood, Artichoke, Elk, Carlos and St. Olaf). Trends in Secchi transparency over their entire period of record have been determined for all Sentinel lakes (Table 3). The MPCA standard metric for a statistically significant change in transparency is a change greater than 0.5 feet per decade. No Sentinel Lakes have declining transparency, and most lakes are stable. A few lakes have increasing transparency, they range from minor (~ 0.5 meter increase in Bearhead) to significant (Lake Carlos, see Figure 6 below).

Table 3. Long-term trends in Secchi Transparency at the Sentinel Lakes, through 2018 (lakes' ecoregion in parenthesis)

Stable Transparency	Increasing Transparency	Decreasing Trends
White Iron (Shield)	Bearhead (Shield)	(None)
Tait (Shield)	S. Twin (N. Forest)	
Echo (Shield)	Carlos (Transition)	
Elk (N. Forest)	Cedar (Transition)	
Hill (N. Forest)	Carrie (Prairie)	
Artichoke (Prairie)	Belle (Transition)	
St. James (Prairie)	Shaokotan (Prairie)	
Madison (Prairie)		
St. Olaf (Prairie)		
Trout (Shield)		
Elephant (Shield)		
Greenwood (Shield)		
Pearl (Transition)		
Peltier (Transition)		
Portage (N. Forest)		
Red Sand (N. Forest)		
South Center (Transition)		
Ten Mile (N. Forest)		

It is important for lake practitioners to critically examine the trend results from the Sentinel Lakes and place the data in historical context. Starting in 2008, there has been annual, consistent data collection on each Tier 1 lake but this represents a shorter time frame compared to longer historical collections potentially resulting in different temporal trends. As an example, shown in Figure 3, there are slight differences in the long-term versus Sentinel program trends on Trout Lake (an oligotrophic lake near Grand Marais). The long term data indicates a slight linear decline in water clarity from 1984 to 2018 compared to a slight increase in clarity from 2008-2018. A more robust Seasonal Kendall non-parametric test indicates no change in water clarity over the long-term (Figure 4). There are numerous factors that influence water quality conditions and trends, such as changes or gaps in annual sampling efforts, variability in weather and climate, landuse changes, food web effects, and natural variability in field and laboratory methods. The strength of the Sentinel Lakes Program is consistent sampling methods employed over the long-term, which minimizes some of this variability. This allows lake managers to determine if trends are of statistical versus environmental significance, and relate results to the program's overall goals. Returning to the example of Trout Lake, water clarity is likely quite stable, and within the bounds of natural annual variability, given the lake's environmental setting and limited disturbance within the watershed.

Figure 3. Long term Secchi Trends in Trout Lake (16-0049). Entire time period linear trend displayed by black line, Sentinel monitoring period (2008-2018) shown in red line.

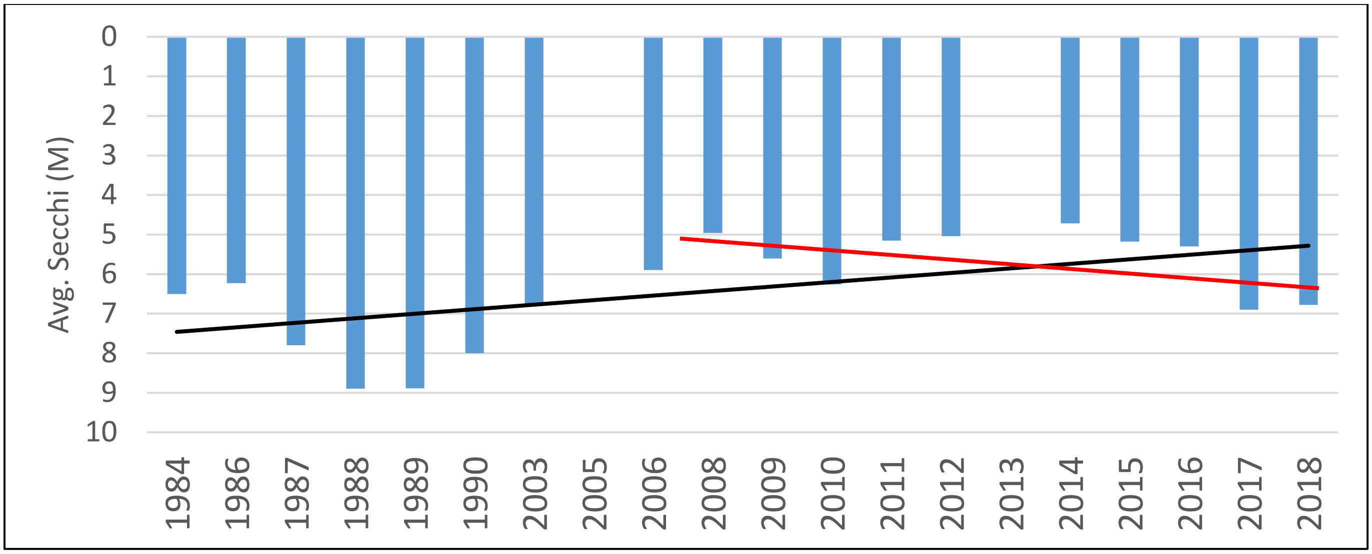
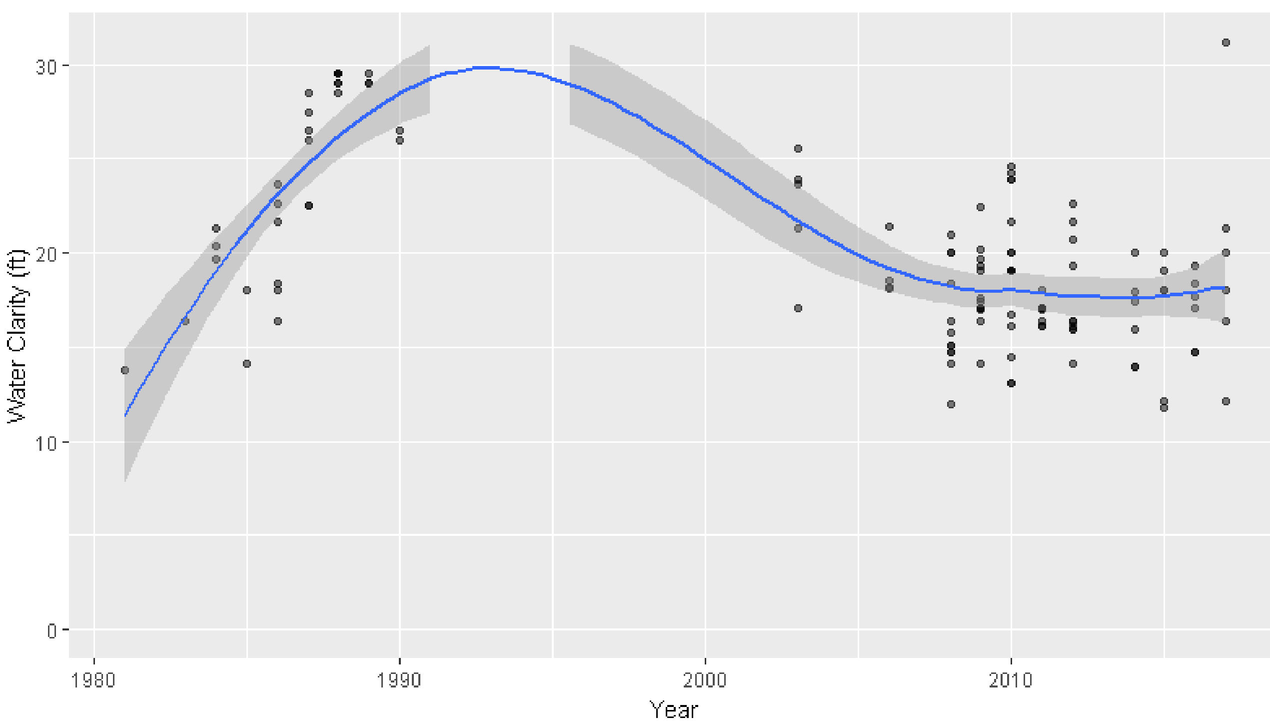


Figure 4. Seasonal Kendal trend test on same Trout Lake dataset. Source, MPCA
https://cf.pca.state.mn.us/water/watershedweb/wdip/waterunit.cfm?wid=16-0049-00

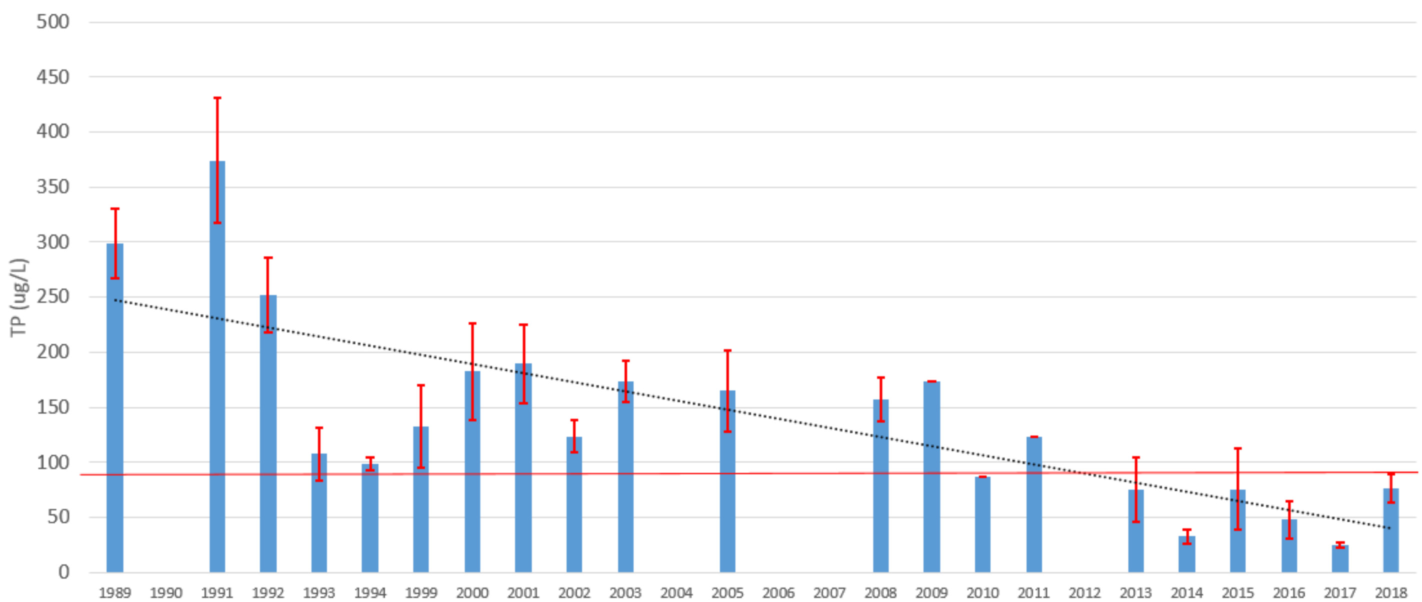


There are several examples of the Sentinel Lakes datasets augmenting past water quality studies and documenting important trends in water quality. Some highlights are discussed below.

Lake Shaokotan, successful water quality restoration

Lake Shaokotan, in southwest Minnesota, is a large, shallow prairie lake within an agricultural landscape. Shaokotan has a long history of nuisance algal blooms. Work began in the early 1990's by the Yellow Medicine County Watershed District, the MPCA and many other partners to study the lake and its pollution sources. Restoration efforts began in 1993, including remediation of feedlots and wetland restoration. The MPCA listed the lake as impaired in 2002, due to exceedances of regional phosphorus and chlorophyll-a standards. Post restoration, monitoring through the Sentinel Lakes Program has shown a continued decline in phosphorus concentrations. In 2016, the lake was removed from the Impaired Waters list, due to attainment of the phosphorus standard (Figure 5). In recent years, the lake has successfully been shifted from the algae dominated turbid water state, to a clear-water state dominated by rooted aquatic macrophytes- the key metric in supporting aquatic recreation. These transitions are difficult to achieve and maintain; continued monitoring will allow the MPCA and DNR to track and better understand the lake's ecology long-term. For more information, visit this website: https://www.pca.state.mn.us/featured/lake-shaokatan-prairie-lake-improving-water-quality

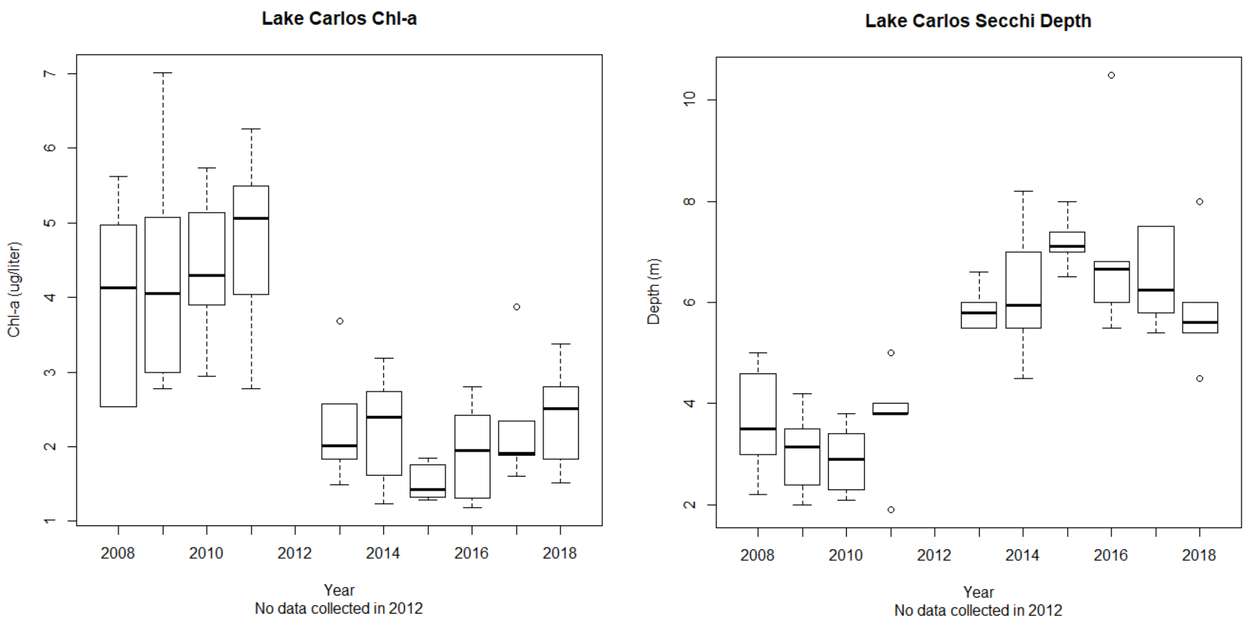
Figure 5. Reduction in total phosphorus concentrations in Lake Shaokotan. Red Line is regional phosphorus standard (90 ug/L); dotted blue line is linear trend.



Lake Carlos, shift in lake productivity following zebra mussel infestation

Lake Carlos was chosen as a Sentinel Lake due its large size, deep basin, low nutrients and healthy cisco population. The lake is a very popular recreation destination, and includes a state park on the North shore. Carlos is infested with the invasive zebra mussel and curly-leaf pondweed. In 2009, zebra mussels were first identified in the lake and by approximately 2013 the population was well established. This transition has had a dramatic effect on water quality as documented through Sentinel Lake monitoring. Chlorophyll concentrations have declined dramatically, and correspondingly, Secchi transparency has approximately doubled from about 3.5 to 7 meters (Figure 6). Similar findings have been documented in other lakes with long-term zebra mussel infestations, such as Lake Millie Lacs and other lakes in the Carlos chain (Heiskary and Egge, 2016).

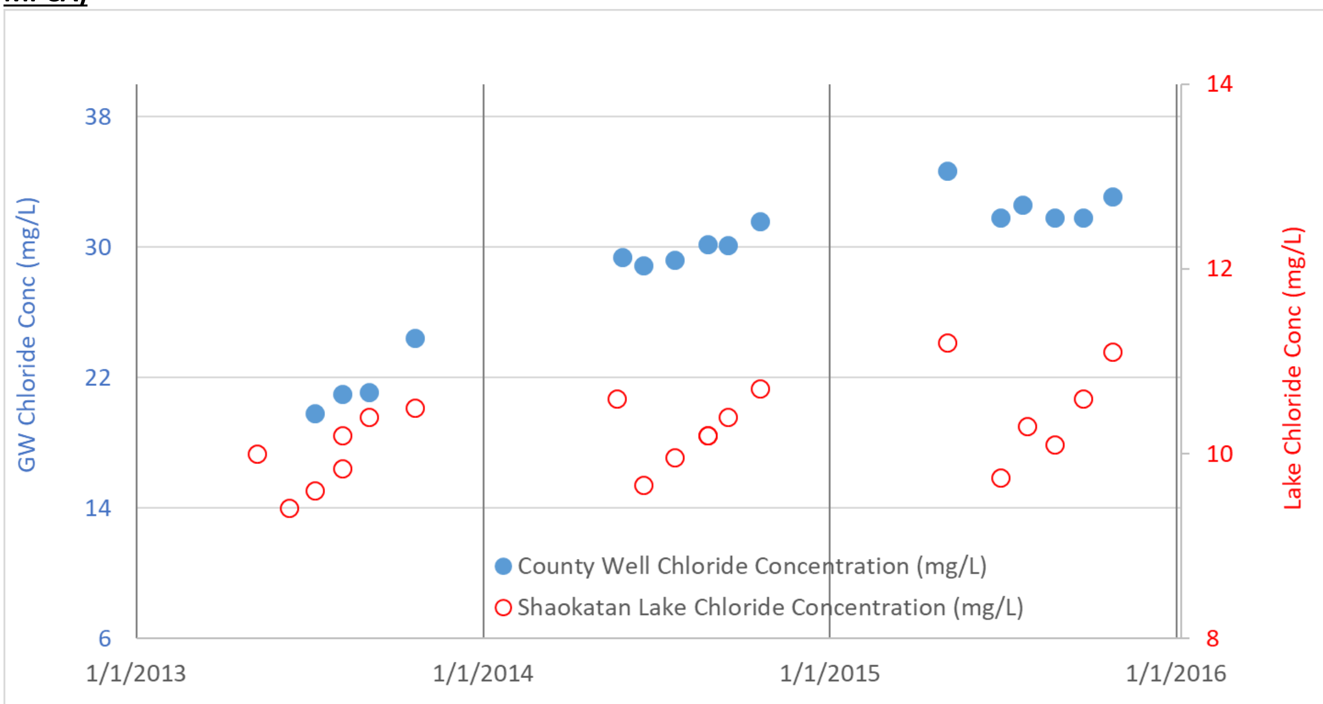
Figure 6. Changes in Chlorophyll-a and Secchi Transparency in Lake Carlos following zebra mussel infestation.



Groundwater / surface water interactions in a subset of Tier 1 Lakes

The consistent water quality and biological monitoring efforts of the Sentinel Lakes network have resulted in numerous monitoring partnerships, and interdisciplinary research to the benefit of all Minnesota lakes. An example is the MPCA's groundwater / surface-water interaction study in a subset of the Tier 1 Sentinel Lakes. From 2013-2016, monitoring wells and instrumentation were installed on the public shorelines of four Tier 1 lakes (Bearhead, Pearl, Madison and Shaokotan) to study annual and seasonal variations in lake level, ground water elevations, and lake and groundwater quality. MPCA staff sample ground water and record groundwater table elevations the same day as lake water samples are collected. Since 2013, some interesting trends have been documented in the paired shallow ground water and lake chloride concentrations in Shaokotan Lake (Figure 7). Ground water chemistry and elevation have a strong control of chloride concentrations in the lake; peaking and quickly declining in spring, and then gradually rising through the growing season. MPCA staff will continue this partnership and are researching the causes and consequences of this phenomena.

Figure 7. Paired chloride concentrations in Lake Shaokotan and shallow groundwater adjacent to lake (Andrew Streitz, MPCA)



In conclusion, two other large sources of lake water quality data illustrate that Minnesota's Sentinel Lakes network is representative of Minnesota's diverse lake population. The EPA's National Lakes Survey takes place every 5 years, and is conducted to survey the condition of the country's lakes and reservoirs. In 2012, the MPCA sampled 149 lakes selected at random for this effort. Over the last decade, the MPCA and our local partners have monitored over 3,000 lakes statewide as part of our Intensive Watershed Monitoring Program, funded through the Clean Water Fund. The median statewide total phosphorus concentration among the Sentinel Lakes, EPA National Survey Lakes, and the MPCA's Lakes Database is similar, approximately 25 µg/L. (Figure 8).

In addition, the proportion of Sentinel Lakes exceeding Minnesota's regional nutrient criteria and declared impaired (28%, 7 of 25; Table 1), is similar to results in the MPCA's statewide assessment dataset (approximately 30% impaired, 70% meeting standards over ~ 2,500 lakes assessed during the last decade).

Figure 8. Median Statewide Total Phosphorus Concentration (ug/L) Across Minnesota's Lake Monitoring Programs

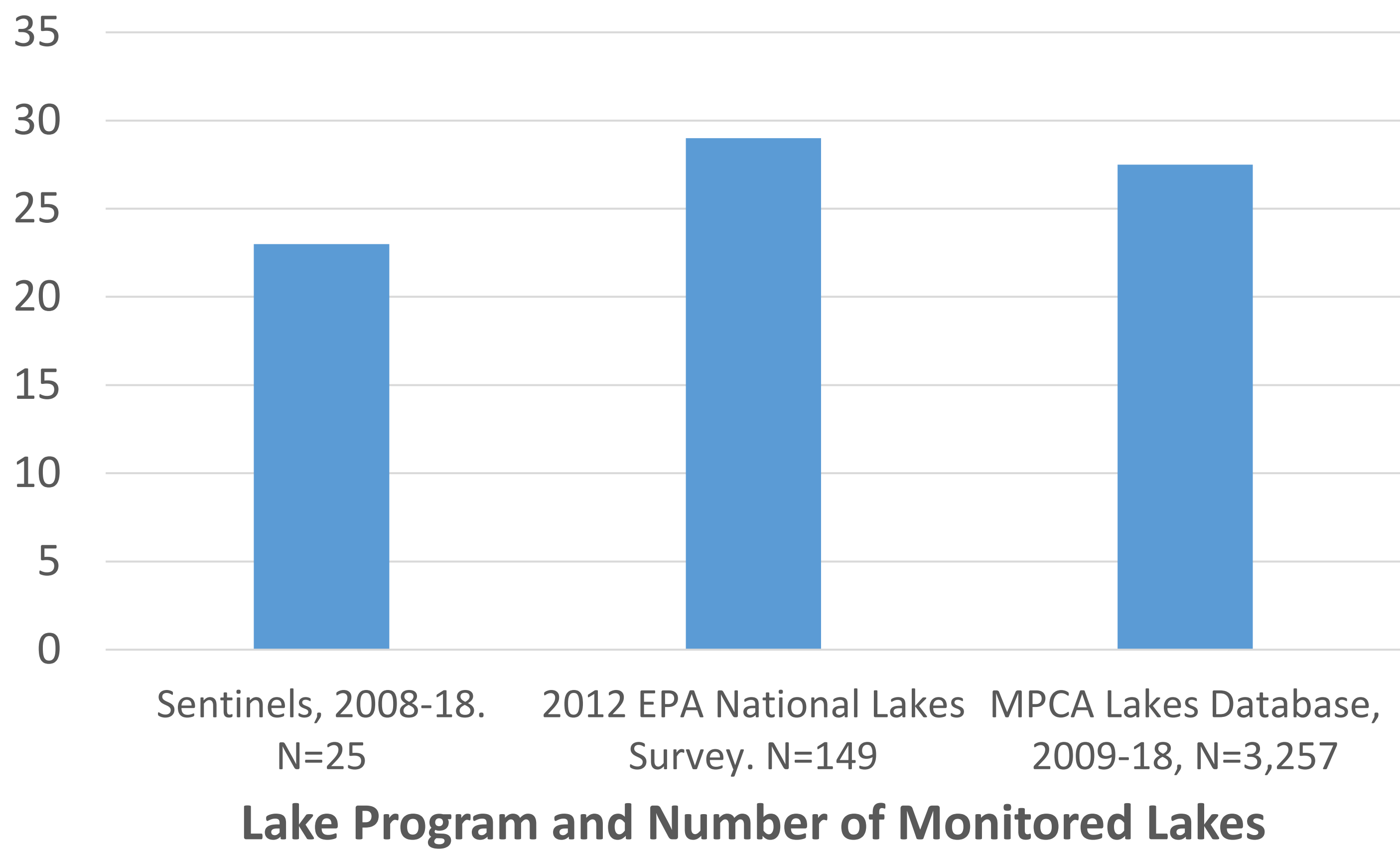


Table 1. 2008-2018 Mean values of select water quality parameters for all Sentinel Lakes. Data are in mg/L unless noted
Lakes in red are impaired waters and exceed the MPCA's Regional Eutrophication Standards.

Lake	Tier 1 / 2 (# Samples)	Eco-Region ***	Alk-alinity	Ca.	Chloride	Chl-a	Secchi Depth (M)	Iron (ug/L)	Total Kjeldahl Nitrogen	Mag.	Total Organic Carbon	pH (su)	Total P.	T. Ortho P	Silica	Sp.Cd. (µs/cm)	SO_4	TSS
Greenwood	1 (22)	CS	10.7	2.6	0.7	3.0	5.0	17.6	0.3	1.0	4.9	7.2	0.007	0.004	1.6	24	1.9	6.0
Trout	1 (62)	CS	14.2	4.2	0.8	1.8	5.4	18.4	0.3	1.6	3.9	7.3	0.007	0.005	6.3	37	3.0	2.2
Echo *	2 (27)	CS	14.7	4.8	1.1	9.2	1.1	419.9	0.8	2.0	14.3	7.1	0.041	0.005	5.3	40	1.6	8.8
Elephant	2 (31)	CS	39.1	10.6	1.1	8.1	3.0	46.0	0.7	4.0	9.2	7.5	0.023	0.006	6.1	83	2.5	2.8
Tait	2 (35)	CS	16.0	5.1	0.8	3.4	2.5	119.2	0.5	1.7	8.7	7.3	0.013	0.005	5.1	39	2.0	3.2
White Iron	2 (35)	CS	20.0	6.3	1.7	4.2	1.8	312.6	0.7	3.4	13.7	7.1	0.017	0.005	6.4	56	3.9	2.9
Bear Head	1 (52)	NLF	16.7	6.4	0.7	5.2	3.4	103.9	0.5	1.6	7.1	7.3	0.011	0.004	2.7	39	1.0	2.3
Elk	1 (60)	NLF	161.2	33.7	0.9	6.0	2.9	25.9	0.6	17.1	6.8	8.4	0.014	0.005	8.1	286	0.9	2.9
Ten Mile	1 (108)	NLF	111.8	25.2	1.5	2.4	5.1	14.6	0.4	11.8	3.5	8.3	0.009	0.005	7.7	206	1.0	2.7
Hill (North Basin)	2 (31)	NLF	152.4	43.1	7.3	9.2	3.0	15.2	0.6	14.2	7.5	8.2	0.026	0.007	8.1	307	7.4	3.3
Portage	2 (39)	NLF	156.1	36.3	7.5	14.1	1.8	41.8	0.8	19.8	4.4	8.3	0.035	0.005	0.2	305	4.6	5.3
Red Sand	2 (11)	NLF	78.9	22.9	16.1	4.3	3.7	121.6	0.9	6.1	8.0	8.4	0.021	0.006	3.7	194	1.0	1.9
South Twin	2 (36)	NLF	165.8	32.0	3.1	3.8	3.8	17.5	0.6	21.4	5.6	8.4	0.014	0.005	13.9	293	1.1	2.4
Carlos	1 (111)	NCHF	169.9	30.6	36.1	2.9	5.4	14.5	0.7	26.9	6.2	8.4	0.012	0.005	8.3	434	8.6	2.6
Pearl	1 (53)	NCHF	156.1	38.7	18.8	20.9	1.4	18.1	0.9	25.3	6.1	8.4	0.040	0.007	17.4	375	23.5	8.0
Belle	2 (25)	NCHF	156.5	32.3	14.6	28.5	1.3	27.2	1.5	22.4	10.7	8.5	0.055	0.007	9.6	330	3.4	10.5
Cedar	2 (37)	NCHF	166.4	36.9	6.4	4.5	4.9	14.2	0.7	20.8	6.1	8.4	0.014	0.006	8.3	329	7.6	2.2
Peltier	2 (13)	NCHF	147.3	43.3	50.1	69.0	1.4	76.5	2.0	13.7	13.4	8.4	0.181	0.067	8.9	436	6.8	11.6
South Center	2 (80)	NCHF	57.9	17.3	24.8	16.3	2.2	44.3	1.1	5.8	9.7	8.2	0.031	0.005	1.2	197	6.4	4.6
Madison	1 (89)	WCBP	144.2	34.2	19.7	42.4	1.7	21.2	1.6	19.9	10.7	8.5	0.059	0.008	8.1	338	6.3	8.8
Shaokotan	1 (52)	WCBP	146.6	64.4	10.0	22.3	1.6	29.6	1.3	49.6	9.1	8.5	0.072	0.022	16.7	688	206.3	7.0
Artichoke	2 (51)	WCBP	288.7	58.2	14.8	24.8	1.0	44.2	2.0	74.9	14.4	8.7	0.232	0.154	12.4	824	177.6	10.0

Carrie	2 (25)	WCBP	206.7	60.3	11.0	6.7	1.4	20.5	0.9	31.2	5.6	8.3	0.021	0.005	13.4	465	39.6	8.8
St. James	2 (50)	WCBP	147.8	42.5	50.4	23.8	1.3	19.5	1.2	36.5	8.3	8.7	0.044	0.006	14.0	547	70.5	8.3
St. Olaf	2 (26)	WCBP	130.4	32.1	20.5	20.1	1.4	26.6	1.2	18.7	7.1	8.6	0.040	0.005	2.7	292	5.5	10.5

* Due to Natural Conditions

*** (See Figure 1)
CS= Canadian Shield
NLF = Northern Lakes and Forest
NCHH= North Central Hardwood Forest
WCBP = Western Corn Belt Plains

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Zooplankton

Zooplankton Summary

The Sentinel Lakes Program was designed to capture changes to multiple trophic levels caused by large-scale stressors such as aquatic invasive species (AIS), land use changes, and climate change. Zooplankton communities are useful indicators of stressors and change because of their short generation time, standardized sampling, and link between lower trophic levels and fishes. In this report we describe trends in the zooplankton communities for the 9 Tier 1 lakes (sampled annually) and describe stressor-induced impacts on the zooplankton community. Zooplankton communities in Tier 2 lakes are sampled less frequently (2 out of 10 years) and therefore were not included in this trend analysis.

Total zooplankton densities in the Tier 1 Sentinel Lakes range from >250 individuals/L in the prairie southwest to <10 individuals/L in the northeast Canadian Shield lakes, similar to densities observed in other Minnesota lakes (Hirsch 2014, Hirsch 2018) and Midwest lakes (Schoenebeck and Brown 2010, Livings et al. 2010, Olds et al. 2014).

Impacts from Stressors

We have documented the effects of stressors, AIS (zebra mussels, *Dreissena polymorpha*, in Carlos and spiny water flea, *Bythotrephes longimanus*, in Trout and Greenwood lakes) and land use change (shift from impaired/turbid stable state to unimpaired/clear water stable state), in several of the Sentinel Lakes. Those stressors affected the zooplankton communities in different ways. Zebra mussels proportionally reduced the density of each zooplankton taxa, while spiny water flea changed the composition of the zooplankton community disproportionately, directly, through predation on small cladocerans, and indirectly, through competition with cyclopoid copepods. The Lake Shaokotan zooplankton community shifted from large *Daphnia* spp. and calanoid copepod taxa to smaller cyclopoid copepods and small cladocerans after a shift in stable state related to land use changes.

Stressor-induced changes that alter the zooplankton community are important, in part, because they may negatively impact fish. Many early life stages of fish are zooplanktivorous, as are some adult fish, such as cisco, an important pelagic prey fish. Zooplanktivorous fish can be selective for particular taxa and sizes of zooplankton prey (Sullivan et al. 2011, Sullivan et al. 2012, Uphoff et al. 2019, Miller et al. 2019). Therefore, changes to either zooplankton community composition or the size distribution of preferred prey taxa could impact fish growth and survival. Changes to the zooplankton community may lead to increased competition for preferred zooplankton taxa and sizes (e.g., large *Daphnia* spp.) or require fish to shift to alternative prey (including different zooplankton taxa), which may have energetic consequences (i.e. increased activity and search time, consumption of more but energetically less profitable taxa or sizes, or exposure to predation).

This report focuses on trends through time, but the Sentinel Lakes zooplankton data should also be investigated to look for taxa-specific changes in size structure and seasonal abundance. As detailed in the water temperature analysis, water temperatures are increasing in the Sentinel Lakes, with the largest increase occurring in June. Total zooplankton abundance is often greatest in the spring, when many larval fish begin exogenous feeding. Changes in water temperature may impact fish hatch date, decoupling the timing of abundant preferred zooplankton taxa with the start of exogenous feeding or subsequent ontogenetic diet shifts. Warmer lake temperatures may increase zooplankton production and increase energy demands and growth rates of zooplanktivorous fish (Uphoff et al. 2013). It would be beneficial to document the food habits and taxa- and size-specific selectivity of fish species during early life history and describe how they relate to seasonal dynamics of the zooplankton community and fish hatch date to increase our understanding of energy flow during this critical life stage. This work would be beyond the bounds of routine Sentinel Lake Program sampling and would require a concerted research effort that the Sentinel Lakes framework could support.

Collection and Lab Methods

The zooplankton component of the Sentinel Lakes Long-Term Monitoring Program is a collaborative effort between MPCA personnel, who collect the samples, and the EWR Division of the MNDNR, who identify, enumerate, and measure the samples. The zooplankton data are housed in a database maintained by EWR. Here we will detail the methodology for this process.

Whole water column vertical tows were collected with a zooplankton net at the deepest area of each lake. Samples from 2008-2013 were collected using a 13-cm, 80-µm mesh Wisconsin style zooplankton net. Samples from 2013 to present were collected using a 30-cm, 80-µm mesh 3:1 simple zooplankton net. (Note that in 2013 both nets were used so comparisons between net catches could be documented and data standardized). For each sample, the zooplankton net was lowered so that the bucket of the net was approximately 0.5 m from the bottom and raised at 0.5 to 1 m s^{-1} to the surface. The sample was rinsed from the bucket of the net into a plastic Nalgene or similar type bottle and preserved with 100% reagent alcohol. Each bottle was labeled with lake name, site number, date, net mouth diameter, and tow length (m). Tows were collected once monthly from May through October. For the purposes of this report, we calculated mean taxa-specific annual zooplankton density and biomass to highlight taxa-specific changes over years and not within seasons.

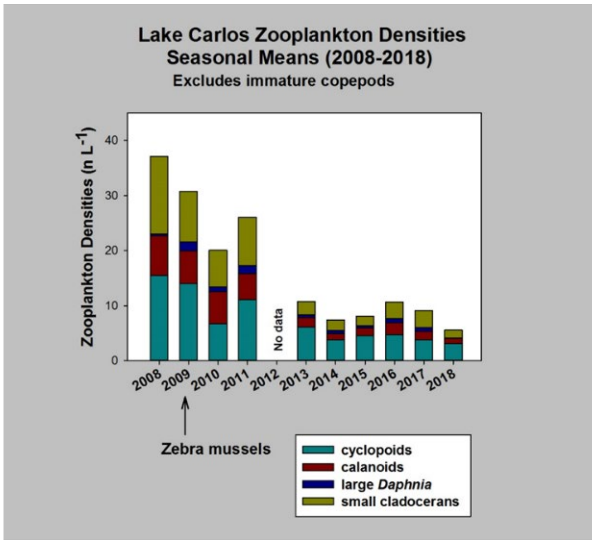
In the laboratory, sample is adjusted to a known volume by filtering the sample through 80-µm mesh netting and rinsing specimens into a graduated beaker. Water is added to the beaker to a volume that provides at least 150-200 organisms per 5-ml aliquot. The beaker is swirled in a figure-eight motion to ensure thorough mixing. A 5-ml aliquot is withdrawn from each sample using a bulb pipet and transferred to a counting grid. Individual zooplankton specimens are identified, counted, and measured using a dissecting microscope and a computerized analysis system. A compound microscope is also used to aid in the identification to species (or the lowest practical taxonomic group). Density (number/liter), biomass (µg/liter), percent composition by number and weight, mean length (mm), mean weight (µg), and total count of each taxon identified is generated by analysis system and is recorded in the MNDNR zooplankton database. Mean weight and biomass estimates are calculated using length-weight regression coefficients from Culver et al. (1985) and Dumont et al. (1975). Individual sample reports (PDF files) and Excel summary reports are generated from this system.

Carlos (Impacts of Zebra Mussels)

Zebra mussels were first reported in Lake Carlos in 2009, and we have documented a resultant decrease in chlorophyll-*a*, an increase in water clarity, and a decrease in overall zooplankton density and biomass post-zebra mussel infestation. There was a 2-3 year lag time for changes to occur to the zooplankton community, probably due to the time required for the zebra mussel population to establish in the lake. All zooplankton functional groups decreased proportionally after zebra mussel infestation, differing from spiny water flea impacts, where small cladocerans tend to decrease the most due to direct predation by *Bythotrephes*. Zooplankton densities and biomass appear to remain somewhat steady in post- zebra mussel years (roughly about one third of what was found in pre-zebra mussel years), although the lowest values recorded were in 2018. Total zooplankton density has decreased to < 10 individuals/L, similar to densities commonly found in the less productive Canadian Shield lakes. Furthermore, large *Daphnia* were very low in 2018, potentially caused by increased competition.

Reduced zooplankton abundance in Carlos are now similar to those naturally found in Ten Mile Lake (~10 individuals/L). Comparable zooplankton densities and thermal properties likely explain the similar age-0 fish growth in both lakes. For example, age-0 Bluegill in Lake Carlos had an October 2018 mean length of 33.9 mm (SD = 9.1), while those in Ten Mile Lake had a mean length of 36.0 mm (SD = 6.2).

Zebra mussels may be impacting the zooplanktivorous Cisco population in Lake Carlos. Zebra mussels have decreased phytoplankton biomass (based on Chlorophyll-*a* levels), increased water clarity, and decreased zooplankton density and biomass, which may create competition for preferred taxa and sizes of zooplankton such as large *Daphnia* spp. Zebra mussels are hypothesized to alter energy pathways within a lake away from pelagic and toward nearshore production (Hecky et al. 2004; Turschak et al. 2014, McEachran et al. 2019). As a coldwater species, Cisco avoid temperatures > 17 °C (Rudstam and Magnuson 1985) which may limit their ability to access nearshore benthic energy pathways during summer stratification. Estimates of Cisco abundance and biomass have slowly decreased in Carlos since zebra mussel infestation and continued monitoring of the Cisco population, including age and growth information, will provide insight into whether declines may be temporary or correlated with changing lake conditions.


Lake Carlos Zooplankton Densities
Seasonal Means (2008-2018)
Excludes immature copepods
Zooplankton Densities (n L-1)
0
10
20
30
40
No data
2008
2009
2010
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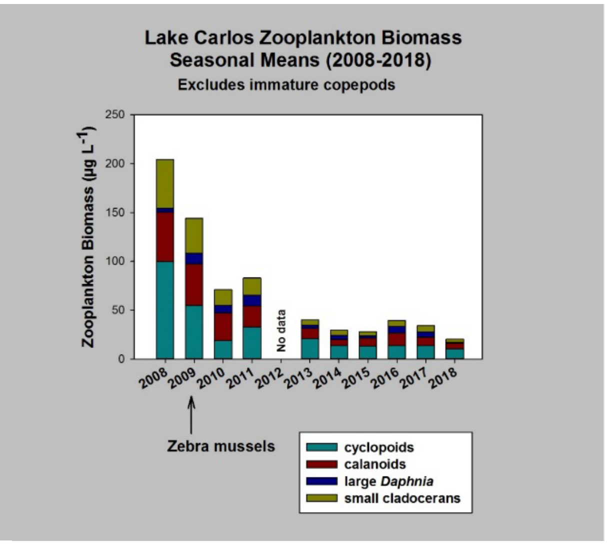
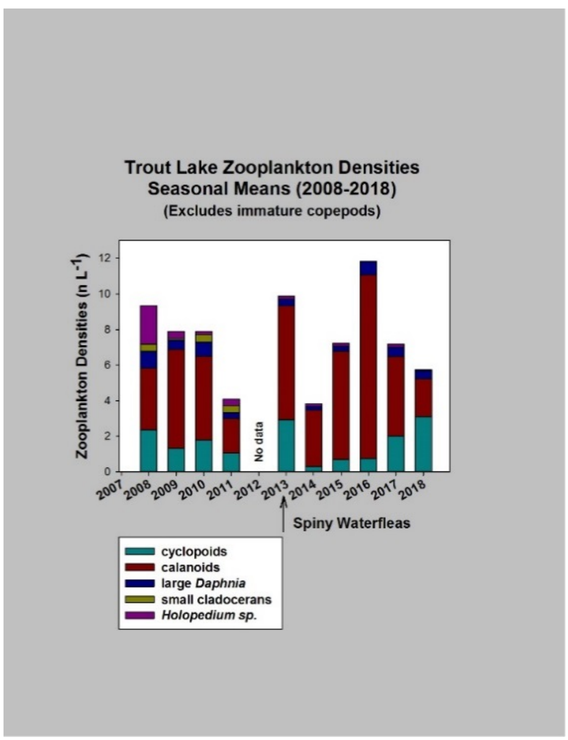
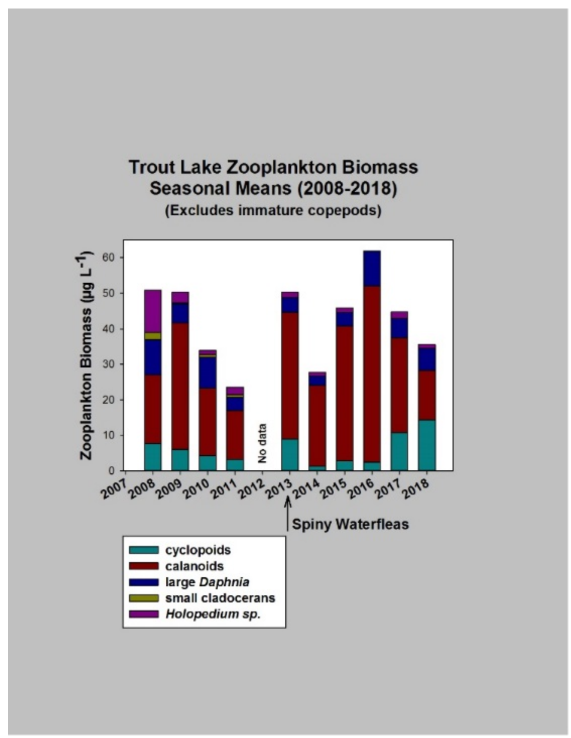
2015
2016
2017
2018
Zebra mussels
cyclopoids
calanoids
large Daphnia
small cladocerans


Lake Carlos Zooplankton Biomass
Seasonal Means (2008-2018)
Excludes immature copepods
Zooplankton Biomass (µg L-1)
0
50
100
150
200
250
No data
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Zebra mussels
cyclopoids
calanoids
large Daphnia
small cladocerans

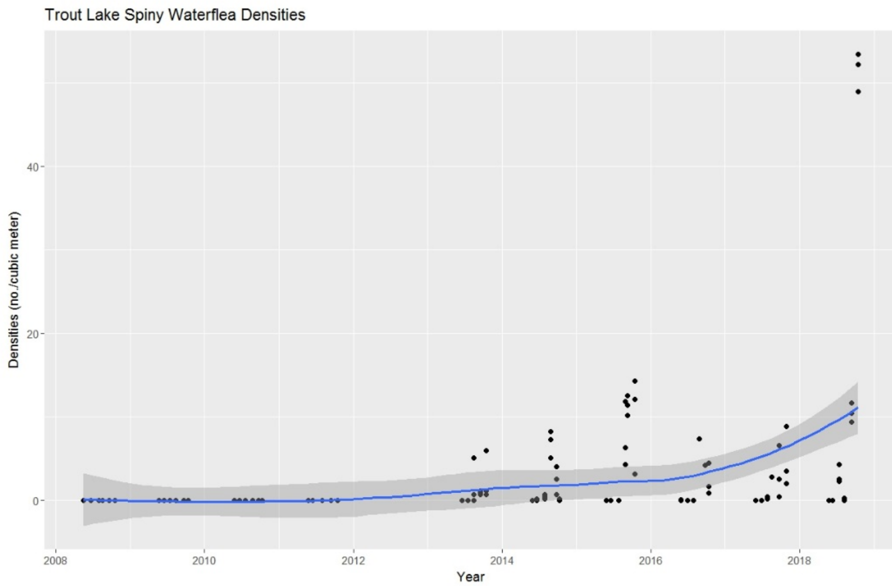
Trout Lake (Impacts of Spiny Water flea)

The zooplankton community of Trout Lake has been impacted by the invasive spiny water flea, which were first documented in 2013. Spiny water flea changed the composition of the zooplankton community disproportionately, as small cladocerans were reduced by direct spiny water flea predation and cyclopoid copepods were reduced through competition. In Trout Lake, small cladocerans have been extirpated since spiny water flea infestation, likely due to direct predation by spiny water flea. Copepod densities and biomass were variable through time, with no significant trend after spiny water flea infestation, although there does appear to be a recent increase in cyclopoid densities and biomass, but this may be year-to-year variability. Large daphnia (*D. galeata mendotae*) densities and biomass have been steady through the years, which is typical of other spiny water flea infested lakes in Minnesota. Unlike other spiny water flea infested lakes that have an overall decrease in total zooplankton, Trout Lake shows a different pattern with no overall change in total zooplankton densities or biomass. This could be due to the zooplankton community composition in this small, oligotrophic lake where calanoid copepods are the dominant taxa that may not be impacted by spiny water flea. Spiny water flea densities appear to be constant since infestation with peaks no higher than 15 m^{-3}, however, there was a recent exception during October 2018 with densities ~50 m^{-3}.



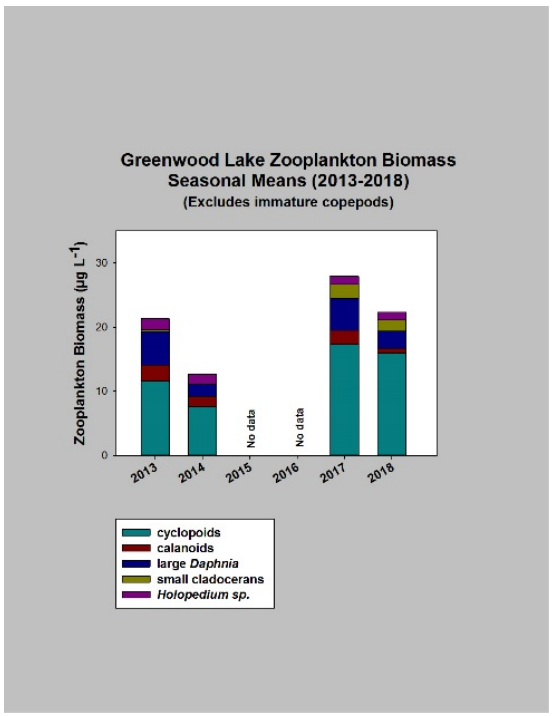


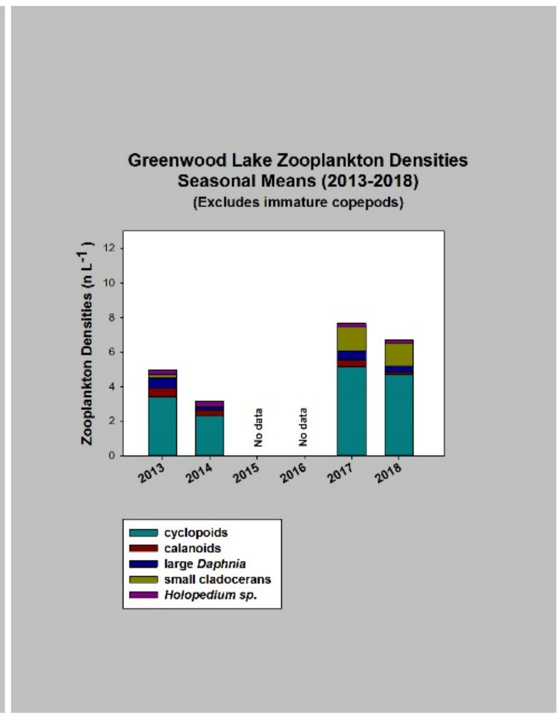
Spiny water flea densities in Trout Lake

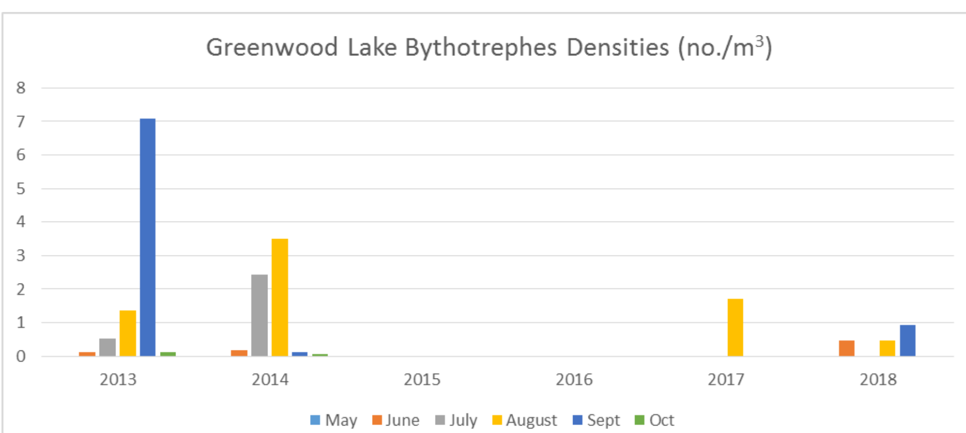


Greenwood Lake (Impacts of Spiny Water flea)

Spiny water fleas were first documented in Greenwood Lake in 2004, nine years prior to Sentinel Lakes sampling on this lake. Although no zooplankton data exist from pre-spiny waterflea years in Greenwood Lake, the post- spiny waterflea zooplankton community in Greenwood Lake is similar to Trout Lake (and other *Bythotrephes* infested lakes in the state) with low densities of small cladocerans. Unlike Trout Lake which had stable spiny water flea densities, spiny water flea densities in Greenwood Lake changed during the sampling period, allowing us to document the responses of small cladocerans and cyclopoid copepods. Spiny water flea densities were greater in 2013 and 2014 than in 2017 and 2018, and both small cladocerans and cyclopoid copepods densities and biomass were lower during years of high spiny water flea abundance. The figure below of monthly spiny water flea densities also shows the summer timing of peak spiny waterflea densities in Greenwood Lake.



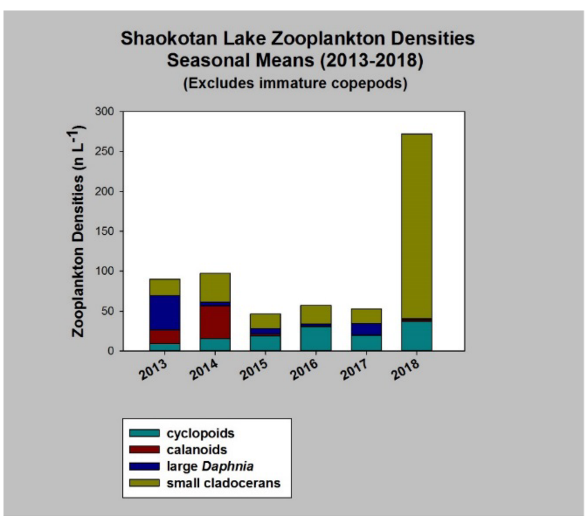


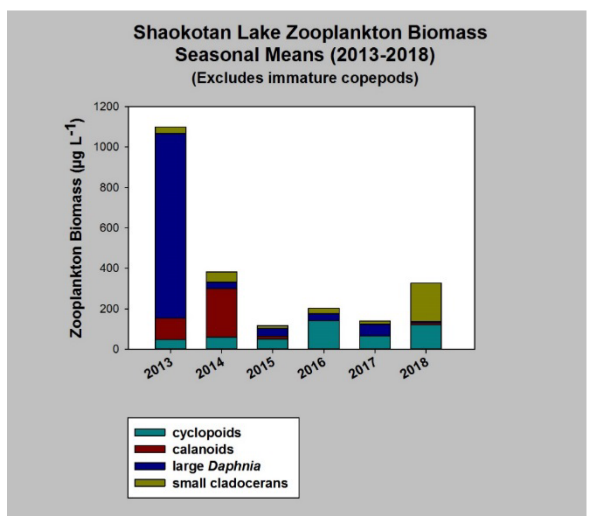


Shaokotan (Impacts from Land use Changes)

The zooplankton community in Lake Shaokotan changed from large *Daphnia* spp. and calanoid copepod taxa to smaller cyclopoid copepods and small cladocerans. Total zooplankton biomass was higher in 2013 than during the following years, due to the elevated number of large *Daphnia pulicaria*. Interestingly, the high number of large *Daphnia pulicaria* in 2013 coincided with a large blue-green algae (*Aphanizomenon flos-aquae*) bloom. Large *Daphnia* and *A. flos-aquae* have been found to co-exist in shallow, hypereutrophic lakes, most likely because large *Daphnia* do not graze on *A. flos-aquae* but preferentially graze on other taxa of algae (Lynch 1981). Furthermore, the physical nature of *A. flos-aquae*, producing large grass-like clippings, may provide refugia for large *Daphnia* in shallow lakes. Total zooplankton densities were significantly higher in 2018 than in past years due to the high number of small cladocerans (mainly *Bosmina sp*.).

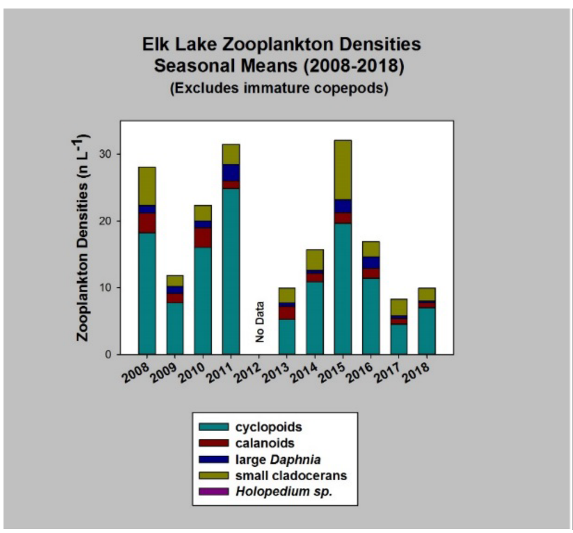
Over this same time, land use changes within the watershed triggered Lake Shaokotan to shift from an algal-dominated stable state to an aquatic vegetation dominated clear water stable state with corresponding changes in phytoplankton, aquatic macrophytes, and water clarity. The fish community has also responded to the habitat change. Yellow Perch gill net CPUE has progressively increased from 16 YEP/gill net in 2013, to 43 in 2014, 80 in 2015, and 147 in 2018. Therefore, one explanation for the shift in the zooplankton community could be increased predation on large *Daphnia* spp. and calanoid copepods by Yellow Perch combined with a shift from pelagic calanoid copepods to taxa associated with aquatic vegetation. Alternatively, habitat changes have impacted the phytoplankton community and consequently resulted in bottom-up control of the zooplankton community as algal taxa changed. As this report was being drafted in the summer of 2019, a permit to chemically treat an area of aquatic vegetation up to 15% of Lake Shaokotan had been issued by the DNR to the Lake Improvement District, and we recommend continued monitoring of this lake post-treatment to document any resultant changes in water chemistry, aquatic vegetation, phytoplankton, zooplankton, and fish populations.

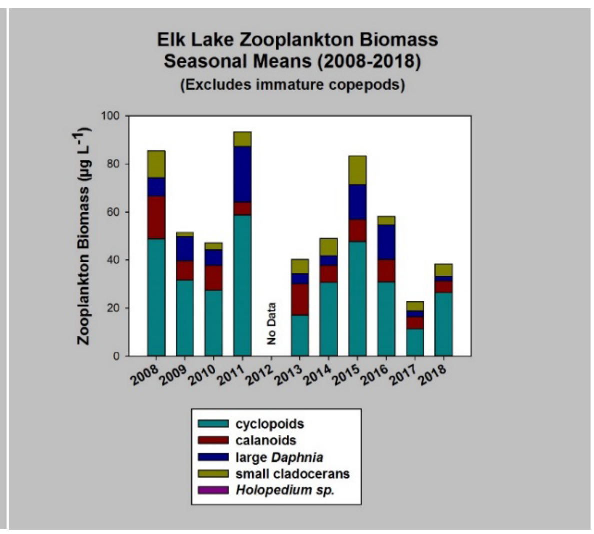




Elk

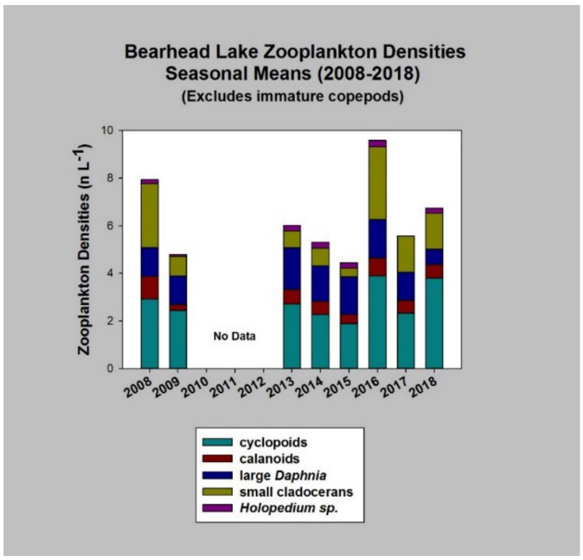
Cyclopoid copepods are the dominant functional group in Elk Lake, comprising over 50% of the density and biomass most years. Zooplankton densities and biomass are variable among years, with no significant increasing or decreasing trends. Fluctuating zooplankton densities may impact zooplanktivorous fish growth if densities of favored zooplankton prey become limited. Zooplankton densities were low in 2017 and 2018 (<10 individuals/L), with low densities of large *Daphnia* spp., but these low zooplankton densities still supported age-0 zooplanktivorous Yellow Perch and Bluegill growth. For example, fall 2018 mean lengths of age-0 Yellow Perch were greater in Elk Lake (68.5 mm, SD = 5.3) compared to Ten Mile Lake (50.1 mm, SD = 3.8) and Pearl Lake (55. 5 mm, SD = 5.9). Similarly, fall 2018 mean lengths of age-0 Bluegill in Elk Lake were greater in Elk (55.1 mm, SD = 10.3) than Lake Carlos (33.9 mm, SD = 9.1), Ten Mile Lake (36 mm, SD = 6.24), and Pearl Lake in 2018 (33.2 mm, SD = 5.1). Faster age-0 fish growth in Elk Lake despite low densities of large *Daphnia* spp. and a lower mean growing degree day (GDD base 5; 2,569) compared to other, more southerly Sentinel Lakes with higher mean GDD, such as Carlos (2,637) and Pearl (2,673), suggests factors other than large *Daphnia* spp. density and water temperature may responsible for age-0 fish growth in Elk. It would be beneficial to document the food habits and taxa- and size-specific selectivity of age-0 zooplanktovirous fish to better understand growth rates and relate them to seasonal dynamics of the zooplankton community. One hypotheses could be age-0 Yellow Perch in Elk make an earlier ontogenetic diet shift from zooplankton to macroinvertebrates (e.g., abundant Chaoborus) which could increase growth rates.

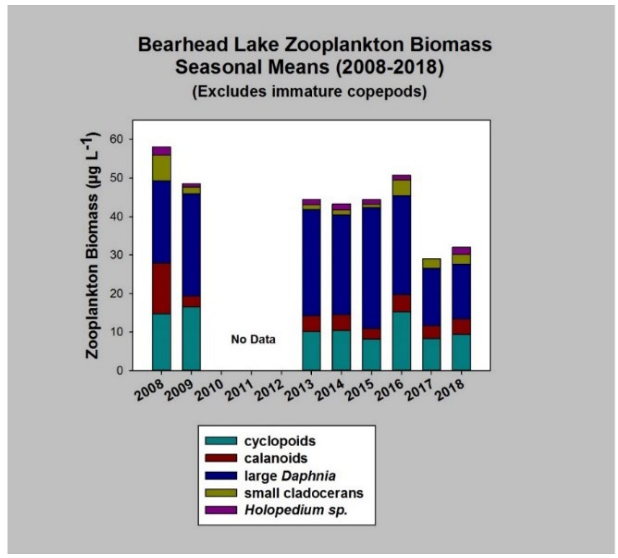




Bearhead

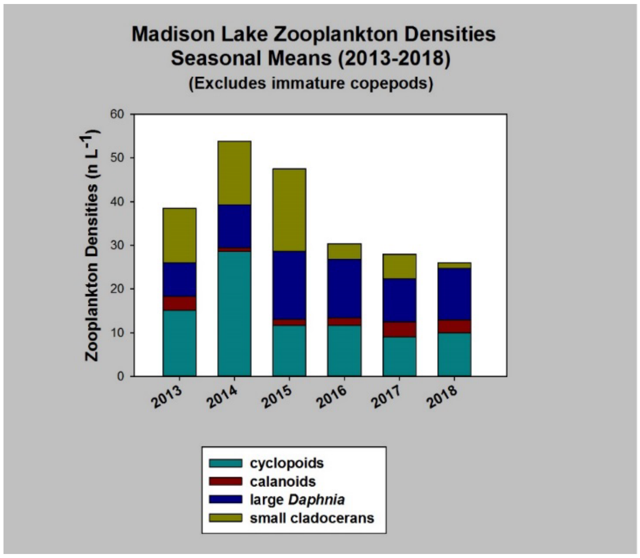
No significant trends in total zooplankton density or biomass occurred in Bearhead over the past six years. Overall, zooplankton densities are low (<10 individuals/L) which is similar to other Canadian Shield lakes. Over 50% of the biomass is large *Daphnia* spp., which suggests sufficient biomass of preferred prey for zooplanktivorous fish.   The densities of small cladocerans were higher during 2016-2018 than 2013-2015. Biomass of large *Daphnia* spp. are lower during the past two years (2017-1018) when compared to all previous years sampled.

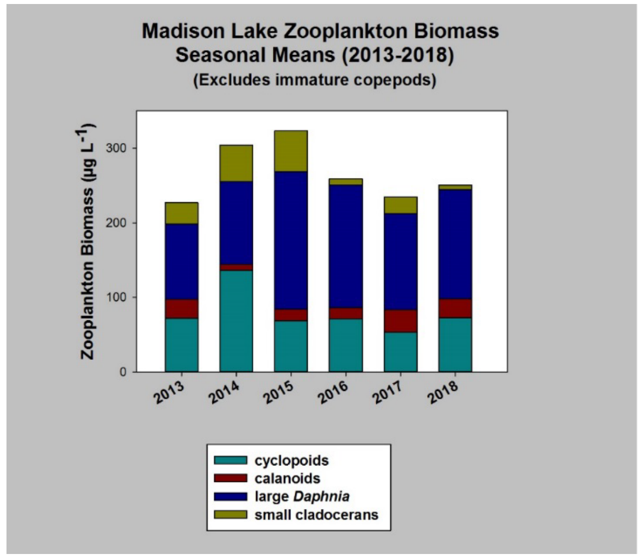




Madison Lake

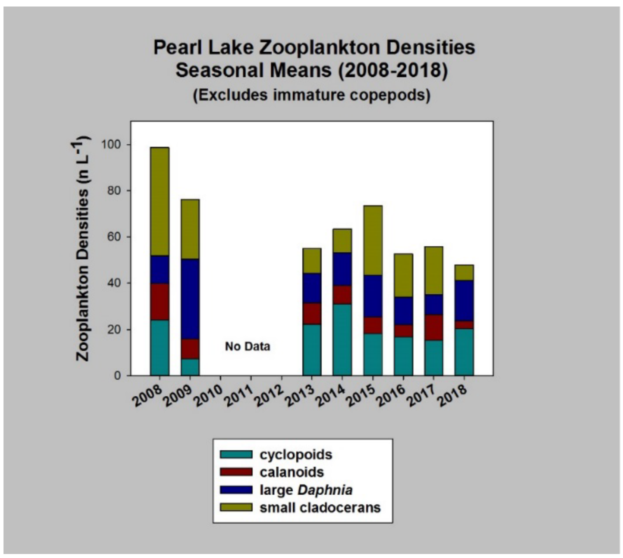
Zooplankton densities vary among years, and small cladoceran densities appear to be decreasing. Similar to Bearhead Lake, zooplankton biomass appears stable with large *Daphnia* contributing > 50% of the biomass in most years, which suggests sufficient biomass of preferred prey for zooplanktivorous fish. Large *Daphnia* are often selected for by juvenile sport fish as desirable relative to other zooplankton taxa given their size and energetic benefit. The dominant species are *Daphnia pulicaria* and *Daphnia galeata mendotae*, depending upon specific years.

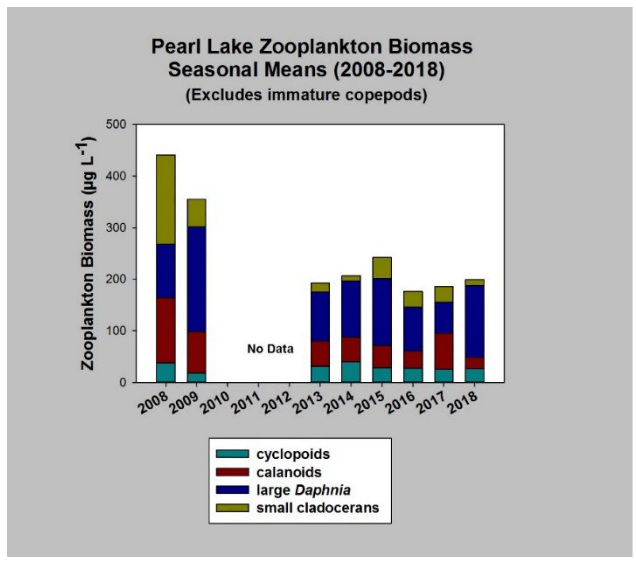




Pearl

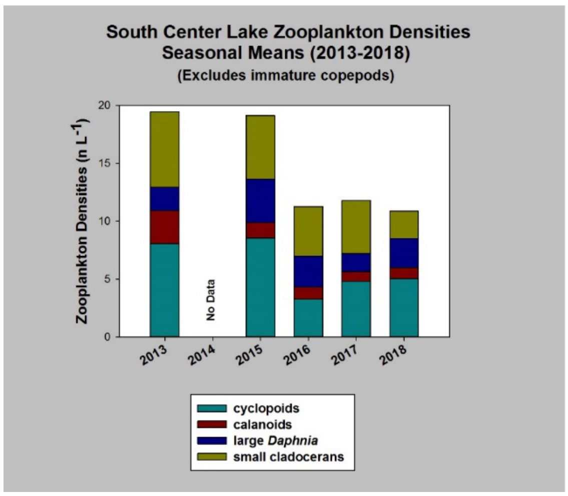
Although total zooplankton density fluctuated annually, there were no significant trends in total zooplankton densities or biomass over the past six years. Total biomass was higher during 2008-2009 compared to 2013-2018. Similar to Madison and Bearhead, large *Daphnia* contribute to >50% of the total biomass during most years, suggesting sufficient biomass of preferred prey for zooplanktivorous fish. Interestingly, despite its relatively high zooplankton density and biomass, composition of large *Daphnia* spp., and higher GDD (Table 1), Pearl did not support the fastest growth of the zooplanktivorous age-0 game fish in the lakes we monitored during 2018. For example, fall 2018 lengths of age-0 Yellow Perch were greater in Elk Lake (68.5 mm SD = 5.3) compared to Pearl (55. 5 mm SD = 5.9) and Ten Mile (50.1 mm SD = 3.8). Water temperature and prey are only two factors that can impact the growth of age-0 fish, and so we suggest further exploration of age-0 fish growth including the energetics surrounding ontogenetic diet shifts.

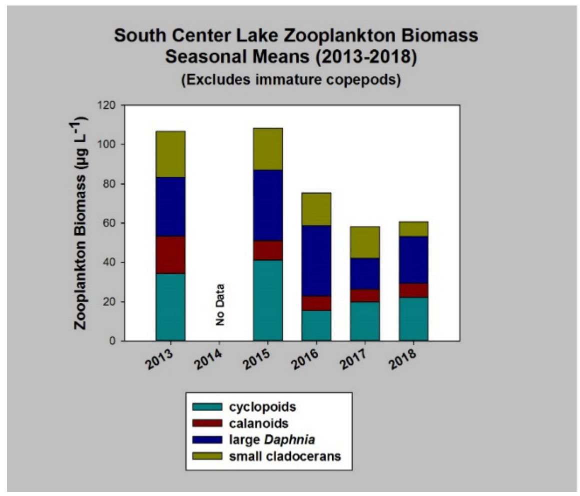




South Center Lake

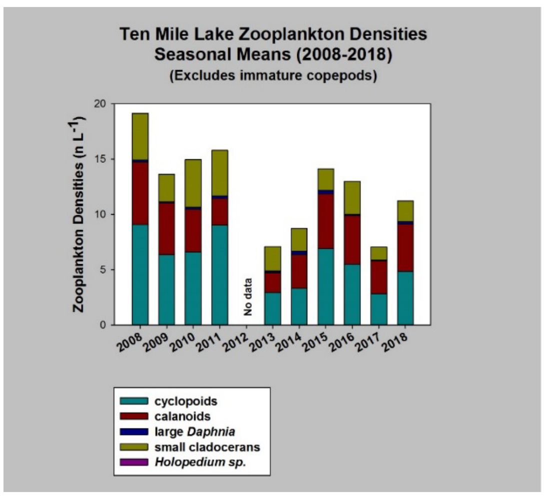
There was no overall change in zooplankton community composition among sampling years in South Center Lake, although total zooplankton densities and biomass appeared to be lower during the last three years. Large *Daphnia* spp. display classic seasonality patterns in South Center Lake, with high densities and biomass in the spring/early summer decreasing the remainder of season.





Ten Mile Lake

Zooplankton densities and biomass in Ten Mile Lake are comparably low relative to other lakes and display year-to-year variation, but no overall upward or downward trends. Ten Mile Lake lacks obvious stressors such as AIS and land use changes within the watershed, so other factors such as water temperature may help explain the variability. Lake water temperatures were warmer during 2015 and 2016 as indicated by higher GDD than in 2013 and 2014 which correlates with zooplankton density and biomass (Table 1). Zooplankton densities and biomass were relatively low in Ten Mile Lake, especially for large *Daphnia* spp. and therefore could be potentially limiting to zooplanktivorous fish growth, especially in years with lower zooplankton abundance. As mentioned above, growth of age-0 zooplanktivirous fish is generally slow in Ten Mile Lake compared to lakes with warmer temperatures and greater zooplankton biomass. Cisco population abundance and biomass estimates have been trending down from 2015 to 2018 with 2017 and 2018 the lowest documented to date, so we recommend continued monitoring of the Ten Mile zooplankton and zooplanktivorous fish.



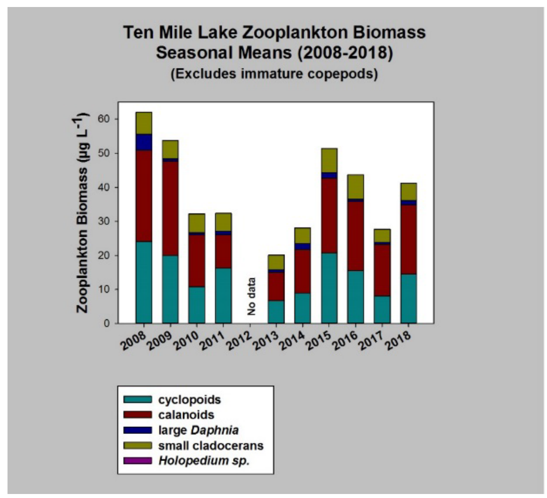


Table 1. Base 5 growing degree days for Tier 1 Sentinel Lakes.

Lake	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Bear Head	2052	2466	2284	2452	NA	2094	2415	2449	2289	2241
Carlos	NA	NA	NA	NA	NA	2407	2758	2759	2623	NA
Elk	2221	3058	NA	NA	NA	2311	2595	2660	NA	NA
Greenwood	NA	NA	NA	NA	NA	1660	1949	2000	1820	NA
Madison	NA	NA	2870	3207	NA	2723	3046	3140	2893	NA
Pearl	2531	NA	NA	2898	2474	2555	2911	NA	NA	NA
Shaokotan	NA	NA	NA	NA	NA	NA	NA	2809	2726	NA
Ten Mile	2085	NA	2278	NA	2130	2133	2462	2472	NA	2233
Trout	1830	2233	2081	2227	1936	1838	2150	2209	2005	NA

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Pelagic Fish

Minnesota Sentinel Lakes Long-Term Monitoring Program:
Pelagic Forage Fish Sampling

Background and Methods

The Sentinel Lakes Long-Term Monitoring Program includes ongoing evaluation of the pelagic fish community in six lakes (Table 1) containing suitable hypolimnetic habitat for coldwater forage species including Cisco (*Coregonus artedi*) and Rainbow Smelt (*Osmerus mordax*). These forage fish are important prey for predatory gamefish species such as Walleye (*Sander vitreus*), Lake trout (*Salvelinus namaychush*), and Northern Pike (*Esox lucius*). Pelagic surveys using vertical gill nets and hydroacoustics have been conducted annually on three lakes (Carlos, Elk and Ten Mile; Figure 1) and occasionally on three other lakes (Greenwood, Trout, and White Iron; Figure 1), although triennial surveys are planned for these lakes in the future. This report summarizes data collected from 2010-2018.

Pelagic surveys were conducted during peak stratification when warm epilimnetic temperatures caused coldwater forage species to move to deeper depths where they were more susceptible to sampling gear. Vertical gill nets of various mesh sizes were set from the surface to the bottom for ~24 hours in the deepest location(s) in each lake (Figure 1). Beginning in 2013, vertical gill nets were standardized to seven meshes (9.5, 12.7, 19.0, 25.4, 31.8, 38.1, and 44.5 mm bar measure) and widths (0.9, 0.9, 1.2, 1.8, 3.0, 3.0, and 3.0 m, respectively). Information recorded for captured individuals included net location, species, mesh, and the depth of capture (m). Additional information describing length (mm), weight (g), sex, maturity, and age were taken on a subsample of cisco (5 individuals per 10 mm length category). Additionally, temperature and dissolved oxygen profiles were collected at each net site.

Hydroacoustic surveys were conducted at night approximately one hour after sunset using equally spaced transects to sample depths greater than 4 m (Figure 1). During the years 2010-2012, hydroacoustic data were collected with a Biosonics 120-kHz 7.6° split-beam transducer and DT-X echosounder using a pulse duration of 0.4 msec. Beginning in 2013, hydroacoustic data were collected with a Simrad 38-kHz 9.6° split-beam transducer and EK60 transceiver using a pulse duration of 0.2 msec. Ping rate was standardized based on the depth of the lake and a calibration was performed using a tungsten-carbide reference sphere prior to each survey (Parker-Stetter et al. 2009).

Hydroacoustic data were analyzed using the MNDNR Standardized Hydroacoustic Data Analysis Protocol for Inland Pelagic Fish Populations (unpublished document available upon request). Vertical gill net and temperature/dissolved oxygen profile information were used to interpret hydroacoustic data and eliminate depths or targets unlikely to be the coldwater forage species of interest. Age-0 cisco were not included in population or biomass estimates because these fish were not equally susceptible to sampling in different lakes due to growth and survey timing. Additionally, forage fish < 90 mm were excluded from the analysis because this size corresponded to the minimum captured in vertical gill nets. Population estimates were converted to biomass estimates using lake-specific length-weight information collected from vertical gillnets. Density and biomass estimates were also standardized for between-lake comparisons using the volume of water in each lake where the bottom depth was > 6 m.

Results and Discussion

Carlos had fairly consistent estimates of mean Cisco density and biomass that varied less than 25% between subsequent years (Tables 2 and 3). However, over the entire time series, densities and biomass estimates have decreased particularly since 2013, with current estimates approximately 40% lower than peak values (Tables 2 and 3). Cisco between 130-169 mm in length (approximately age-1) comprised approximately 24% of the overall catch in 2010-2013 compared with only 4% of the overall catch in 2014-2018, suggesting that recruitment may be limiting in recent years. One significant change over the time series was the confirmation of the presence of Zebra Mussels in 2009. Zebra mussels have decreased phytoplankton, increased water clarity, and decreased zooplankton density and biomass which may create competition for preferred taxa and sizes of zooplankton such as large Daphnia spp. As Zebra Mussels increase in abundance, they are hypothesized to alter energy pathways within a lake causing increased nearshore benthic production (Hecky et al. 2004; Turschak et al. 2014; McEachran et al. 2019). As a coldwater species, Cisco avoid temperatures > 17 °C (Rudstam and Magnuson 1985) which may limit their ability to access nearshore benthic energy pathways during summer stratification. Continued monitoring of the Cisco population in Carlos will provide insight into whether density and biomass declines may be temporary or correlated with changing lake conditions.

Elk had variable hydroacoustic density estimates fluctuating by as much as 100% between subsequent years (Table 2). However, biomass estimates were more consistent, varying by less than 25% between subsequent years (Table 3) indicating that years with decreased density were associated with larger mean weight. In Elk, Cisco were squeezed into marginal thermal habitat during summer stratification due to low hypolimnetic oxygen. As a result of being pushed into warmer metalimnetic temperatures, Cisco in Elk had higher annual growth rates and achieved a larger maximum size compared to other lakes being monitored in the Program. Age-1 fish could be identified separately from other year classes in the vertical gill nets and successful year classes were produced in five of the eight sampled years (2009, 2011, 2012, 2015, and 2016). In Elk, consistent recruitment throughout the time series combined with several years of normal summer temperatures reducing lethal warm-weather die-offs may have contributed to an overall increase in Cisco density and biomass.

Ten Mile contains a phenotypic population of dwarf Cisco (Shields et al. 1990) that rarely exceeded a maximum size of 170 mm during the years it was monitored with pelagic surveys. Overall, Cisco population and biomass in Ten Mile remained relatively unchanged from 2010-2015, before decreasing sharply from 2016-2018 (Figure 2), suggesting that there may have been a lack of recruitment during this recent time period. Unlike in Elk, age-1 fish could not be differentiated in vertical gill nets. However, size structure has been increasing over time as Cisco between 90-109 mm in length comprised only 7% of the overall catch in 2016-2018 compared with an average of 24% of the overall catch in the preceding six years. An inverse relationship between Cisco density and length has been observed in Elk Lake and in other studies (Rudstam 1984; Bowen et al. 1991); however, it is unknown if the observed size structure changes in Ten Mile were primarily the result of an aging population caused by limited recruitment or increased growth rates caused by reduced competition and/or changes in food resources.

Three lakes were sampled occasionally with hydroacoustics during 2010-2018, including Greenwood, Trout, and White Iron. Of these lakes, Greenwood had the lowest coefficient of variation of all lakes sampled in all years, likely because it is a deep, stratified lake containing a relatively even distribution of Cisco. In contrast, White Iron is a shallow, polymictic lake that was mixed when it was sampled in 2010.

Cisco were likely distributed throughout the water column in White Iron in 2010, including into surface waters where the fish were not susceptible to hydroacoustic sampling. As a result, there was particularly high variation around the mean (CV = 1.0, Table 2). When White Iron was sampled again in 2011, it was temporarily stratified allowing for a comparatively precise population estimate (CV = 0.33).

Trout Lake was the only lake monitored with pelagic surveys as part of Program that contained the coldwater forage species Rainbow Smelt. Although Trout Lake historically contained Cisco, Rainbow Smelt were first observed in 1981 and subsequently Cisco were last surveyed in the lake during a standard assessment in 1999. It is likely that Cisco were extirpated after the introduction of Rainbow Smelt through competition and predation on juveniles leading to declines in Cisco recruitment (Evans and Loftus 1987; Hrabik et al. 1998; Myers et al. 2009). Rainbow Smelt were in low abundance in Trout Lake and were patchily distributed. As a result, confidence in the population and biomass estimates during both years of pelagic assessments (2010, 2017) were low (Table 2 and Table 3).

Standardized density estimates (#/m^3) were compared between lakes (Figure 3). Pelagic forage fish densities were consistently highest in Ten Mile Lake, although the densities dropped considerably in 2017-2018 and were more similar to those found in Elk Lake in 2017. Aku and Tonn (1997) found that Cisco densities increased and mean size decreased as the volume of cold, oxygenated hypolimnetic habitat increased. The volume of pelagic habitat may be one explanation for high densities of Cisco observed in Ten Mile because there is considerably more habitat compared to the other long-term monitoring lakes (Table 1). However, Greenwood had a greater volume of pelagic habitat compared with Elk, Trout, and White Iron (Table 1) but Cisco density in Greenwood was among the lowest observed (Figure 3). Cisco were introduced into Greenwood from Lake Superior in the 1920s, so the low density may be due to behavioral differences such as a greater reliance on planktivory compared with inland Cisco (Jacobson et al. 2018) or other factors such as lake productivity and surface geology.

Standardized biomass estimates (g/m^3) were also compared between lakes (Figure 4). Elk Lake had the highest standardized biomass of all the lakes in the long-term monitoring dataset while Carlos, Greenwood, Ten Mile, and White Iron had comparable biomass estimates (Figure 4). Trout, the only lake in the dataset containing the small-bodied Rainbow Smelt as the primary pelagic coldwater forage species, contained significantly lower pelagic forage biomass compared with the other five Cisco lakes (Figure 4).

Continued long-term pelagic assessments of these six lakes will be important for monitoring the coldwater pelagic forage fish communities as these lakes change over time due to altered land-use, climate change, and invasive species introductions.

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Table 1. Characteristics of lakes with ongoing pelagic fish assessments as part of the Sentinel Lakes Long-Term Monitoring program. The temperature at which the dissolved oxygen was 3 mg/L (TD03) was calculated using temperature profiles collected between July 15 and August 30 and averaged across years for each lake. Pelagic volume was calculated as the volume of water in each lake with a bottom depth > 6 m. Aquatic invasive species include Eurasian Watermilfoil (EWM), Zebra Mussels (ZM), and Spiny Waterflea (SWF).

Lake	DOW	Area (ha)	Max Depth (m)	Pelagic volume (km^3)	Total P (ppb)	TDO3 (°C)	Mixing class	Aquatic invasive species (year confirmed)
Carlos	21005700	1,055	49	0.138	13	6.5	Stratified	EWM (2012), ZM (2009)
Elk	15001000	121	30	0.012	12	10.4	Stratified	
Greenwood	16007700	827	34	0.069	6	7.7	Stratified	SWF (2004)
Ten Mile	11041300	2,051	63	0.297	8	7.5	Stratified	
Trout	16004900	105	23	0.009	7	7.5	Stratified	SWF (2012)
White Iron	69000400	1,312	13	0.046	19	18.5	Mixed	

Table 2. Population estimated with hydroacoustics for each lake and each year that it was sampled as part of the long-term monitoring program.

Year	Carlos	Elk	Greenwood	Ten Mile	Trout	White Iron
2010	671,000 ± 201,000	25,000 ± 6,000		5,038,000 ± 1,435,000	25,000 ± 17,000*	68,000 ± 68,000*
2011	537,000 ± 75,000	50,000 ± 26,000		4,496,000 ± 1,415,000		120,000 ± 40,000
2012	608,000 ± 204,000			4,372,000 ± 1,628,000		
2013	732,000 ± 160,000	72,000 ± 12,000		5,679,000 ± 1,122,000		
2014	650,000 ± 112,000	42,000 ± 8,000		4,553,000 ± 887,000		
2015	520,000 ± 60,000	60,000 ± 8,000		6,503,000 ± 1,905,000		
2016	548,000 ± 132,000	64,000 ± 12,000		4,650,000 ± 1,483,000		
2017	399,000 ± 99,000	123,000 ± 14,000	97,000 ± 8,000	2,713,000 ± 706,000		
2018	447,000 ± 53,000	61,000 ± 7,000		2,454,000 ± 273,000	26,000 ± 25,300*	

*Surveys with low confidence in the estimate. See text for more details.

Table 3. Total biomass (kg) estimated with hydroacoustics for each lake and each year that it was sampled as part of the long-term monitoring program.

Year	Carlos	Elk	Greenwood	Ten Mile	Trout	White Iron
2010	41,700 ± 2,700	8,000 ± 1,800		87,000 ± 26,500	300 ± 210*	11,600 ± 11,600*
2011	34,000 ± 4,700	5,900 ± 3,100		73,500 ± 23,100		15,200 ± 5,000
2012	43,000 ± 14,200			79,300 ± 29,700		
2013	39,400 ± 8,700	7,900 ± 1,700		87,300 ± 17,100		
2014	37,000 ± 6,400	9,200 ± 2,100		92,500 ± 17,400		
2015	33,400 ± 4,100	13,500 ± 1,900		107,400 ± 29,300		
2016	37,100 ± 9,100	11,600 ± 2,500		86,900 ± 26,300		
2017	28,900 ± 3,900	15,200 ± 1,600	24,500 ± 2,300	62,400 ± 16,800		
2018	38,900 ± 6,900	7,700 ± 900		47,800 ± 5,200	330 ± 310*	

*Surveys with low confidence in the estimate. See text for more details.

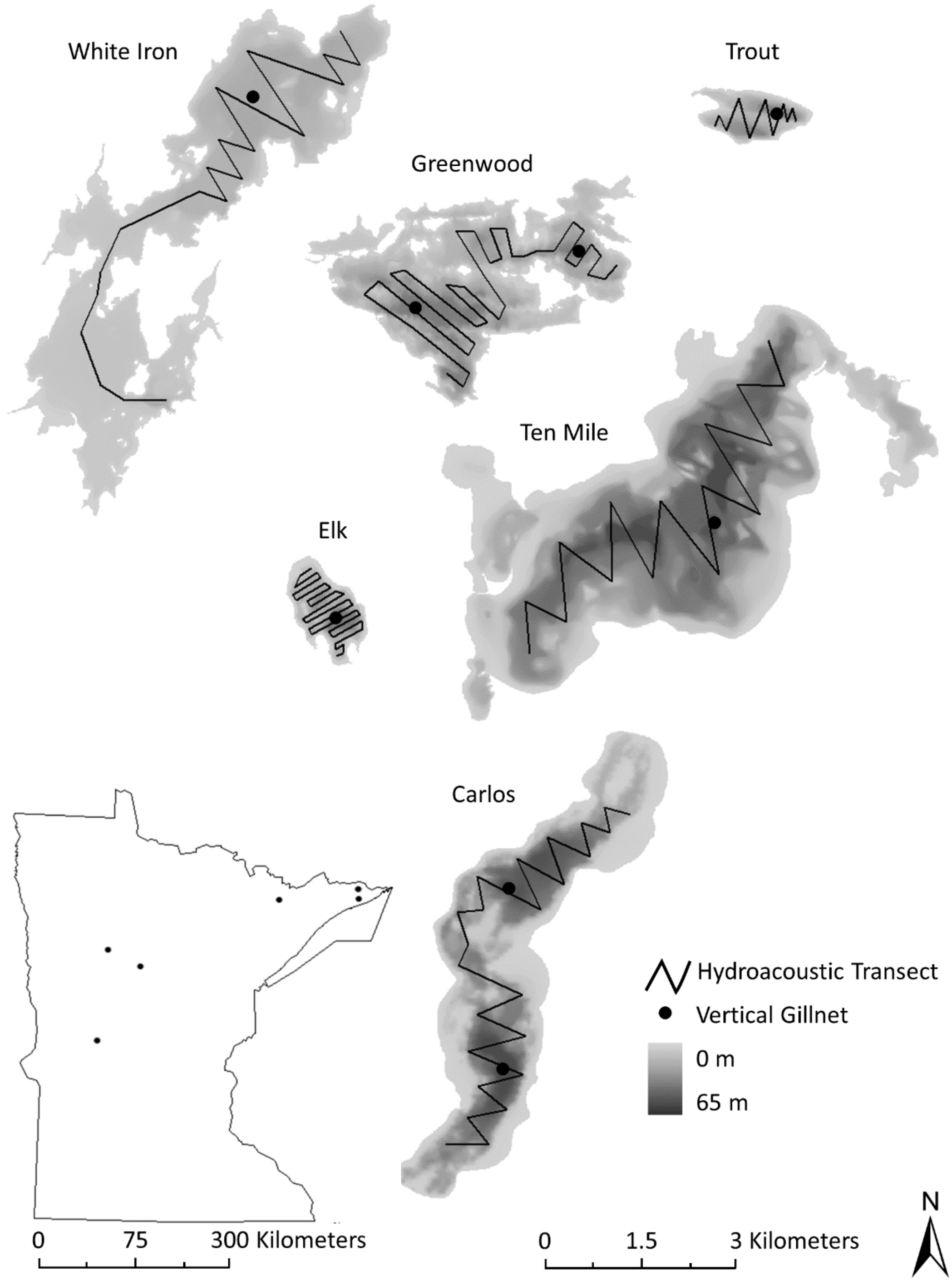

Figure 1. Survey design for each lake currently being sampled as part of the long-term monitoring program.

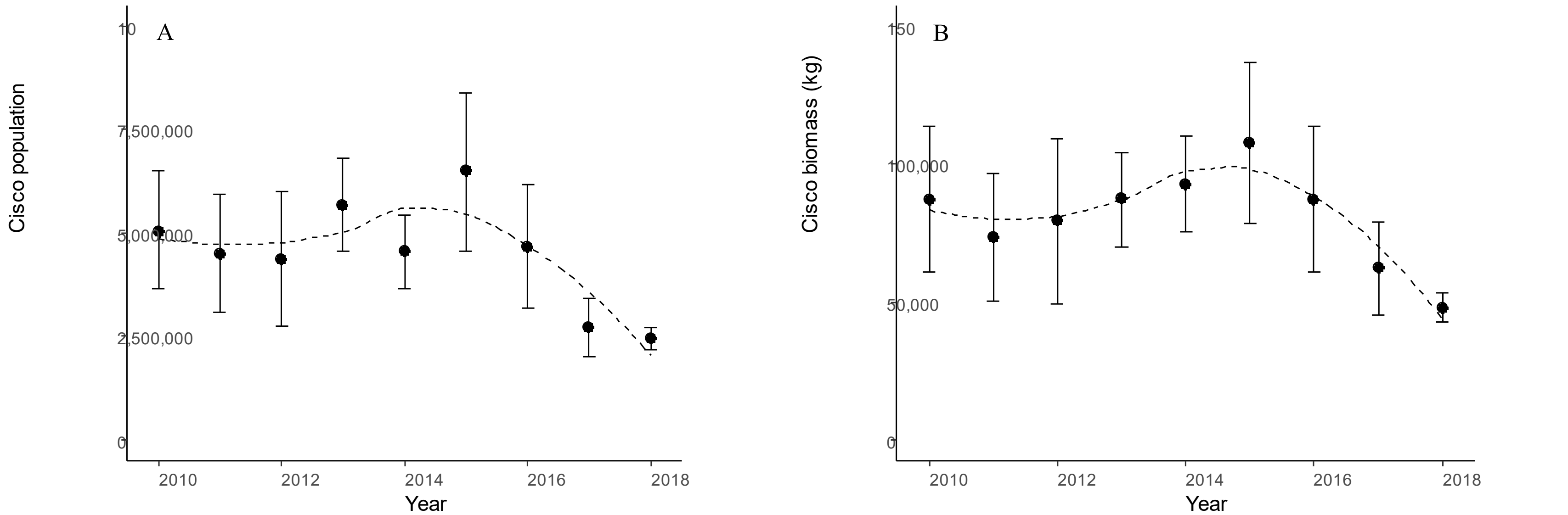

Figure 2. Changes in Ten Mile Cisco population (Figure 2A) and biomass (Figure 2B) from 2010-2018. Overall, population and biomass estimates remained relatively unchanged between 2010-2015 and have since declined every year. Error bars are 95% confidence intervals. Estimates were fit with loess spline (dashed line).

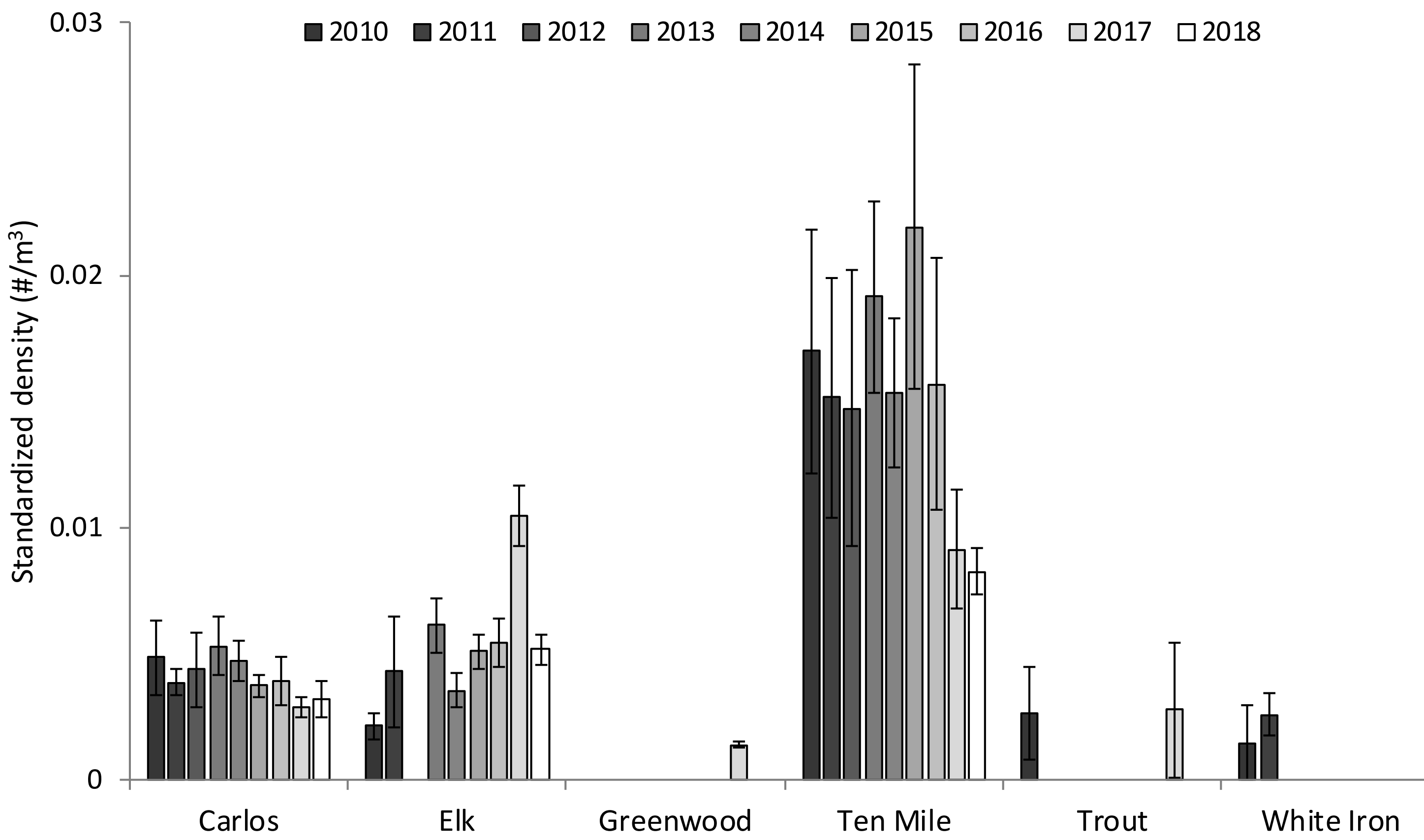

Figure 3. Standardized density (#/m^3) for the lakes currently being sampled as part of the LTM program. Population estimates were standardized by the volume of water with a bottom depth > 6 m (Table 1).

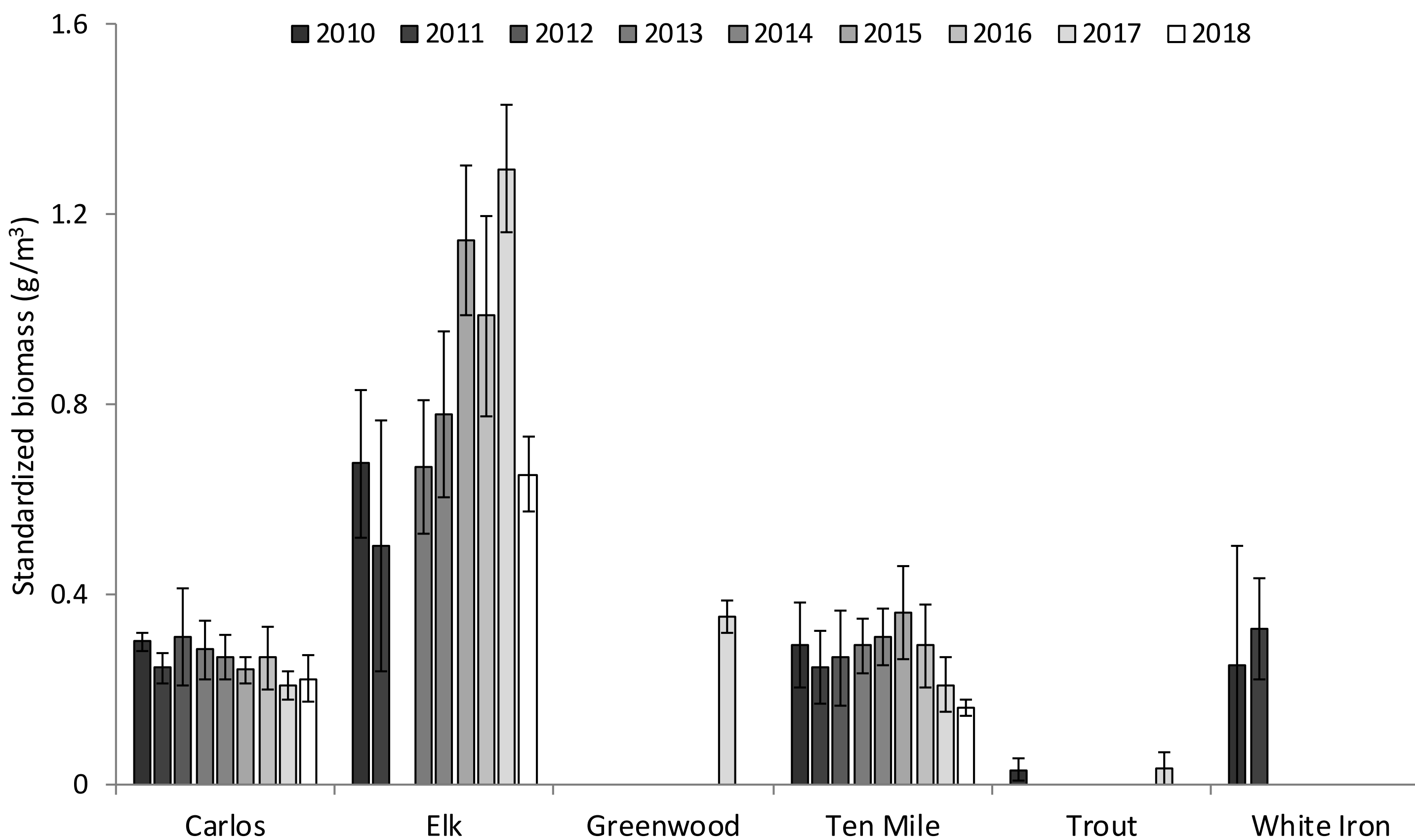

Figure 4. Standardized biomass (g/m^3) for the lakes currently being sampled as part of the LTM program. Population estimates were standardized by the volume of water with a bottom depth > 6 m (Table 1).

Fish Trends

Fish Trends in Catch per Unit Effort since 1970 in Sentinel Lakes and Similarity with Statewide Trends

Intro and Methods

Fish populations in freshwater lakes can experience dramatic shifts in composition and abundance, often driven by a variety of physical, chemical, and biological factors (Nalepa et al. 1996; Jackson et al. 2001; Thao et al. 2016). Natural and human induced change can lead to changes in fish abundance with consequences for species, ecosystems, and fisheries management (Goeman et al. 1995; Fayram et al. 2005). The Sentinel Lakes Program provides a unique framework to pair a robust dataset of physical, chemical and biological variables with fish data from the Lake Survey program. These data can then be used to identify potential drivers impacting fish populations in the 25 Sentinel Lakes. The information on potential mechanisms impacting fish populations identified in the Sentinel Lakes could potentially be used to inform fish management on other similar lakes statewide.

We examined historical fish catch data from the Sentinel Lakes to identify trends in fish catches and asses the similarity between them and statewide trends. Trends in catch per unit effort (CPUE) from fish sampled during standard fisheries surveys from 1970-present were calculated and analyzed for 25 Sentinel Lakes using linear regression, otherwise following the methods of Bethke and Staples (2015). We obtained the survey data from the Minnesota DNR Lakefinder website and selected a gear appropriate CPUE for each fish species (boat electrofishing – Largemouth Bass and Smallmouth Bass; gill nets – Black Bullhead, Brown Bullhead, Yellow Bullhead, Northern Pike, Rock Bass, White Sucker, and Yellow Perch; trap nets – Black Crappie and Bluegill). Note, there was a difference in the gear used to sample Largemouth Bass and Smallmouth Bass between the two analyses (Sentinel Lakes used boat electrofishing CPUE and Bethke and Staples used gill net CPUE). We acknowledge that summer trap nets may not provide accurate estimates of abundance for BLG and BLC, however, they are currently the best available option for these two species. Also, we acknowledge the assumption that CPUE is proportionally related to abundance which has not been evaluated for many of the species included in this analysis and therefore would be a helpful area of future research (see McInerny and Cross 2000 and Schoenebeck et al. 2015). CPUE is often highly variable, even within a single lake. Standard sampling methods are employed (e.g. standardized net locations, time of sampling, gear type, etc.) to reduce uncertainty as much as possible, however it should be acknowledged that a significant amount of uncertainty still remains so this analysis focused on long-term trends in CPUE. Per Bethke and Staples (2015), we added a value of one to each CPUE value to account for zero CPUE values and then natural log transformed those data. For the analyses, we ran a simple linear regression between the natural log transformed CPUEs and time to calculate the slope and evaluate the significance of the slope for each species on each lake. We selected only lake and species combinations with more than four sampling events to calculate the mean slope and determine if a species had an overall positive or negative trend in CPUE across all lakes. We evaluated and reported significance at both the 0.05 and 0.1 levels. Finally, we made comparisons of trends between our results and those seen in the 1499 Minnesota lakes examined by Bethke and Staples (2015).

Centrarchids

Black Crappie and Largemouth Bass CPUE increased more often than decreased in the Sentinel Lakes over time.

Black Crappie CPUE increased in 3 lakes and decreased in 2 lakes at the 0.01 significance level. Largemouth Bass CPUE increased in 4 lakes and decreased in 1 lake at the 0.01 significance level. Rock Bass CPUE only increased marginally in a single lake (Ten Mile) and overall Rock Bass CPUE did not change, however Rock Bass typically occupy a more cool water oligotrophic niche than other Centrarchid species in Minnesota (Jacobson et al. 2017). Bluegill CPUE increased in 2 lakes, and decreased in 2 lakes. Increased Centrarchid relative abundance in the Sentinel Lakes is similar to changes observed in Minnesota (Bethke and Staples 2015), Wisconsin (Hansen et al. 2015; Hansen et al. 2017), and southern Ontario (Finigan et al. 2018). Changes in lake physical characteristics, especially increasing water clarity, aquatic macrophyte abundance, and water temperature, may potentially create more favorable conditions for Centrarchids in the Sentinel Lakes (Nalepa et al. 1996; Hansel-Welch et al. 2003; Robillard and Fox 2006; Breeggemann et al. 2016; Jacobson et al. 2017; Miller et al. 2018; McEachran et al. 2019). Water clarity trends have been stable or increasing in all 25 Sentinel Lakes over the period of record (see water quality analysis) which often leads to increased macrophyte abundance (e.g. Hansel-Welch et al. 2003). Analyses of aquatic macrophyte trends in the Sentinel Lakes is currently in progress by EWR and once completed will help inform fish community changes. Generally, water temperatures in the Sentinel Lakes have been increasing during the relatively short time (2009-2018) data has been collected (see water temperature analysis), and continued collection of temperature data will benefit future analyses. Additionally, changes in angler attitudes towards harvest of some species may also impact CPUE. For example, voluntary release rates of Largemouth Bass by anglers have increased over the past serval decades in several states including Minnesota (Myers et al. 2008; Isermann et al. 2013).

In some cases range expansion and increases in Centrarchid relative abundance may come at the expense of other species (i.e. Percids) and result in the restructuring of whole lake fish communities (Fayram et al. 2005; Robillard and Fox 2006; Van Zuiden et al. 2016). Shifts in fish communities favoring Centrarchids over Percids may have important consequences for the management of popular sport fishes, e.g. Walleye and Yellow Perch.

Northern Pike

Northern Pike CPUE has increased more often than decreased in the Sentinel Lakes over time.

Similar to some of the Centrarchid species, CPUE of Northern Pike also increased over time in several of the Sentinel Lakes, with a significant increase in seven lakes and a significant decrease in only one lake (Artichoke) at the 0.1 level. Northern Pike are visual predators often associated with vegetated habitats, and similar to Centrarchids, increasing water clarity and aquatic macrophyte abundance may create more favorable conditions for pike (Pflieger 1975). Three of the seven lakes with significant Northern Pike increases (Bearhead, South Twin, and Belle) also showed significant increases in water clarity. As top predators Northern Pike have the potential to impact fish communities through predation on other species, and are also a popular sportfish with anglers. Recent changes in statewide Northern Pike regulations (implementation of zone based regulations in 2018 with a goal of maintaining or increasing size structure) have the potential to impact fish communities over the long term by structuring Northern Pike population dynamics. The long term monitoring framework provided by the Sentinel Lakes program offers an excellent opportunity to evaluate lake-wide effects of these regulation changes, beyond impacts on the pike population. For example, changes in the population dynamics of forage species or top down impacts on the zooplankton community. There are Sentinel Lakes located in the Northeast, North Central, and Southern Northern Pike Management zones.

Percids

Yellow Perch CPUE decreased more often than increased in the Sentinel Lakes over time.

Yellow Perch CPUE decreased in 5 lakes and increased in 2 lakes at the 0.1 significance level. Yellow Perch are a popular species with recreational anglers, and an important forage species in many lakes in the upper Midwest and Canada, so declines could be impactful. Several potential explanations for the observed decline in yellow perch relative abundance could be harvest, predation, competition, or changes in size structure that would influence catch rates in standard gill nets. Yellow Perch display female-biased sexual size dimorphism (SSD) were female growth is faster than males (Uphoff and Schoenebeck 2013) and because anglers are size selective this can concentrate harvest on female Yellow Perch removing the fastest growing and largest fish from a population (Schoenebeck et al. 2010, Schoenebeck and Brown 2011). We do not have empirical data to evaluate if there was a change in harvest but suspect this mechanism is not as likely as other potential drivers because of the relatively small size structure of these populations and Yellow Perch size structure did not meaningfully change since 1994 in the four Sentinel Lakes with significant decreases in perch CPUE (Fig 1.). Regardless of harvest, Yellow Perch natural mortality can far exceed harvest mortality even in populations with harvestable length perch (Schoenebeck and Brown 2011). Yellow Perch populations can be influenced by top down effects such as predation and abundant predators can decrease Yellow Perch abundance (Johnson et al. 1992; Bertolo and Magnan 2005; Thao et al. 2016). Northern Pike in particular have been shown to decrease Yellow Perch abundance when pike occur in high densities or become established in novel systems (Paukert et al. 2003, Nicholson et al. 2015). The increasing trend in Northern Pike CPUE in the Sentinel Lakes may indicate predation is partially responsible for the observed decline in Yellow Perch relative abundance. Walleye can also impact Yellow Perch relative abundance through predation, and are naturally present or supplemented by stocking in most Sentinel Lakes (Pierce et al. 2006). Yellow Perch are also potentially impacted through competition with Bluegill (Schoenebeck and Brown 2010) and therefore increasing Bluegill populations may compete with Yellow Perch. The density of large Daphnia spp., a preferred prey when Yellow Perch are zooplanktivorous, has declined in some of the lakes that have also seen a decline in yellow perch CPUE (Carlos, Ten Mile) and large Daphnia spp. densities are high in South Center Lake where both Yellow Perch and Bluegill CPUE have declined. Alternatively, reductions in Yellow Perch CPUE may be due to changes in catchability. Shifts in Yellow Perch size structure or changes in behavior may influence their vulnerability to capture and underrepresent abundance as indexed with gill net CPUE. Yellow Perch in some central Minnesota lakes frequently mature at sizes too small to be effectively sampled by standard gears (150 mm; MN DNR Brainerd Area Office, personal communication). Similarly a large number of 100 mm and smaller Yellow Perch were sampled by Sentinel Lakes staff in Pearl Lake while slowly boat electrofishing during the fall of 2018, where perch are rarely sampled using standard survey gear. An upcoming DNR project will focus on Yellow Perch population dynamics and sampling, including 3 Sentinel Lakes, which will help elucidate changes in perch CPUE.

While Walleye did show significant increasing and decreasing trends in some Sentinel Lakes, the frequency and variability of stocking as a management activity in the majority of lakes would make identifying mechanisms behind these changes difficult.

White Sucker

White Sucker CPUE decreased in over 30% of the Sentinel Lakes over time.

White Sucker CPUE significantly declined in 6 ($P < 0.10$) of 19 Sentinel Lakes and did not increase in any lakes, mirroring declines documented across all Minnesota lakes by Bethke and Staples (2015). Several potential explanations for the observed decline in White Sucker could be the result of increased predation or environmental stressors. White Sucker are an important prey species for Northern Pike and Walleye in many lakes, and predation can negatively impact White Sucker abundance. Bertolo and Magnan (2005) found that predation by Northern Pike and Walleye had a negative effect on White Sucker abundance in headwater lakes of the Canadian Shield. In three other Canadian lakes White Sucker were extirpated after the introduction of Northern Pike to the novel systems (Nicholson et al. 2015). Similar to Yellow Perch, increased abundance of Northern Pike in the Sentinel Lakes may be contributing to the negative trend in CPUE observed for White Sucker. For example, Bearhead and Pearl Lakes have seen significant negative trends in White Sucker CPUE correlating with significant positive trends in Northern Pike CPUE.

Alternatively, White Sucker are sensitive to a variety of environmental stressors including acidification, heavy metal pollution, eutrophication, thermal stress and habitat degradation (McFarlane and Franzin 1978; Mills et al. 1987). However, environmental stressors and habitat degradation on a large scale do not appear to be a factor as relatively pristine lakes such as Tait, Bear Head and Ten Mile saw significant declines in White Sucker CPUE. Lakes with declines in White Sucker CPUE span a wide range of sampled water quality parameters including alkalinity, ph, and total phosphorous. Thermal stress is a possibility, as early indications suggest water temperatures in the Sentinel lakes are generally warming (see temperature analysis), but more data is needed to fully investigate warming water temperature as a potential mechanism for decreases in White Sucker CPUE.

Bullheads

CPUE of all 3 Bullhead species have declined more often than increased in the Sentinel Lakes over time.

CPUE of Black Bullhead, Brown Bullhead, and Yellow Bullhead all decreased more often than increased in the Sentinel Lakes, with Black Bullhead having the most negative trend in Belle Lake. Brown Bullhead and Yellow Bullhead generally occupy habitats with clearer water and more abundant macrophyte growth than Black Bullheads, which are generally found in more turbid habitats (Pflieger 1975; Brown et al. 1999). Increasing water clarity and aquatic macrophyte growth in Sentinel Lakes may favor Brown Bullhead and Yellow Bullhead, potentially explaining the greater decline of Black Bullhead. Three of the seven lakes that had significant declining trends in Bullhead CPUE (Belle, Cedar, and Carlos) also had significant increases in water clarity.

Overall trends and comparison to other Minnesota lakes.

Species-specific trends in CPUE over time observed in the Sentinel Lakes were similar to those documented in an analysis of 1499 Minnesota lakes (Bethke and Staples 2015).

In both analyses, CPUE of Centrarchids (Bluegill, Black Crappie, and Largemouth Bass) and Northern Pike have increased since 1970 while the CPUE of Yellow Perch and White Sucker have decreased. Bethke and Staples (2015) used gill net and trap net CPUE for all species, while in the Sentinel Lakes comparison used gill nets (BLB, BRB, NOP, RKB, WAE, WTS, YEB, YEP), trap nets (BLC, BLG) and boat electrofishing (LMB, SMB). In addition, the Sentinel Lakes analysis investigated trends of several new species such as Rock Bass and Bullhead species (detailed herein) and Cisco (detailed in the Sentinel Lakes pelagic fish report) and we suggest that an effort to support or contrast the trends of these particular species beyond the Sentinel Lakes would be informative. Gill net and trap net Smallmouth Bass CPUE increased in the Bethke and Staples (2015) analysis, however, only two Sentinel Lakes had sufficient Smallmouth Bass data for analysis and therefore the Sentinel Lakes Smallmouth Bass trends should only be considered at the lake level and not extrapolated to the state level. In general, the trends observed in the Sentinel Lakes agree with those found by Bethke and Staples (2015) and suggest that the Sentinel Lakes are representative of fish community trends in Minnesota Lakes.

Table I. Trends in CPUE for 12 species of fish sampled during standard fisheries surveys in the Sentinel Lakes from 1970-present. Species, lake number, and lakes with significant trends at α=0.05 and α= 0.1 are listed. Annual percent change in CPUE's were calculated using the formula (e^slope)*-100. This removed the natural log from the trend line and gave an approximate percent change in the CPUE per year. Species: Black Bullhead (BLB); Black Crappie (BLC); Bluegill (BLG); Brown Bullhead (BRB); Largemouth Bass (LMB); Northern Pike (NOP); Rock Bass (RKB); Smallmouth Bass (SMB); Walleye (WAE); White Sucker (WTS); Yellow Bullhead (YEB); Yellow Perch (YEP). Lakes: Belle (BEL); Bear Head (BHD); Portage (PTG); Elephant (EPH); Red Sand (RDS); White Iron (WHI); South Center (SCR); Carlos (CLS); Ten Mile (TEN); Madison (MAD); Artichoke (ART); Pearl (PRL); Peltier (PLT); South Twin (STW); St. James (STJ); St. Olaf (STO); Hill (HIL); Echo (ECH); Tait (TAI); Cedar (CED).

Species	Number of Lakes	CPUE % Change per Year	Pos Trend 0.05	Neg Trend 0.05	Pos Trend 0.1	Neg Trend 0.1
BLB	12	-3.15		BEL		BEL
BLC	20	1.21	EPH, RDS	BHD	BEL, EPH, RDS	BHD, PTG
BLG	23	0.30	PTG	RDS	PTG, WHI	RDS, SCR, TEN
BRB	7	-0.80		CLS		CLS, SCR, TEN
LMB	12	2.53	BHD, MAD		ART, BHD, MAD, RDS	HIL
NOP	23	1.51	BHD, PRL, STJ, STO	ART	BHD, BEL, PRL, PLT, STW, STJ, STO	ART
RKB	7	-0.30				
SMB	2	-8.5				ECH, EPH
WAE	20	-0.50		HIL, PRL, TAI	STJ	ART, HIL, PRL, TAI
WTS	19	-1.29		BHD, HIL, PRL, TAI, TEN, WHI		BHD, HIL, PRL, TAI, TEN, WHI
YEB	11	-0.90		CED, HIL		BEL, CED, HIL, MAD, STO
YEP	21	-1.69	TAI	SCR, TEN	SHK, TAI	BHD, CLS, PTG, SCR, TEN

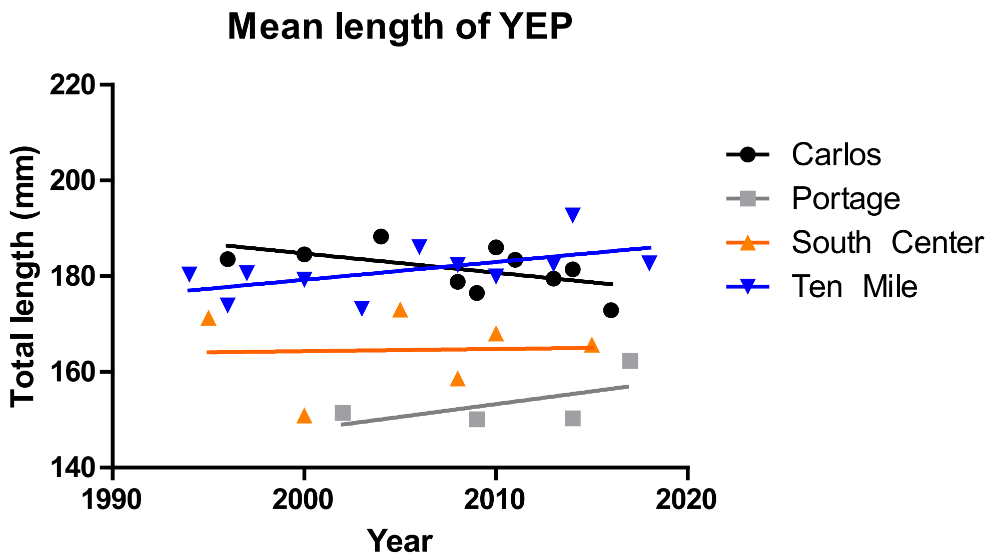

Figure 1. Mean total length (mm) of Yellow Perch sampled in standard survey gillnets from 1994 to 2018 in Carlos, Portage, South Center, and Ten Mile Lakes. No trends were significant.

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Outcome 3 - We have identified dissolved oxygen monitoring as a data gap for long-term monitoring of aquatic systems and we have already made progress over the last 3 years to fill this gap. We received continuous dissolved oxygen (DO) sensors through support from the US Fish and Wildlife Service and the MNDNR Fisheries Habitat program (approximately $43,000) and deployed them as sensor chains, much like the temperature sensor chains, during 2018 in Carlos, Greenwood, and South Center lakes. In order to maintain consistency amongst lakes, we developed methods to determine which depths the sensors should be placed along the chains. We also pursued and received funding ($46,500) through a competitive grant from the Midwest Glacial Lakes National Fish Habitat Partnership and we received additional funds from the MN DNR Habitat program ($21,000) which allowed us to purchase and deploy additional DO logger chains on lakes Madison, Ten Mile, and White Iron. Additionally, three more Sentinel Lakes will have DO sensors deployed on them this fall by Fisheries Areas including lakes Artichoke, St. James, and Shaokotan. The University of Minnesota Itasca Biological Research Station will deploy a sensor buoy on Elk Lake which will collect continuous DO data as well as a variety of other lake metrics.

Other data gaps that would be informative include creel surveys to quantify angler stress on Sentinel Lake fisheries, estimates of primary, secondary and when possible tertiary production (e.g., Cisco) to model and forecast impacts from large stressors on the energy flow of Sentinel Lakes, and baseline fish physiology and energetics especially surrounding early life history such as energetics surrounding ontogenetic diet shifts.

ACTIVITY 2: Temperature, Biological and Water Chemistry Monitoring of Sentinel Lakes and Establishing a Supporting Network of Temperature Monitoring in Minnesota Lakes.

Description: To date, most of our temperature monitoring has focused on the thermal habitat requirements of cold water species such as Cisco. We propose to expand our water temperature monitoring in the Sentinel Lakes to include the shallower, littoral areas of lakes. This added temperature monitoring will provide us insight into just how variable water temperatures in shallower areas might be and how that variability may affect cool and warm water fish species. We also propose to continue detailed water chemistry analyses on the 25 lakes as well as continuing to assist partners with sampling on an as needed basis.

Summary Budget Information for Activity 2: **ENRTF Budget: $ 243,438**
Amount Spent: $ 221,019
Balance: $ 22,419

Outcome	Completion Date
1. *Expanded Temperature Monitoring of Sentinel Lakes*	30 June 2019
2. *Water Chemistry Analysis on Selected Sentinel Lakes*	30 June 2019
3. *Assist with Monitoring Biological Communities in Sentinel Lakes*	30 June 2019

Activity Status as of 11/30/2016:

Outcome 1 – Three interns stationed out of Glenwood and a Long-Term Monitoring (LTM) Biologist stationed out of Brainerd were hired to assist with outcomes 1 and 3. Since July 1st, temperature monitoring has been expanded in Lake Carlos with the addition of 2 new temperature logger chains and new chains will also be placed in Ten Mile, South Center, St. Olaf, and St. James this winter (2016-2017). Area fisheries management supervisors were contacted and asked to designate someone as a LTM contact in each area with a Sentinel Lake. Area LTM contacts were then asked to download temperature data from Sentinel Lakes in their area and thus far temperature loggers have been downloaded on Red Sand, Bear Head, Echo, Elephant, White Iron, Elk, Carlos, Pearl and Shaokotan. In support of this effort, 48 temperature loggers have been distributed to 9 areas to replace existing temperature loggers if needed and another order of temperature loggers will occur this winter to support further temperature monitoring in the Sentinel Lakes.

Outcome 2 – Pursuant to the Interagency Agreement which began July 1st 2016, the Minnesota Pollution Control Agency (MPCA) collected water samples monthly from July to October and the Minnesota Department of Health (MDH) analyzed and reported water quality analytes which were placed in MPCA's EQuIS database by MPCA staff.

Outcome 3 –Sentinel Lakes Program staff assisted area DNR biologists with standardized population assessments (gillnets and trap nets targeting sportfish such as Walleye, Yellow Perch, and Bluegill) and using a combination of backpack electrofishing and seines to sample the littoral fish community using the Index of Biotic Integrity metric for Elk and Carlos Lakes. Pelagic fish communities, consisting mainly of Cisco and Lake Whitefish, were assessed using vertical gill nets (VGN) and hydroacoustics on Carlos, Elk, and Ten Mile lakes in cooperation with DNR staff. In October of 2016, Sentinel Lakes Program staff completed boat electrofishing surveys on Carlos, Elk, and Ten Mile Lakes which targeted young-of-the-year Largemouth Bass, Smallmouth Bass, Yellow Perch, Rock Bass, and Bluegill to assess pre-winter lengths of these species. Sentinel Lake population assessment (Elk, Carlos) and IBI (Elk, Carlos) data have been entered into the Fisheries Survey database (DNR). Vertical gillnet data and corresponding temperature and dissolved oxygen profiles (Elk, Carlos) have been entered and sent to Lucas Borgstrom (DNR) who maintains the VGN database. In concert with water chemistry sampling, zooplankton tows were collected from May through October and will be processed and entered this winter (DNR).

Activity Status as of 3/31/2017:

Outcome 1 - We have purchased 104 continuous temperature loggers and have distributed some of those loggers to area representatives to replace expired existing loggers. Sentinel lakes that currently do not have temperature loggers (South Center, St. Olaf, Peltier, and St. James) will be outfitted with temperature loggers this spring and summer so that all 25 Sentinel lakes have continuous temperature monitoring data. Temperature loggers from 9 lakes were downloaded this winter (other areas elect to download during open water). Previously-collected temperature data that was located on the DNR shared drive has been organized and the data management position will combine and organize the remaining temperature data into a single, centralized Access database to facilitate broad scale data analysis. We are also exploring ways to standardize measures from continuous temperature data (develop metrics meaningful in biological analysis).

Outcome 2 – No water samples were collected after October so no new samples were processed.

Outcome 3 –LTM Biologist Derek Bahr reanalyzed previous 2010 -2012 hydroacoustic data and analyzed 2016 data to estimate pelagic fish density and biomass in Carlos, Cedar, Elk, South Twin, Ten Mile, and Trout lakes using the standardized DNR hydroacoustic sampling protocol. This allows us to compare estimates across sampling years.

In cooperation with Glenwood Area management, the Sentinel Lakes Program set 20 baited (salted and unsalted) hoop nets targeting Burbot in Lake Carlos.

Activity Status as of 9/30/2017:

Outcome 1 – In the summer of 2017 temperature loggers were placed in 4 Sentinel lakes that did not have loggers (South Center, St. Olaf, Peltier, and St. James) so that all 25 Sentinel Lakes now have continuous water temperature monitoring. In addition, a temperature logger chain was deployed on Ten Mile Lake to replace a single logger unit. We developed standard operating procedures for continuous water temperature and water level monitoring for the Sentinel Lakes Program which are currently under peer review and we delivered a webinar and workshop describing these procedures. We increased the number of lakes receiving OTT Orpheus mini pressure transducers that continuously measure changes in lake elevation to include all 9 tier 1 lakes and improvements were made to make those housings more efficient.

Outcome 2 –The Minnesota Pollution Control Agency (MPCA) collected water samples monthly from July to October and the Minnesota Department of Health (MDH) analyzed and reported water quality analytes which were placed in MPCA's EQuIS database by MPCA staff.

Outcome 3 –Pelagic fish community sampling was expanded to include 2 new lakes for 2017 (Trout and Greenwood) in additional to the annual sampling of Carlos, Elk, and Ten Mile using vertical gill nets (VGN) and hydroacoustic surveys. Vertical gillnet data and corresponding temperature and dissolved oxygen profiles have been entered and sent to nearshore sampling IBI Program who maintains the VGN database. Sentinel Lakes Program staff also sampled nearshore fish communities using the Index of Biotic Integrity metric. In concert with water chemistry sampling, zooplankton tows were collected from May through October and will be processed and entered this winter by DNR.

Activity Status as of 3/31/2018:

Outcome 1 – All 25 Sentinel Lakes have continuous water temperature loggers at this time with the exception of Pearl (the chain was not recovered so it will be replaced). Temperature loggers from 8 lakes were downloaded this fall or winter (other areas elect to download during open water). These data have been QAQCed and added to the continuous water temperature database.

Outcome 2 – No water samples were collected after October so no new samples were processed.

Outcome 3 – We sampled juvenile fish via October boat electrofishing in Elk, Carlos and Ten Mile Lakes. During 2017 yellow perch, largemouth bass, and bluegill grew faster in Elk Lake compared to Carlos and Ten Mile. Interestingly, bimodal length distributions were noted for age-0 largemouth bass (2017 year class) in all 3 lakes. Corresponding water temperature data suggest these bimodal distributions may have been caused by a sharp drop in water temperature during mid to late May, which likely interrupted largemouth bass spawning activity in these lakes resulting in two discrete groups of hatch dates.

The lake whitefish population in Ten Mile Lake appears to be slow growing, late maturing, with a top heavy age structure which suggests a relatively unexploited fish population. Lake whitefish in Ten Mile Lake did not sexually mature until 15-20 years of age, and more than 50% of the sampled fish were 25 years of age or older with a maximum of 62 years old. By comparison, Cisco from Ten Mile Lake ranged from 1 to 14 years in age, with the majority of individuals in the 5-8 year range.

Activity Status as of 9/30/2018:

Outcome 1 – Continuous water temperature loggers were downloaded by the areas and these data have been QAQCed and added to the continuous water temperature database.

Outcome 2 – The Minnesota Pollution Control Agency (MPCA) collected water samples monthly from July to October and data were entered in MPCA's EQuIS database by MPCA staff.

Outcome 3 – The Sentinel Lakes Program completed the first full year of intensive (fall and spring) juvenile fish sampling on Lake Carlos, Elk Lake, and Ten Mile Lake in May of 2018 and found multiple instances of size-selective overwinter mortality. Sampling was done via targeted boat electrofishing in areas likely to contain juvenile fish targeting Bluegill, Largemouth Bass, Rock Bass, and Yellow Perch. LTM biologists sampled 497 juvenile fish in the fall of 2017, and collected length, weight and structures for age and growth analyses. An additional 724 juvenile fish were sampled in the spring of 2018 to examine overwinter survival. Quantile quantile plots of age-0 length distributions were compared between fall and spring electrofishing to asses if overwinter mortality was length-dependent (Figure 1).

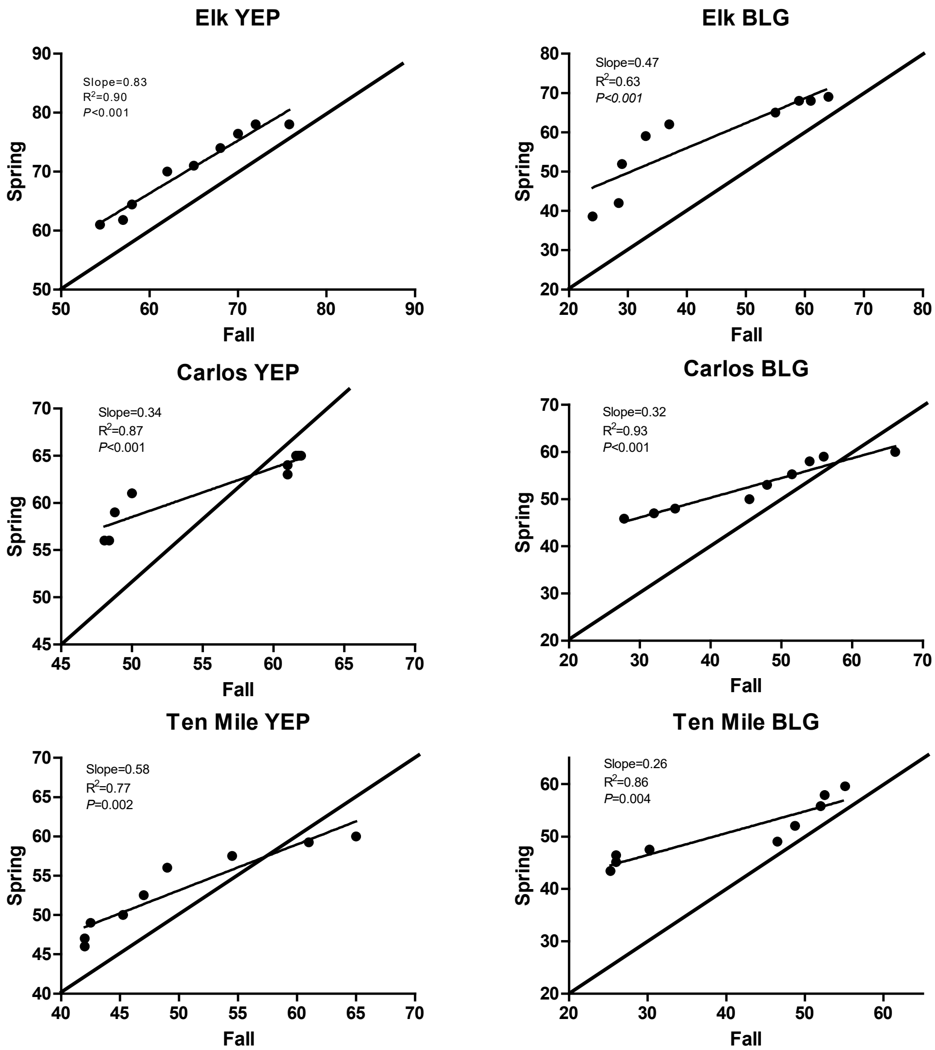


Figure 1. Quantile quantile plots of length distributions from sampled age-0 Yellow Perch and Bluegill sampled in fall 2017 and spring 2018 from Elk Lake, Lake Carlos, and Ten Mile Lake via boat electrofishing. Significant positive slopes indicate size selective overwinter mortality favoring larger individuals likely occurred.

Age-0 Yellow Perch were sampled in in all three lakes during the fall of 2017, and a single cohort of age-0 fish were present in each lake. Growth of age-0 Yellow Perch differed between lakes, with a mean length of 64 mm (SE=0.55) in Elk Lake, 56mm (SE=3.04) in Lake Carlos, and 48mm (SE=1.12) in Ten Mile Lake. Quantile quantile plots of fall and spring length distributions suggest that size selective mortality favoring larger age-0 Yellow Perch occurred in Elk Lake (R2=0.90, P<0.001), Lake Carlos (R2=0.87, P<0.001), and Ten Mile Lake (R2=0.77, P=0.002) during the winter of 2017/18 (Figure 2).

Two length groups (a group of early and late hatch fish) of age-0 Bluegill were sampled in Elk Lake, Lake Carlos, and Ten Mile Lake. This is not uncommon, as Bluegill will often spawn more than once during a summer, resulting in early and late hatch age-0 fish. Mean lengths of the early hatch group were 57mm (SE=0.55) in Elk Lake, 49mm (SE= 0.51) in Lake Carlos, and 49mm (SE=0.66) in Ten Mile Lake. The mean length of the late hatch group of age-0 bluegills was 34mm (SE=0.42) in Elk Lake, 31mm (SE=0.92) in Lake Carlos, and 30mm (SE=1.42) in Ten Mile Lake. Quantile quantile regression plots of fall and spring length distributions indicate size selective mortality occurred over the winter of 2017/18 in Elk Lake ($R2=0.63$, $P<0.001$), Lake Carlos ($R2=0.93$, $P<0.001$), and Ten Mile Lake ($R2=0.86$, $P=0.004$) as the late hatch group of Bluegill did not survive the winter in all three lakes (Figure 2).

Similar to Bluegill, two length groups of age-0 Largemouth Bass were also sampled during the fall of 2017 in Elk Lake, Lake Carlos, and Ten Mile Lake. However, unlike Bluegill, this is not a common occurrence with Largemouth Bass, and may have been the result of a spawn interrupted by a prolonged cold front that occurred in the spring of 2017. Mean lengths of the early hatch group were 72mm (SE=1.76) in Elk Lake, 70mm (SE=2.63) in Lake Carlos, and 57mm (SE=1.41) in Ten Mile Lake. Mean lengths of the late hatch group of Largemouth Bass were 43mm (SE=1.50) in Elk Lake, 49mm (SE=0.99) in Lake Carlos, and 44mm (SE=0.76) in Ten Mile Lake. No age-0 Largemouth Bass were sampled in Ten Mile Lake (Figure 2) and only a single age-0 Largemouth Bass was sampled in Elk Lake and Lak Carlos in the spring of 2018. Largemouth Bass appeared to have poor overwinter survival in all three sampled lakes during 2017/18, potentially indicating a weak 2017 year class in central and north central Minnesota.

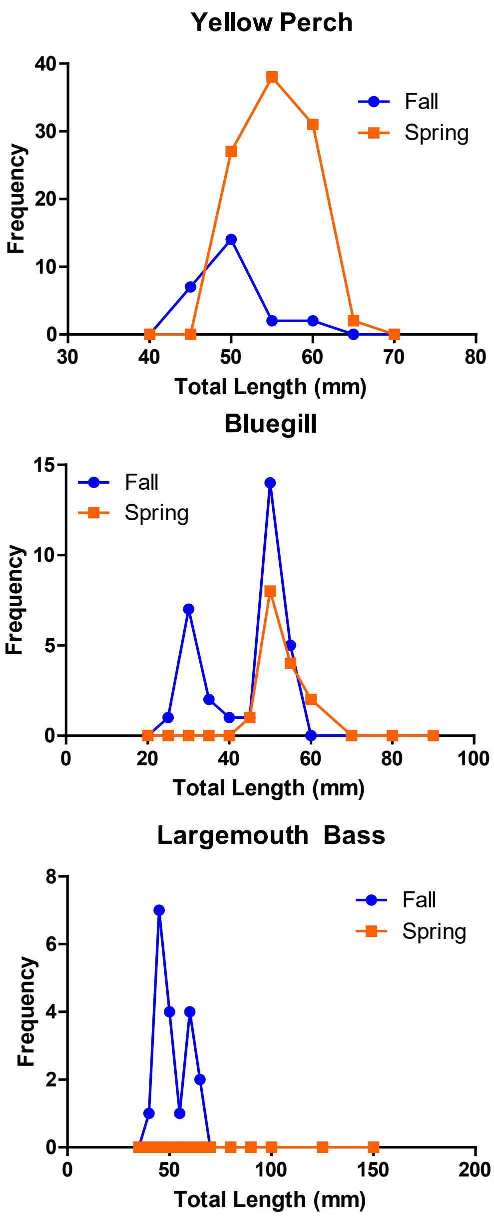


Figure 2. Length frequency histograms of age-0 Yellow Perch, Bluegill, and Largemouth Bass sampled from Ten Mile Lake via boat electrofishing in the fall of 2017 and spring of 2018. Notice the missing early hatch group of Bluegill and both early and late hatch groups of Largemouth Bass in the spring of 2018.

Rock Bass were only sampled in sufficient numbers in Elk Lake during the fall of 2017 and spring of 2018. Unlike the other two Centrarchid species (Bluegill and Largemouth Bass), only a single length group of age-0 Rock Bass was sampled. The mean length of age-0 Rock Bass was 38mm (SE=0.42), and quantile quantile regression plots indicated that size selective mortality favoring larger individuals occurred during the winter of 2017/18 ($R2=0.87$, $P<0.001$).

Targeted sampling of pelagic fish, specifically Cisco and Lake Whitefish was conducted using vertical gillnets during the summer 2018 on Elk Lake, Lake Carlos, and Ten Mile Lake. Lengths, weights, and aging structures were collected. LTM staff sampled 48 Cisco ranging from 200mm to 370mm and collected 43 structures from Elk Lake. Staff sampled 376 Cisco ranging from 80mm to 390mm from Lake Carlos and collected 69 structures for aging. Staff sampled 88 Cisco and 6 Lake Whitefish from Ten Mile Lake and collected 40 structures for aging. Twenty nine otoliths were aged from Cisco collected in Ten Mile Lake in 2016, and 34 otoliths from 2017. Cisco ranged from 0 to 18 years of age, and 85% of sampled fish were 5 years of age or less. The oldest Cisco sampled was an 18y old male that was 184mm in length, and the majority of fish were mature by age-3. Sixty eight otoliths were aged from Cisco collected in Lake Carlos in 2017. Cisco sampled from Lake Carlos ranged in age from 0 to 12 years of age, and 62% of sampled fish were 5 years of age or less. The oldest Cisco sampled was a 12 year old male that was 330mm in length and the majority of fish were mature by age-4. A total of 38 otoliths from Lake Whitefish collected from Ten Mile Lake were prepared and aged. Lake whitefish sampled from Ten Mile Lake in 2016 and 2017 ranged from 11 to 62 years in age, and 55% of fish sampled were 20 years of age or older. The oldest Lake Whitefish sampled was a 62 year old male. This is likely one of the oldest inland Lake Whitefish ever sampled and aged in Minnesota. Both Male and Female Lake Whitefish did not reach maturity until 15-20 years of age. The abundance of old individuals, relatively slow growth, and late age at maturity (15-20) of the Ten Mile Lake Whitefish population suggest relatively low levels of exploitation, and a potential opportunity to observe the effects of increased exploitation or other stressors if and when they might occur.

Activity Status as of 3/31/2019:

Outcome 1 – Continuous water temperature loggers were downloaded by the areas and these data have been QAQCed and added to the continuous water temperature database.

Outcome 2 – No water samples were collected after October so no new samples were processed.

Outcome 3 - The Sentinel Lakes Program completed intensive juvenile fish sampling for Bluegill, Largemouth Bass, Rock Bass, and Yellow Perch on Lake Carlos, Elk Lake, Pearl Lake, and Ten Mile Lake in October of 2018. Sampling was done via targeted boat electrofishing in areas likely to contain juvenile fish and we sampled 1,107 juvenile fish and collected length, weight and structures for age and growth analyses. Juvenile Yellow Perch were sampled in Ten Mile Lake, Elk Lake and Pearl Lake, but not in Lake Carlos during the fall of 2018, and a single cohort of age-0 fish were present in each lake. Growth of age-0 Yellow Perch differed between lakes, with a mean length of 50.1 mm (SD = 3.8) in Ten Mile Lake, 68.5 mm (SD = 5.3) in Elk Lake and 55. 5 mm (SD = 5.9) in Pearl Lake. Mean length of Yellow Perch in Elk Lake and Ten Mile Lake was 20% (13 mm) and 4% (2.1 mm) longer respectively in 2018 than in 2017. Maturity data was collected for Yellow Perch sampled in the fall of 2018. Male age-0 Yellow Perch sampled from Elk Lake were mature at a mean length of 72.0 mm (SD = 3.8), while the only mature female Yellow Perch collected was a 135 mm 3 year old. Male age-0 Yellow Perch sampled from Pearl Lake were mature at a mean length of 55.3 mm (SD = 6.0), while female Yellow Perch were mature at age-1 and a mean length of 109 mm (SD = 6.7). Only one mature male age-0 YEP (52mm) was sampled from Ten Mile Lake. The early age and small size at maturity observed in the Yellow Perch populations of Elk Lake and Pearl Lake is similar to observations made by MN DNR fisheries staff in other central Minnesota lakes and ties in to the upcoming DNR Yellow Perch project which will incorporate several Sentinel Lakes.

Juvenile Bluegill were sampled in Carlos, Elk, Ten Mile, and Pearl Lakes during October of 2018. A single group of age-0 Bluegill was sampled during 2018, in contrast to 2017 where two groups (late/small and early/large) of age-0 Bluegill were sampled. The late ice-out for many Minnesota lakes in 2018 may have limited the success of early spawning bluegill, resulting in a single group in 2018. Mean length of sampled age-0 Bluegill in Elk Lake was 55.1 mm (SD = 10.3), similar in size to the larger group in 2017 (57 mm). Age-0 Bluegill in Lake Carlos had a mean length of 33.9 mm (SD = 9.1), significantly smaller than the larger cohort in 2017 (49 mm). Age-0 Bluegill in Ten Mile Lake had a mean length of 36 mm (SD = 6.24), roughly between the sizes of the early and late hatch groups found in 2017. Sampled age-0 Bluegill from Pearl Lake in 2018 had a mean length of 33.2 mm (SD = 5.1), and while no 2017 data from Pearl is available, this is similar to the size of the small age-0 cohort observed in the other sampled lakes in 2017.

Juvenile Largemouth Bass were sampled in Elk Lake, Lake Carlos, Ten Mile Lake, and Pearl Lake in the fall of 2018. Unlike the fall of 2017 where bimodal length distributions of age-0 Largemouth Bass were observed in all sampled lakes, only age-0 Largemouth Bass from Lake Carlos and Ten Mile Lake showed a bimodal distribution in 2018. In Lake Carlos the larger group in 2018 had a mean length of 84.1 mm (SD = 6.1), and the smaller group had a mean length of 57.6 mm (SD = 6.6). Both groups were larger in the fall of 2018 than the respective large (70 mm) and small (49 mm) groups sampled in the fall of 2017. Largemouth Bass sampled from Ten Mile Lake in 2018 had a mean length of 78.8mm (SD=23.2) for the larger cohort and 50.5mm (SD=5.33) for the smaller cohort. These were larger than the respective cohorts sampled in 2017 (57mm and 44mm). Age-0 Largemouth Bass sampled in Elk Lake and Pearl Lake had monomodal length distributions in 2018. Mean length of sampled fish was 66.5 mm (SD = 12.4) in Elk Lake, smaller than the large group in 2017 (70 mm), and 94.0 mm (SD = 8.0) in Pearl Lake.

Final Report Summary:

Outcome 1 – We have outfitted all 25 Sentinel Lakes with continuous water temperature loggers ranging from single loggers in some shallow, polymictic lakes to chains of loggers in deep, stratified lakes. Over the last 3 years we have purchased 204 new loggers (104 using $11,004 of LCCMR funds and 100 using DNR in-kind support) and have used them to outfit new chains (South Center, St. Olaf, Peltier, and St. James), upgraded single logger lakes to multiple logger chains (e.g., Ten Mile), replace worn out loggers on existing chains, and have launched several littoral chains for a total of 180 currently active recording water temperature loggers in the Sentinel Lakes. In addition, we have increased the number of lakes receiving OTT Orpheus mini pressure transducers that continuously measure changes in lake elevation to include all 9 tier 1 lakes which is relevant to this outcome because these loggers simultaneously collect water temperature in addition to lake level. The continuous water temperature data are being used to track annual lake thermal cycles and quantify changes in the depth and duration of stratification. Furthermore, acknowledging continuous dissolved oxygen as a knowledge gap and allocating resources, including in-kind support, to collect DO data (Activity 1, Outcome 3) will allow us to better understand oxythermal habitat and the impact on MN fish and lower trophic levels. Indeed, this dataset is a strength of the Program and we suggest this be an area of in depth analyses expanding on the outcomes detailed in the water temperature analyses (Activity 1 Outcome 2).

Outcome 2 – The Minnesota Pollution Control Agency (MPCA) collected water samples monthly from July 2016 to June 2017 and the Minnesota Department of Health (MDH) analyzed and reported water quality analyses which were placed in MPCA's EQuIS database by MPCA staff. This first year of water quality analyses was paid from this grant ($29,612) but starting July 2017 the PCA has been contributing the water quality collection (personnel time and statewide travel) and analysis ($30,000 per year) as in-kind support toward the Sentinel Lakes effort which far exceeded the proposed amount of $75,000 for in-kind support. Not only are the PCA efforts and contributions valuable for water quality but water collected by the PCA during water quality sampling are brought back to St Paul so that DNR can analyze samples for zooplankton saving DNR time and money. We thank the PCA for all of their contributions toward the Sentinel Lakes effort and look forward to a continued strong partnership.

Note - the trend analysis of the water quality data are detailed under Activity 1, Outcome 2.

Outcome 3 – Area DNR biologists, sometimes assisted by Sentinel Lakes staff, conducted standardized population assessments (gillnets and trap nets targeting sportfish such as Walleye, Yellow Perch, and Bluegill) and the IBI Program sampled the littoral fish community using a combination of backpack electrofishing and seines to calculate an Index of Biotic Integrity metric. Both the area fisheries staff and the IBI Program provided in-kind support to this project through equipment, travel expenses, and personnel time for field sampling and structure processing which far exceeded the proposed amount of $225,000 for in-kind support. Indeed, these internal collaborators were instrumental in the Sentinel Lakes fisheries and remote monitoring efforts. Sentinel Lakes Program staff led sampling efforts targeting juvenile fish and the pelagic fish community. The pelagic fish community consists mainly of Cisco and Lake Whitefish, which were sampled on Carlos, Elk, and Ten Mile lakes using annual vertical gill nets (VGN) and hydroacoustics surveys in cooperation with DNR fisheries research staff who contributed in-kind support through field and hydroacoustic data processing time. In addition to the annual surveys we also surveyed Trout and Greenwood lakes in 2017 and White Iron in 2019 and plan to continue those pelagic surveys on a frequency of every third year. In October of 2016, 2017, 2018 and May of 2018 and 2019, Sentinel Lakes Program staff completed juvenile fish surveys on Carlos, Elk, and Ten Mile Lakes (Pearl added fall of 2018) which targeted juvenile Largemouth Bass, Yellow Perch, Rock Bass, and Bluegill to assess pre-winter length at age for these species and to compare fall to spring lengths to better understand if overwinter mortality was length-dependent.

We compared quantile-quantile plots of age-0 length distributions between fall 2017 and spring 2018 to asses if overwinter mortality was length-dependent and found multiple instances of size-selective overwinter mortality. For Yellow Perch, we found evidence of length-dependent overwinter mortality favoring larger age-0 Yellow Perch in all 3 lakes. For age-0 Bluegill, two length groups (a group of early and late hatch fish) were sampled in all 3 lakes which is not uncommon as Bluegill will often spawn more than once during a summer, resulting in early and late hatch age-0 fish. Interestingly, length selective mortality may have occurred in all 3 lakes as no late hatch Bluegill were collected during spring sampling. Similar to Bluegill, two length groups of age-0 Largemouth Bass were also sampled during the fall of 2017 in all 3 lakes. However, unlike Bluegill, this is not a common occurrence and may have been the result of an interrupted spawn caused by a prolonged cold front as indicated by the corresponding water temperature data. The following spring, no age-0 Largemouth Bass were sampled in Ten Mile Lake and only a single age-0 Largemouth Bass was sampled in Elk Lake and Lake Carlos suggesting Largemouth Bass appeared to have poor overwinter survival in all three lakes during the winter of 2017/18. Rock Bass were only sampled in sufficient numbers in Elk Lake during the fall of 2017 and spring of 2018. Unlike the other two Centrarchid species (Bluegill and Largemouth Bass), only a single length group of age-0 Rock Bass was sampled and quantile quantile regression plots indicated that size selective mortality favoring larger individuals occurred.

Maturity data was collected for Yellow Perch sampled in the fall of 2018 to support work for an upcoming DNR Yellow Perch project which will incorporate several Sentinel Lakes. In general, Yellow Perch matured at an early age and small size. For example, male age-0 Yellow Perch sampled from Pearl Lake were mature at a mean length of 55.3 mm (SD = 6.0), while female Yellow Perch were mature at age-1 and a mean length of 109 mm (SD = 6.7). The importance of targeted juvenile fish sampling by the Sentinel Lakes Program is highlighted when you consider Yellow Perch are maturing early and not reaching sizes to be sampled with standard fish survey equipment (gill nets and trap nets) until years after maturing and therefore completing much of their life cycle without being surveyed; a question addressed by the upcoming DNR Yellow Perch project.

Targeted sampling of the pelagic fish community was conducted annually on Elk Lake, Lake Carlos, and Ten Mile Lake and consists mainly of Cisco except Ten Mile Lake which also has Lake Whitefish. Cisco ranged from 0 to 18 years of age on Ten Mile, and 85% of sampled fish were 5 years of age or less. The oldest Cisco sampled was an 18 year old male that was 184mm in length, and the majority of fish were mature by age-3. Cisco sampled from

Lake Carlos ranged in age from 0 to 12 years of age, and 62% of sampled fish were 5 years of age or less. The oldest Cisco sampled was a 12 year old male that was 330 mm in length and the majority of fish were mature by age-4. Details of the trends in Cisco population abundance and biomass over time are found in Activity 1 Outcome 2.

The lake whitefish population in Ten Mile Lake appears to be slow growing, late maturing, with a top heavy age structure which suggests a relatively unexploited fish population. Lake whitefish in Ten Mile Lake did not sexually mature until 15-20 years of age, and more than 50% of the sampled fish were 25 years of age or older with a maximum of 62 years old. This is likely one of the oldest inland Lake Whitefish ever sampled and aged in Minnesota. Both Male and Female Lake Whitefish did not reach maturity until 15-20 years of age. The abundance of old individuals, relatively slow growth, and late age at maturity of the Ten Mile Lake Whitefish population suggest relatively low levels of exploitation, and a potential opportunity to observe the effects of increased exploitation or other stressors if and when they might occur.

V. DISSEMINATION:

Description:

In addition to the scheduled status updates, and the Phase 2 final report due to LCCMR, we currently provide or envision:

1. An updated description of the overall long-term lake monitoring program will be available on MN DNR's public website at (http://www.dnr.state.mn.us/fisheries/slice/index.html). Basic "fact-sheets" and retrospective lake assessment reports on all 25 sentinel lakes are available on MN PCA's public website at (http://www.pca.state.mn.us/water/sentinel-lakes.html).
2. Development of data warehouse or "data mart" including download tools to obtain variables measured as part of the long-term lake monitoring program. Ultimately, we envision a scenario where graphs and data will be accessible for download shortly after data becomes available, typically within a few months after the field season.
3. Minimally, fish, zooplankton, aquatic plant, and water quality data will be housed in central databases and will be made available upon request.
4. Manuscripts will be developed by project staff and project partners (PCA, USGS, and university partners) and submitted to peer-reviewed journals.
5. Technical presentations and general program overviews will be given at state, regional, national, and potentially international symposia. Local outlets include MN chapter of the American Fisheries Society and organized lake groups.
6. Sentinel lakes data will be housed on a shared network drive that will be available to all internal DNR staff throughout the state.
7. A data sharing philosophy that encourages free access to comprehensive high quality data by outside researchers. The program and the state benefit greatly from analyses performed by outside researchers on raw datasets. These partnerships may bring in additional matching grants from outside funding sources.

Status as of 11/30/2016:

An internal oversight committee was assembled (consisting of 3 representatives from fisheries management, biometrician, 3 representatives from fisheries research, and the program coordinator) on November 3rd in Cloquet, MN and featured Program updates and feedback on Program direction from committee members.

Casey Schoenebeck presented on the Sentinel Lakes Program at an Interagency meeting with the Minnesota Department of Agriculture, Board of Water and Soil Resources, Minnesota Pollution Control Agency, University of Minnesota, the St. Croix Watershed Research Station, and the Department of Natural Resources on November 15th in St Paul.

Casey Schoenebeck presented on the Sentinel Lakes Program at Bemidji State University on October 26th.

Several meetings with potential internal and external cooperators focused on how the Sentinel Lakes Program could be used to create value through collaborative research opportunities including curly leaf pondweed and burbot sampling, lake whitefish, and changes in trophic ecology.

Status as of 3/31/2017:

Sentinel Lakes Program is working with Minnesota's Biological Survey Program (Hannah Texler and Erika Rowe) and the recently approved Statewide Monitoring Network for Changing Habitats in Minnesota (LCCMR funded as M.L. 2016, Chp. 186, Sec. 2, Subd. 03d) to potentially integrate some of the proposed terrestrial long-term monitoring sites into Sentinel Lake watersheds so that collaboratively we can connect aquatic and terrestrial systems and view impacts of stressors at the watershed scale.

Sentinel Lakes data were used to assist several projects that were presented at the Minnesota Chapter of the American Fisheries Society meeting held in St. Cloud, MN in February including Bemidji State University (John Kempe and Andrew Hafs) and Minnesota DNR (Tanner Stevens).

The Sentinel Lakes Program (PCA and DNR) is collaborating with Region 5 of the Environmental Protection Agency (EPA, Mari Nord) on the National Lake Assessment which focuses on minimally disturbed lakes (like Elk Lake, a tier 1 Sentinel Lake). In addition we are working with EPA on the creation of a regional lake monitoring network encompassing a variety of nutrient levels and mixing types so the tier 1 Sentinel Lakes were suggested (Jen Stamp). Casey Schoenebeck has been asked to develop and present (via webinar) the Sentinel Lakes standard operating procedure for continuous monitoring equipment which will then be shared with area representatives, the EPA, and other long-term monitoring programs. The Sentinel Lakes were described on the EPA's State Water Agency Practices for Climate Adaptation database. We are also discussing potential collaborations using the Sentinel Lakes with the Wisconsin DNR long-term monitoring program (Katie Hein).

Several meetings with potential internal and external cooperators focused on how the Sentinel Lakes could be used to create value through collaborative research opportunities including state-wide investigations of energy flow using stable isotope analysis. In addition, several collaborators (Lee Engle, Jodie Hirsch, and Heidi Rantala) are using Sentinel Lake data from Lake Carlos to describe the impacts of zebra mussels on several trophic levels.

Casey Schoenebeck presented an update on the Sentinel Lakes Program at the NW Regional Fisheries Meeting, Park Rapids, MN

Status as of 9/30/2017:

Proposed LCCMR project "Linking water Quality Services to Lake Plant Communities" will rely in part on Sentinel Lake data to identify patterns of plant community composition and functional traits, link key functional traits to key ecosystem services, and model statewide water quality services. The Sentinel Lakes Program will provide in-kind support including sharing of long-term monitoring data, technical consultation, and coordination with other Sentinel Lakes research and monitoring activities.

Proposed LCCMR project "The Future of Minnesota's Coldwater Fish Habitat" will rely in part on Sentinel Lake data to identify the causes and timing of coldwater fish habitat loss in Minnesota lakes. The Sentinel Lakes

Program will provide in-kind support including provide advice on lake selection and existing temperature and fish data, will participate in model development, and developing management recommendations to protect coldwater fish habitat.

Shared Tait Lake continuous water temperature data with Tansey Smith (Climate Change Specialist) and Tyler Kaspar (Environmental Biologist) with the 1834 Treaty Authority who have been monitoring Tait Lake and 20 other lakes within the Ceded Territory since 2015.

Shared Elk Lake continuous weather station data with Richard Kiesling (USGS)

Shared Elk Lake data with Jim Cotner (UMN) and Leslie Knoll (UMN, Itasca Biological Research Station) in preparation to collaborate on a proposal with several DNR researchers for the purchase of continuous dissolved oxygen sensors on several LTM lakes to complement existing meters and initiated a project investigating potential changes in the duration and depth of thermal stratification.

Casey Schoenebeck presented (via webinar) on the Sentinel Lakes standard operating procedure for continuous monitoring equipment to the EPA's regional lake monitoring network and presented and instructed participants at the Remote sensing Workshop held in Cloquet, MN.

Status as of 3/31/2018:

Proposed LCCMR project "A Survey of Microplastics in Minnesota's Inland Aquatic Food Webs" will rely in part on Sentinel Lake fish sampling. The Sentinel Lakes Program will provide in-kind support including provide advice on lake selection and will lead fish sampling.

Worked with Leslie Knoll (UMN, Itasca Biological Research Station) and several DNR researchers to submit a proposal to Midwest Glacial Lakes National Fish Habitat Partnership requesting funds to support the purchase of continuous dissolved oxygen sensors on several Sentinel Lakes to complement existing meters. In addition, USFWS and MN DNR have also contributed funds toward the purchase of continuous dissolved oxygen meters which will be deployed in three Sentinel Lakes spring 2018.

We have updated the continuous water temperature SOP to also include the adapted R scripts and QAQC procedures and we have shared this document with the Environmental Protection Agency, the Regional Monitoring Network, and the 1854 Treaty Authority.

Provided phytoplankton and zooplankton data from Trout Lake to Erik Smith (USGS) who working with Richard Kiesling (USGS) and the Sentinel Lakes Program to develop a LCCMR proposal using lake models to forecast changes in primary and secondary production.

Provided trend analysis and figures documenting impacts of zebra mussels in Carlos Lake to Doug Schultz and Carl Pederson.

Provided aquatic plant data to Donna Perleberg (DNR) and water temperature and dissolved oxygen data to Peter Jacobson (DNR).

Provided continuous water temperature data to Jen Stamp (TetraTech) to help develop software specific for continuous water temperature profiles.

Sentinel Lakes Program staff (Will French, Tim Martin, and Casey Schoenebeck) gave 10 professional presentations at 3 conferences including the Midwest Fish and Wildlife Conference in Milwaukee, WI, the Minnesota Chapter of the American Fisheries Society in St. Cloud, MN and the MN DNR Fisheries Academy in Ft. Ripley, MN. Presentations focused on the duration of lake stratification, early life history, and the impacts of zebra mussels.

Deputy Director Pat Rivers (DNR) shared Sentinel lakes thermal stratification analysis with the Climate and Renewable Energy Steering Team (CREST).

Manuscript “Stable isotopes indicate zebra mussels increase dependence of lake food webs on littoral energy” by Brian Herwig and colleagues was submitted to the journal of Freshwater Biology documenting energy flow change pre and post zebra mussels infestation in Lake Carlos.

Status as of 9/30/2018:

Working with a group led by researchers at the University of Minnesota, the Sentinel Lakes Program was able to purchase (using funds provided by the U.S. Fish and Wildlife Service and the MNDNR Fisheries Habitat program) and deploy continuous Dissolved Oxygen (DO) sensor chains on three Sentinel Lakes (Carlos, Greenwood, and South Center) during the summer of 2018. In total the program placed 42 continuous DO sensors at different depth intervals chosen based upon the mean thermal layer depths calculated from the temperature data we have already been collecting on these lakes. As of September 2018, we have successfully retrieved the logged data from Greenwood and South Center lakes and have verified that the loggers are functioning correctly and collecting the data properly. In addition to these three lakes, Drs. Jim Cotner and Lesley Knoll of the University of Minnesota will be deploying a sensor buoy on Elk Lake (tier one Sentinel Lake) which will include DO collection sensors. We have also been awarded funding from the Midwest Glacial Lakes Fish Habitat Partnership that will allow us to deploy DO sensors on 3 additional Sentinel Lakes (Madison, Ten Mile, and Trout lakes). The work group is interested in how changes in oxythermal habitat may impact nutrient cycling processes and pelagic fish communities. Lesley Knoll (UMN, Itasca Biological Research Station) presented some of the preliminary findings at Association for the Sciences of Limnology and Oceanography, Victoria, British Columbia.

Kathryn Schreiner (UMD, and Large Lakes Observatory) and colleagues submitted and received LCCMR support for a proposed project “A Survey of Microplastics in Minnesota’s Inland Aquatic Food Webs” which will rely on the Sentinel Lake Program to sample fish. The Sentinel Lakes Program will provide in-kind support and will lead fish sampling efforts.

Provided data to the University of Minnesota Duluth/NRRI (Dr. Andrew Bramburger) to study harmful algal bloom ecology on Tait, White Iron, Ten Mile, Hill, Carrie, and Peltier.

Provided continuous lake level data for 9 Sentinel Lakes to Tamlin Pavelsky (University of North Carolina) and Catherine Hein (WI DNR) who have a NASA grant to calculate changes in water storage by combining changes in lake area (from satellite imagery) with changes in lake level (from on the ground monitoring efforts).

Provided water temperature data to Tyler Ahrenstorff (MN DNR) to use in a bioenergetics model.

Several public media articles discussing impacts of zebra mussels using Sentinel Lakes data including Minnesota Public Radio, The Echo Press, and the Outdoor News

Shared water temperature data SOP with Jason De Vries, Water Regulatory and Restoration Specialist, Lac du Flambeau Band of Lake Superior Chippewa Indians

Provided zooplankton and phytoplankton data to Erik Smith (USGS) who will see how lake model calibrations will work when we only have lake elevations and not the continuous inflow/outflow data. If this works, then we should be able to have success with the data we currently have on any other lakes where we at least have daily elevations and were able to develop regression equations for inflow/outflow in the past. That would include Trout, Elk, Pearl, Madison, and Carlos.

Status as of 3/31/2019:

The Second Sentinel Lakes Summit will occur on March 27 and 28 in Alexandria, MN. This event will bring people working on the Sentinel Lakes together to learn, discuss, and advance the science related to long term monitoring and changes in Minnesota lakes using a combination of clustered presentations and moderated discussions. We are excited for the quality and scope of topics covered which spans every trophic level from water quality to fisheries. This is a great opportunity to not only communicate project findings to a broad audience (expecting 60-70 people from DNR, PCA, university faculty and federal researchers, as well as some LCCMR staff and committee members) but will also advance the science in general.

We have also been working with the DNR Outreach group to update the Sentinel Lakes section of the DNR website including new information and a smart phone friendly design. In addition to the program description and contacts list we have also included detailed lake descriptions, methodology, and updated research project descriptions.

In 2019 and 2020, Fisheries Management staff and Research Scientists at the Department of Natural Resources will be conducting experimental sampling of yellow perch that will include three Sentinel Lakes: Hill, Shaokotan, and Carlos. Funded by the Dingel-Johnson Sportfish Restoration Fund, this work seeks to understand a statewide long-term decline in catch of yellow perch in standard gears by expanding sampling to additional sizes of the species (especially fish less than 140 mm) and to quantify life history traits across a wide variety of population types in the state.

Beginning in 2019, Department of Natural Resources fisheries scientists, along with researchers from Bemidji State University and University of St. Thomas, will be initiating a food-web study that will include three Sentinel Lakes – Elk, South Center, and Ten Mile. The work is based on research previously funded by LCCMR in DNR's Sentinel Lake Long-term monitoring program (Phase 2, including Elk and Carlos lakes). This study will examine the differences in diets of predatory fish, including Walleye, Northern Pike, Largemouth and Smallmouth Bass, and Muskellunge. Of particular interest is how the presence or absence of Muskellunge may or may not influence the diets of other predators. Elk Lake is the only Sentinel Lake with Muskellunge. South Center and Ten Mile will serve as reference lakes.

Provided water quality and continuous temperature data for all 25 lakes to undergraduate students at the University of Minnesota Twin Cities for a class project on the impacts of climate change on thermal stratification.

Provided continuous water temperature data for all 25 lakes to the University of Minnesota Twin Cities (Gretchen Hansen).

Provided continuous water temperature data for Shaokotan, Pearl, Madison, and Bear Head to PCA (Andrew Streitz) to compare with groundwater temperatures. This information will be presented at the Sentinel Lakes Summit.

Provided vertical gill net data including cisco ages and lengths from Greenwood, Carlos, Elk and Ten Mile to Brett Nelson (MDNR).

Sentinel Lakes Program staff (Will French, Tim Martin, and Casey Schoenebeck) gave 4 professional presentations at the Joint Annual Meeting of the Minnesota and Dakota Chapter of the American Fisheries Society, Fargo, North Dakota. Presentations focused on stressor induced changes to zooplankton, early life history, and data visualization tools.

Final Report Summary:

We have prioritized the dissemination of Sentinel Lakes data and information over the last 3 years which has resulted in an updated public website (https://www.dnr.state.mn.us/fisheries/slice/index.html), data sharing with numerous collaborators, 30+ presentations, public media coverage, and research proposals and funded projects with collaborators. Specifics are provided in the date specific updates with highlights below.

The updated Sentinel Lakes section of the DNR website includes new information and a smart phone friendly design. In addition to the program description and contacts list we have also included detailed lake descriptions, methodology, and updated research project descriptions.

The Sentinel Lakes datasets have been gathered, assembled, standardized, undergone QA/QC, and metadata have been created for each dataset with all data and metadata available upon request. We are working with MNiT staff to ensure compatibility with existing DNR database architecture, branding and ADA requirements. Details located under Activity 1 Outcome 1.

We have fostered a data sharing philosophy that has encouraged outside researchers to request Sentinel Lakes data. Now that data are reviewed for QA/QC and metadata have been created, data requests can be filled quickly and are complemented by trophic level specific metadata. As noted, data sharing is an important part of the Sentinel Lakes Program and one that we will continue to promote. In the past 3 years we have shared data with collaborators who include: Universities (University of Minnesota Twin Cities, University of Minnesota Duluth and Large Lakes Observatory, Bemidji State University, University of North Carolina, Kalamazoo College), Federal scientists (Environmental Protection Agency, USGS, USFWS, NPS), Tribal Biologists (1834 Treaty Authority, Lac du Flambeau Band of Lake Superior Chippewa Indians, Red Lake Department of Natural Resources), state agencies (Wisconsin DNR, MN PCA, and MN DNR) and private industry (TetraTech).

Data sharing has resulted in numerous submitted research proposals including several funded grants and projects including $46,500 from Midwest Glacial Lakes Fish Habitat Partnership to support dissolved oxygen monitoring, 2 funded Sport Fish Restoration projects lead by DNR, and LCCMR support for Kathryn Schreiner (UMD and Large Lakes Observatory) and colleagues for the project “A Survey of Microplastics in Minnesota’s Inland Aquatic Food Webs”.

We have given 30+ presentations to groups like The Association for the Sciences of Limnology and Oceanography; Midwest Fish and Wildlife Conference; Annual Meeting of the Minnesota Chapter of the American Fisheries Society; Bemidji State University; the Fish and Wildlife Division’s Climate and Renewable Energy Steering Team; Section, Region, and Unit specific DNR meetings; Interagency research meeting with the Minnesota Department of Agriculture; Board of Water and Soil Resources; Minnesota Pollution Control Agency; University of Minnesota; the St. Croix Watershed Research Station; and the Department of Natural Resources. Also several webinars were given to EPA’s regional lake monitoring network and we presented and instructed participants at the Remote Sensing Workshop.

Several public media outlets have featured Sentinel Lakes stories including Minnesota Public Radio, The Star Tribune, The Echo Press, and the Outdoor News.

Manuscript "Stable isotopes indicate that zebra mussels increase dependence of lake food webs on littoral energy sources" by Brian Herwig and colleagues was published in 2018 in the journal of Freshwater Biology documenting energy flow change pre and post zebra mussels infestation in Lake Carlos.

The Second Sentinel Lakes Summit brought 70 collaborators from DNR, PCA, university faculty and federal researchers together to learn, discuss, and advance the science related to long term monitoring and changes in Minnesota lakes.

An oversight committee was assembled consisting of representatives from PCA, EWR, fisheries management, a biometrician, fisheries research, and external collaborators to help guide future Program direction and to help disseminate information. The committee has reviewed and their comments have improved the final reports included under Activity 1 Outcome 2.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$289,450	1 NR Specialist Data Manager (1 FTE) to assemble, manage, integrate, and analyze the wide range of data sets that have been collected in the Sentinel Lakes Program. 1 NR Specialist Long-Term Monitoring Biologist (1 FTE) to coordinate project surveys, train and lead field crews in data collection efforts, enter data into spreadsheets and databases, perform data QA/QC, and assist with reporting on status and trends for sentinel lakes. 3 Student Interns (0.33 FTE each, total 1 FTE), field data collection activities in support of project objectives.
Direct and Necessary Services:*	$28,187	Direct and Necessary Services for the Appropriation
Equipment/Tools/Supplies:	$48,363	Continuously-recording temperature sensors (100 to 140 loggers at ~$100 each), miscellaneous survey equipment, consumables, and repairs (~$3,800), and water chemistry analytical services (~$31,000) in support of long-term monitoring objectives outlined in the proposal.
Travel Expenses in MN:	$35,000	In support of project objectives, with approximate breakdown as follows: 60% for fleet for travel to study lakes to install equipment and conduct survey work, and to

		attend coordination meetings; 30% for hotels for overnight stays associated with lake survey work and project coordination; 10% for meal reimbursement in accordance with DNR travel guidelines, and meal reimbursement limits.
TOTAL ENRTF BUDGET:	**$401,000**	

* Direct and Necessary expenses include both Department Support Services and Division Support Services (Personnel support $5,820, Safety $1,372, Financial $5,219, Communication/IT $13,648, Planning $1,658 and Procurement $470). Department Support Services are described in agency Service Level Agreements, and billed internally to divisions based on indices that have been developed for each area of service. Department leadership (Commissioner's Office and Regional Directors) are not assessed. Division Support Services include costs associated with Division, business office and clerical support. Those elements of individual projects that put little or no demand on support services such as large single-source contracts, large land acquisitions, and funds that are passed-thru to other entities are not assessed Direct and Necessary costs for those activities.

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: N/A

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 6 FTE

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			
Midwest Glacial Lakes National Fish Habitat Partnership	$0	$46,500	Grant for the purchase of DO sensors
State			
DNR Div. of Fish and Wildlife	$225,000	$225,000+	In-kind match funding for new Sentinel Lakes Program coordinator position, as well as for program administration, fisheries field and technical support, and data management and analysis efforts by research and management staff
DNR Div. of EWR	$127,000	$127,000+	In-kind match funding to support zooplankton and benthic invertebrate sampling and analysis, aquatic vegetation surveys, and lake level monitoring.
MPCA – Env. Anlys. & Outcomes	$75,000	$75,000+	In-kind matching funds to support water quality assessments and analytical costs, sampling assistance, ground-water monitoring and volunteer coordination
TOTAL OTHER FUNDS:	**$427,000**	**$473,500+**	

VII. PROJECT STRATEGY:

A. Project Partners:

1. DNR Division of Fish and Wildlife Section of Fisheries – Program administration, Fisheries technical and field support, data management, ($401,000 ENRTF + in-kind; Melissa Treml Project Manager).

Partners providing support but not receiving funds from the ENRTF:

2. DNR Division of Ecological and Water Resources – Zooplankton and benthic invertebrate sampling and analysis, aquatic vegetation surveys, and lake level monitoring (DNR Div. EWR, in-kind).
3. MPCA – Environmental Analysis and Outcomes Division – Water quality assessments, ground-water monitoring, volunteer coordination (in-kind).

B. Project Impact and Long-term Strategy:

Healthy lakes are an important aspect of Minnesota's cultural heritage. While losses to lake health have already occurred in many areas, numerous high-quality lakes still exist throughout the state, yet all lakes remain vulnerable to a myriad of threats (excess nutrients from land use and human populations, climate changes, and invasive species, to name a few). Lakes are especially vulnerable as lakes collect and integrate the surface waters that move across the landscape (and thus strongly reflect human modifications within watersheds), and lakes are also sensitive integrators of climatic conditions. The Sentinel Lakes Program has and will continue to provide lake managers, conservation planners, lakeshore residents, fishers, other recreational users, and the Minnesota public a better understanding of changes occurring in Minnesota lakes and the resultant impacts.

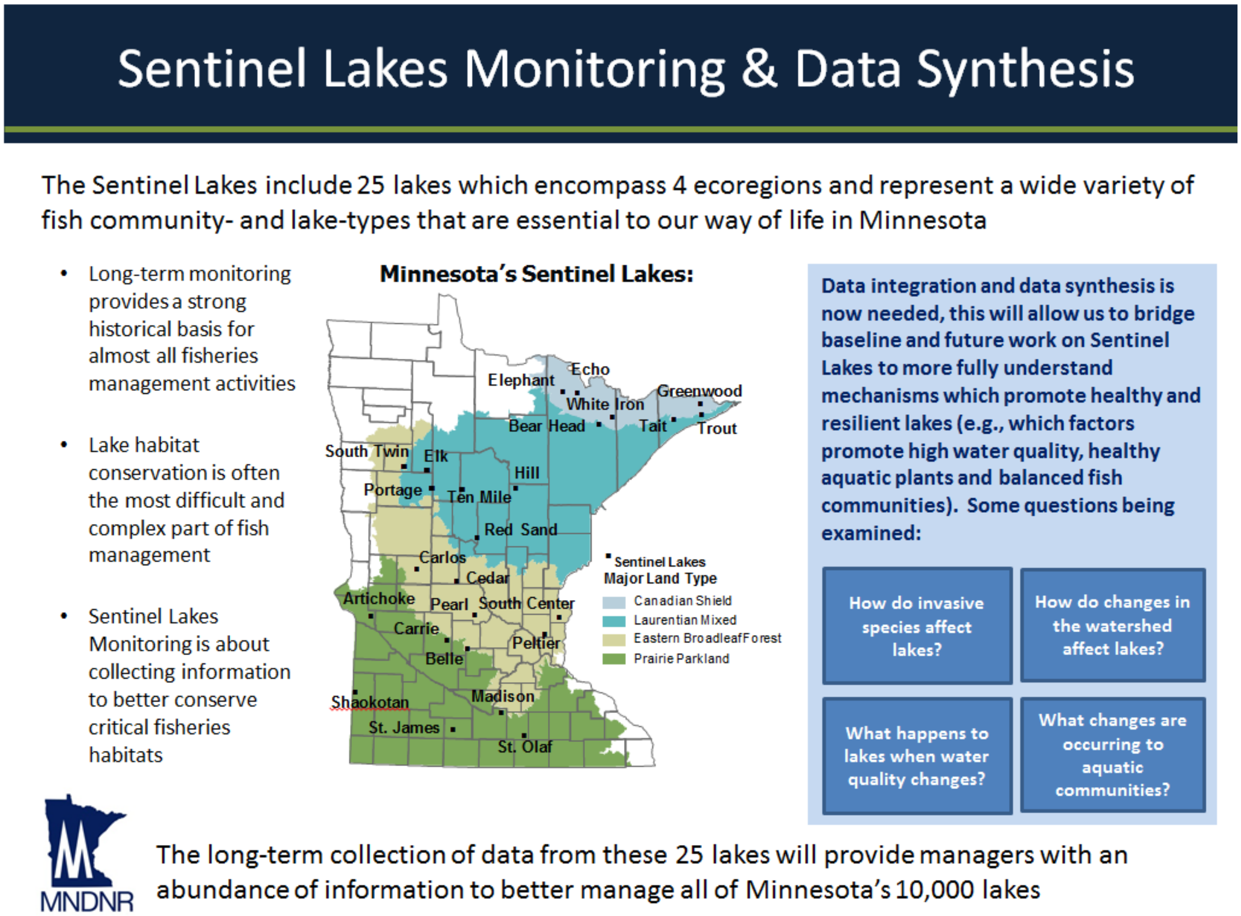
Our long-term strategy to establish a fully integrated lake monitoring program that combines and focuses the activities of key, collaborative management agencies (e.g. DNR and MPCA) and our partners (e.g., universities, USGS, St. Croix Watershed Research Station) has been accomplished. DNR and PCA have ensured the continuation of the program including DNR fisheries support for 3 permanent Sentinel Lakes staff positions who will direct program activities and lead remote monitoring and pelagic and juvenile fish sampling, area fisheries staff and IBI Program support through continued fish sampling and remote monitoring, and PCA and EWR support through continued water quality, zooplankton, macroinvertebrate and aquatic plant collection and analysis. These monitoring activities will foster the continuation of the long-term monitoring framework and help collaborators utilize the existing framework to investigate specific questions. New questions and subsequent requests to ENRTF are likely to arise as monitoring efforts continue, but these requests will take the form of specific research projects conducted by or in collaboration with our partners. Such projects are likely to be outside the scope of routine monitoring activities and our expertise.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
ENRTF (SLICE Phase 1)	M.L. 2009	$825,000
ENRTF (SLICE Phase 2)	M.L. 2013	$1,200,000
In-kind support originating from the Game and Fish Fund, USGS cooperative funds, US Forest Service operating budgets, PCA operating budgets and Clean Water Legacy. FY12-16 includes equipment purchases for the SLICE Phase 2 project and 50% salary for project coordinators, Jeff Reed and Brian Herwig, to finish the SLICE Phase 1 project and to design, coordinate, and implement the SLICE Phase 2 project.	FY10-FY16	$991,000
DJ Study 605 - Designing a long-term monitoring program to track the status of fish communities and their habitats in Minnesota lakes, identify efficient indicators, and evaluate mechanisms.	FY09-FY13	$595,873

VIII. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS: N/A

IX. VISUAL COMPONENT or MAP(S): update visual attached



X. RESEARCH ADDENDUM: Peer reviewed in Phase I.

XI. REPORTING REQUIREMENTS: Periodic work plan status update reports will be submitted no later than 11/30/2016, 3/31/2017, 9/30/2017, 3/31/2018, 9/30/2018, and 3/31/2019. A final report and associated products will be submitted between June 30 and August 15, 2019.

Environment and Natural Resources Trust Fund
M.L. 2016 Final Project Budget

Project Title: Sentinel Lakes Monitoring and Data Synthesis – Phase III
Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 03g
Project Manager: Melissa Treml
Organization: Minnesota Department of Natural Resources
M.L. 2016 ENRTF Appropriation: $401,000
Project Length and Completion Date: 3 years, June 30 2019
Date of Report: August 15, 2019

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Activity 1 Budget (4/27/17)	Amount Spent	Activity 1 Balance	Revised Activity 2 Budget (4/27/17)	Amount Spent	Activity 2 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM								
Personnel (Wages and Benefits) - Overall	$129,375		$30,479	$160,075	$143,056	$17,019	$289,450	$47,499
1 NR Specialist Long-Term Monitoring Biologist: $116,875 (77% salary, 23% benefits); 1 FTE for 2 years					$114,974			
3 Student Interns: $43,200 (100% salary); 1 FTE for 12 weeks in FY17, 5 weeks in FY18					$28,082			
1 NR Specialist Data Manager: $129,375 (77% salary, 23% benefits); 1 FTE for 2 years		$98,896						
Professional/Technical/Service Contracts (11/30/2016)								
Direct and Necessary Services for the Appropriation	$28,187	$28,187	$0				$28,187	$0
Equipment/Tools/Supplies (estimates, actual costs may vary slightly)								
Temperature loggers, 100 to 140 @ ~ $100/ea				$13,500	$11,004	$2,496	$13,500	$2,496
Water chemistry analytical services, $31,000				$31,000	$29,612	$1,388	$31,000	$1,388
Miscellaneous survey equipment, consumables, and repairs				$3,863	$3,582	$281	$3,863	$281
Travel expenses in Minnesota								
For DNR field staff to conduct regular bi-monthly sampling to all study lakes, and specialized seasonal sampling at study lakes, and to attend coordination meetings (hotels, fleet costs, meals)				$35,000	$33,766	$1,234	$35,000	$1,234
COLUMN TOTAL	**$157,562**	**$127,083**	**$30,479**	**$243,438**	**$221,019**	**$22,419**	**$401,000**	**$52,898**

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ORIGINAL ARTICLE

WILEY Freshwater Biology

Stable isotopes indicate that zebra mussels (*Dreissena polymorpha*) increase dependence of lake food webs on littoral energy sources

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Funding information
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Abstract

1. The influence of zebra mussels (*Dreissena polymorpha*) on phytoplankton abundance is well known, but their community-level impact on energy flow is less clear. Reduced phytoplankton abundance could increase reliance of fish and aquatic invertebrates on alternative energy sources such as epiphyton and benthic algae.
2. We assessed impacts of zebra mussels on energy flow by comparing food webs in two Minnesota, USA, lakes during summers of 2013 and 2014. Lake Carlos had a dense population of zebra mussels, while upstream Lake Ida was free of zebra mussels until this study began and maintained low densities during our study.
3. We used baseline-corrected (BC) $\delta^{13}C$ to test whether fish and littoral invertebrate primary and secondary consumers were more reliant on littoral carbon in Carlos compared to Ida. We also used BC $\delta^{15}N$ to determine if trophic position of fish species differed between lakes. Lastly, we compared isotopic niche space by estimating standard ellipse areas for fish species in Carlos and Ida lakes, and tested whether the community-level range of trophic levels, reliance on littoral carbon and standard ellipse area differed between lakes.
4. Results showed invertebrate secondary consumers had more enriched BC $\delta^{13}C$ in Carlos than in Ida, indicating greater reliance on littoral energy. Mixing models indicated that 10 of 11 fish species were more reliant on littoral carbon in Carlos, with littoral carbon use in the 10 species 1.5-fold higher in Carlos. Isotopic niche analysis also showed increased littoral reliance in Carlos fish, as the same 10 fish species in Carlos had statistically distinct ellipses that were enriched in $\delta^{13}C$. Mixing models also indicated that seven of 11 fish species analysed had significantly higher trophic positions in Lake Carlos.
5. In contrast, community-scale metrics for fish showed no difference between lakes in the range of trophic levels, range of reliance on littoral energy, or size of standardised ellipse area of isotopic niche space. This indicates that, despite most individual fish species increasing their reliance on littoral energy and shifting upwards in trophic position, the overall size of the community isotopic niche area remained similar between lakes.

6. Our results indicate that zebra mussels have community-wide impacts on energy flow in lakes, with invertebrate predators and many species of fish increasing their reliance on littoral energy sources, and most species of fish shifting to higher trophic positions. A key question is whether increased water clarity associated with zebra mussels can increase littoral production sufficiently to compensate for higher demand. If not, it is plausible that invertebrate and fish production will decline due to increased intra- and inter-specific competition.

KEYWORDS

energy flow, niche space, trophic position, zebra mussel invasion

1 | INTRODUCTION

Since the first zebra mussel (*Dreissena polymorpha*) was sampled in Lake St. Clair in 1988 (Hebert, Muncaster, & Mackie, 1989), these highly invasive bivalve mussels have spread quickly to lakes and river systems across the eastern USA due to their prolific reproduction and multiple dispersal strategies, including natural as well as human-transport pathways (Griffiths, Schloesser, Leach, & Kovalak, 1991; Ludyanskiy, McDonald, & MacNeill, 1993). In Minnesota, zebra mussels were first found in the Duluth/Superior harbour of Lake Superior in 1989 and were subsequently detected and spread throughout the Mississippi River during 1992–1995, but introductions to inland lakes were delayed, beginning in 2006 (MN DNR 2017; http://www.dnr.state.mn.us/invasives/ais/infested.html, accessed 16 October 2017). As of October 2017, zebra mussels have been confirmed in 156 lakes, rivers and wetlands in Minnesota, a very small percentage of the state's 11,842 lakes >4.05 ha (MN DNR 2017; http://www.dnr.state.mn.us/faq/mnfacts/water.html; retrieved from 16 October 2017). However, the two most recent years have marked the highest rates of new infestations, with zebra mussels discovered in 32 and 34 water bodies in 2016 and 2017, respectively.

Fishing in Minnesota is an economic engine, generating $2.4 billion/year in direct expenditures (US Department of the Interior, 2011) and features strongly as a component of Minnesota's cultural identity. The rapid expansion of zebra mussels highlights the need to understand the ecological and fishery impacts of this invasive species, which features among a group of the world's worst biological invaders (Lowe, Browne, Boudjelas, & De Poorter, 2000). Many studies have been conducted to document and synthesise ecological impacts of zebra mussels in freshwater ecosystems (Higgins & Vander Zanden, 2010), but very few assessments of impacts to fish communities of inland lakes have been conducted (but see Colvin, Pierce, & Stewart, 2015; Irwin, 2016).

Zebra mussels are ecosystem engineers, and through a process termed *benthification* alter abiotic and biotic physical habitat at both local and whole-lake scales, and generally increase the importance of littoral–benthic (hereafter littoral) relative to pelagic pathways in lakes (Higgins & Vander Zanden, 2010; Mayer, Zhu, & Cecala, 2016; Mayer et al., 2014). At local spatial scales, zebra mussels form dense aggregations, or druses, and by releasing faecal deposits, increase available nutrients, bacteria, and benthic algae (Armenio, Mayer, Heckathorn, Bridgeman, & Panek, 2016; Higgins & Vander Zanden, 2010). Habitat complexity resulting from druse architecture can boost certain invertebrate populations (Botts, Patterson, & Schloesser, 1996; Stewart, Miner, & Lowe, 1998), but Mayer et al. (2016) showed that increased benthic invertebrate production at the whole-lake scale was modest (4% increase). In a meta-analysis encompassing hundreds of studies, Higgins and Vander Zanden (2010) reported an average non-dreissenid zoobenthos biomass decrease of 45% in profundal habitats and a 210% increase in littoral habitats.

Perhaps the most consistent and dramatic effect of zebra mussels in lakes is the decrease in phytoplankton biomass and subsequent increase in water clarity (Heiskary, Hirsch, & Rantala, 2016; Higgins & Vander Zanden, 2010; Higgins, Vander Zanden, Joppa, & Vadeboncoeur, 2011; Idrisi, Mills, Rudstam, & Stewart, 2001; Mayer et al., 2016; Miller & Watzin, 2007). Two additional but somewhat inconsistent lower trophic level impacts are decreased zooplankton populations (Higgins & Vander Zanden, 2010) and increased growth of toxic cyanobacteria (Armenio et al., 2016; Fishman, Adlerstein, Vanderploeg, Fahnenstiel, & Scavia, 2009; Knoll et al., 2008). Relatively few studies have examined impacts of zebra mussels on fish communities, but the general response has been an increased reliance on littoral energy sources as evidenced by enriched $\delta^{13}C$ in fish following colonisation (Fera, Rennie, & Dunlop, 2017; Rennie, Evans, & Young, 2013).

Carbon (C) and nitrogen (N) stable isotopes are widely used biological tracers that record information on trophic ecology and spatial feeding patterns. In lakes, boundary-layer effects limit the amount of C fractionation by benthic and littoral sessile primary producers relative to free-floating pelagic phytoplankton (Hecky & Hesslein, 1995). This results in naturally-occurring differences in stable isotopes of C in pelagic versus littoral primary producers, and these differences persist as energy from those sources is transferred to consumers (France, 1995; Hecky & Hesslein, 1995; Post, 2002). Because trophic enrichment of $\delta^{13}C$ is known (0.4‰; Post, 2002), a consumer's $\delta^{13}C$ can be used to identify its energy source (Cole et al., 2011; Peterson & Fry, 1987; Post, 2002). Additionally, $\delta^{15}N$ shows a fractionation of 3.4‰ between trophic levels, making it useful for assessing trophic position in food webs (Post, 2002). Together, $\delta^{15}N$ and $\delta^{13}C$ isotope ratios can be used to estimate the proportion of energy derived from littoral sources (Post, 2002) as well as the isotopic niche space of individual species (Jackson, Inger, Parnell, & Bearhop, 2011).

In this study, we assess the impact of zebra mussels on energy use and trophic structure of fish and aquatic invertebrates by comparing a lake with a well-established zebra mussel population to a similar lake where zebra mussels were first detected during our study and populations remained very low. We measured $\delta^{13}C$ and $\delta^{15}N$ of littoral and pelagic primary and secondary consumers to estimate the importance of littoral resources for fish and aquatic invertebrates in each lake. We hypothesised that: (a) littoral support would be significantly more important for invertebrate secondary consumers and fish in the lake with zebra mussels; (b) the two pelagic fish in our study (yellow perch *Perca flavescens* and walleye *Sander vitreus* [Percidae]) would show the smallest shift towards littoral resources in the lake with zebra mussels; and (c) despite difference in the importance of littoral resources between lakes, trophic positions of fish would be similar for fish species.

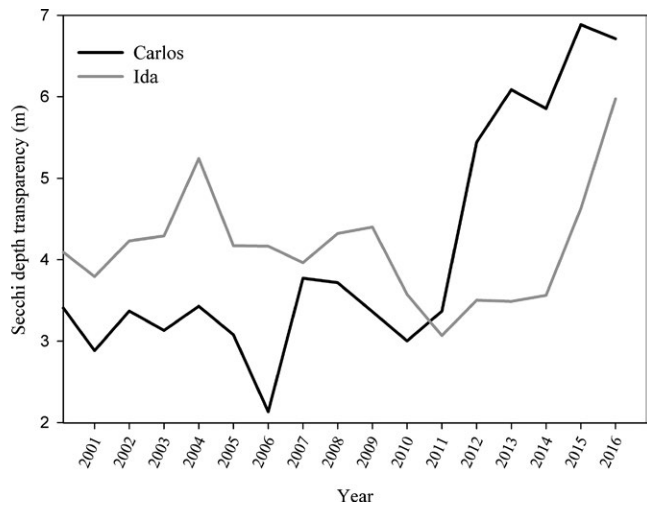

FIGURE 1 Mean Secchi depth transparency (m) using all available data for Lake Carlos (black line) and Lake Ida (grey line) lakes from 2001 to 2016. Arrows indicate the year zebra mussels were first detected in each of the study lakes

2 | METHODS

Our study, conducted during summers 2013–2014, was focused on two lakes, Carlos and Ida, which are in a chain of interconnected lakes in the midst of zebra mussel colonisation, north of Alexandria, Minnesota, USA. Lake Carlos and Lake Ida are popular recreation lakes, with moderate water quality and a fish community supporting various warm-, cool- and cold-water fish species. At least 37 fish species have been documented in the two study lakes and fish communities in each lake are similar. A couple exceptions are that Carlos contains the cold-water species, burbot (*Lota lota*, Lotidae) while Ida does not, and vice versa for muskellunge (*Esox masquinongy*, Esocidae), where a low-density population exists in Lake Ida due to downstream movement from Lake Miltona. Lake Carlos is the smaller and deeper of the lakes, with a surface area of 1,055 ha and a maximum and mean depth of 50 m and 15.2 m, respectively, while Lake Ida encompasses 1,792 ha and has a maximum and mean depth of 32 m and 8.5 m, respectively. Percent littoral area is larger in Ida (40%) compared to Carlos (35%). Both lakes are classified as mesotrophic with a 10-year (2006–2015) mean summer epilimnetic total phosphorus concentrations of 13 $\mu g\ L^{-1}$ and 16 $\mu g\ L^{-1}$ in Carlos and Ida lakes, respectively (MPCA 2017: https://cf.pca.state.mn.us/water/watershedweb/wdip/waterunit.cfm?wid=21-0123-00).

Zebra mussels were first detected in Lake Carlos in 2009 and were well established by 2013 (Heiskary et al., 2016). Over this period, Secchi depth transparency doubled to >6 m (Figure 1), while chlorophyll-*a* dropped over 50% to approximately 5 $\mu g\ L^{-1}$ by 2013 (Engel, Valley, & Anderson, 2010; Heiskary et al., 2016). Zooplankton densities also declined over 57%, from >35 animals/L during 2008 and 2009 to <15 animals/L during 2013 and 2014 (Heiskary et al., 2016). In contrast, zebra mussels were first detected in extremely low densities in Lake Ida during the last year of this study (2014), and changes in water clarity were not observed until the summer of 2015 (Figure 1). These patterns indicate that zebra mussels were well established in Lake Carlos and had impacted pelagic primary and secondary production in 2013–2014 compared to Lake Ida. Thus, we used Lake Carlos as an example lake heavily colonised with zebra mussels, while Ida served as a non-colonised contrast.

Preliminary sampling was done in Carlos in July of 2013 and Carlos and Ida were both sampled during June and July of 2014. Target fish species were collected using trap nets, vertical and horizontal gill nets, beach seines, and back-pack and boat-mounted electrofishing equipment (Table 1). The fish were sacrificed and a tissue sample was removed from the lateral muscle for medium and large-bodied fish, kept on ice, and frozen until analysis in the laboratory. For smaller fish such as young-of-year bluegill (*Lepomis macrochirus*, Centrarchidae) and bluntnose minnow (*Pimephales notatus*, Cyprinidae), the entire body (minus the digestive tract) was frozen until analysis in the laboratory. Zooplankton were collected by towing a 163-μm plankton net from 1 m above the bottom of the lake to the lake surface at three locations along the centre axis of each lake with repeated tows taken at each location to collect sufficient material. Collected animals were rinsed with lake water into plastic sample jars and placed on ice until processed in the laboratory. Each location was analysed separately unless insufficient material was collected, in which case two or more stations were combined into composite samples.

Profundal and littoral habitats were sampled for representative groups of aquatic macroinvertebrates. Chironomids were collected from profundal habitats with a ponar grab and placed in lake water on ice until analysis in the laboratory. Littoral macroinvertebrates were collected from various habitats in each lake using dip nets and by hand, then placed in lake water until they could be sorted into taxonomic groups in the laboratory. Littoral macroinvertebrates collected in both lakes and analysed for stable isotopes included both primary consumers (snails [Planorbidae, Physidae], caddisflies [Trichoptera],

TABLE 1 Mean, standard deviation (*SD*) and sample size of lipid corrected $\delta^{13}C$ and $\delta^{15}N$ of fish and aquatic invertebrate taxonomic groups used in this study from Lake Ida and Lake Carlos. Sample sizes for $\delta^{13}C$ and $\delta^{15}N$ were the same for each taxonomic group in each lake

	Lake Carlos		Lake Ida	
Common name	$\bar{x}$ $\delta^{13}C$ (1 *SD*, *n*)	$\bar{x}$ $\delta^{15}N$ (1 *SD*)	$\bar{x}$ $\delta^{13}C$ (1 *SD*, *n*)	$\bar{x}$ $\delta^{15}N$ (1 *SD*)
Black crappie	−24.5 (0.4, 10)	13.2 (0.5)	−23.9 (0.2, 7)	12.8 (0.5)
Bluegill	−24.2 (0.8, 8)	10.7 (0.8)	−23.3 (0.3, 6)	11.7 (1.0)
Bluntnose minnow	−22.7 (0.3, 15)	9.7 (0.4)	−22.7 (1.1, 7)	10.3 (1.3)
Largemouth bass	−23.8 (0.8, 15)	14.1 (0.7)	−23.2 (0.8, 7)	13.3 (0.8)
Northern pike	−23.8 (0.7, 10)	12.8 (1.2)	−22.8 (0.5, 6)	12.9 (1.0)
Pumpkinseed	−23.6 (0.8. 11)	10.1 (0.5)	−23.0 (0.9, 7)	10.8 (1.3)
Rock bass	−24.5 (1.2, 10)	11.3 (2.5)	−21.5 (1.2, 7)	12.4 (0.6)
Smallmouth bass	−22.8 (0.6, 6)	13.3 (0.7)	−22.1 (0.5, 7)	12.5 (0.6)
Walleye	−23.8 (0.6, 15)	14.1 (1.3)	−23.3 (0.6, 10)	14.2 (0.4)
Yellow bullhead	−24.0 (0.7, 8)	12.5 (0.9)	−22.6 (0.6, 7)	12.0 (1.2)
Yellow perch	−23.4 (0.7, 13)	12.9 (0.4)	−24.0 (1.3, 7)	11.2 (0.5)
Caddisfly	−21.6 (1.9, 5)	5.8 (0.7)	−18.1 (2.8, 4)	3.2 (1.7)
Profundal midge	−28.6 (1.1, 5)	7.8 (0.6)	−26.3 (0.5, 7)	5.4 (0.4)
Littoral midge	−22.7 (1.3, 3)	6.2 (2.3)	−23.4 (3.7, 3)	7.5 (4.8)
Damselfly	−23.5 (0.3, 6)	7.0 (0.5)	−22.7 (0.7, 4)	6.9 (0.5)
Dragonfly	−23.3 (1.3, 6)	5.8 (1.0)	−23.5 (1.4, 7)	4.5 (0.5)
Hyalella	−20.5 (1.4, 5)	4.8 (0.7)	−18.4 (2.2, 7)	3.4 (0.7)
Mayfly	−25.4 (1.2, 6)	3.9 (0.2)	−22.9 (1.0, 4)	3.3 (0.2)
Snail	−25.9 (1.9, 4)	4.6 (0.9)	−20.9 (0.8, 6)	6.4 (1.4)
Mussels	−29.0 (1.3, 14)	7.4 (0.3)	−25.1 (1.0, 8)	6.3 (0.7)
Water scorpion	−21.8 (0.4, 5)	5.6 (0.1)	−22.4 (0.4, 3)	5.9 (0.6)
Zooplankton	−29.1 (1.5, 7)	7.6 (1.6)	−26.7 (0.8, 10)	7.9 (0.9)

Note. Taxonomic names are as follows: black crappie, *Pomoxis nigromaculatus*; bluegill, *Lepomis macrochrius;* bluntnose minnow, *Pimephales notatus;* largemouth bass, *Micropterus salmoides*; northern pike, *Esox lucius*; pumpkinseed, *Lepomis gibbosus*; rock bass, *Ambloplites rupestris*; smallmouth bass, *Micropterus dolomieu*; walleye, *Sander vitreus*; yellow bullhead, *Ameiurus natalis*; yellow perch, *Perca flavescens*; caddisfly, Trichoptera; littoral and profundal midges Chironomidae; damselfly, Zygoptera; dragonfly, Anisoptera; mayfly, Ephemeroptera; snail, Physidae and Planorbidae; mussel, *Lampsilis siliquoidea*; water scorpion, Nepidae; zooplankton, primarily Cladocera.

Hyalella azteca, mayflies [Ephemeroptera], midges [Chironomidae]) and secondary consumers (damselfly larvae [Zygoptera], dragonfly larvae [Anisoptera], water scorpions [Nepidae]). We failed to find any native mussels in Lake Carlos, probably due to extirpation caused by zebra mussels. Thus, we collected zebra mussels in Lake Carlos and both zebra mussels and native mussels in Lake Ida. Similar to other studies (Post, 2002), we found no significant difference in $\delta^{13}C$ between zebra mussels and native mussels in Ida ($T_{1,6}$ = 1.20, p = .274) or $\delta^{15}N$ ($T_{1,6}$ = 1.18, p = .282). Thus, we used zebra mussels in Carlos and both native and zebra mussels in Ida.

In the laboratory, zooplankton were condensed onto 80-µm mesh and detrital material and non-herbivorous zooplankton were removed by hand. The remaining sample was rinsed with nanopure water and filtered onto GF/F glass fibre filters and then frozen. We were unable to remove small secondary consumer zooplankton from our samples, but examination of sample content indicated mostly cladocerans *Bosmina* and *Daphnia* spp., and secondary consumers constituted a small fraction of sample contents and would have minimal influence on isotope values. Macroinvertebrates were sorted into the above taxonomic groups, rinsed with nanopure water, and frozen. The exceptions were snails and mussels, where we first manually removed the shells and only analysed soft tissue due to the shells being constructed largely from ambient dissolved inorganic C (reviewed by McConnaughey & Gillikin, 2008).

Fish and macroinvertebrate tissue and zooplankton filters were dried at 60°C until a constant weight was achieved. Fish and macroinvertebrate tissue were subsequently ground into a fine powder and weighed, and all samples were analysed by the University of California Davis Stable Isotope Facility. Samples (excluding zooplankton on filters) were analysed for $\delta^{13}C$ and $\delta^{15}N$ using a PDZ Europa ANCA-GSL elemental analyser interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK). Zooplankton filters were analysed for $\delta^{13}C$ and $\delta^{15}N$ using an Elementar Vario EL Cube or Micro Cube elemental analyser (Elementar Analysensysteme GmbH, Hanau, Germany) interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK). Analytical precision (standard deviation) was ±0.2‰ for ^{13}C and ±0.3‰ for ^{15}N, respectively. Standard deviations for duplicate samples were 0.2‰ for $\delta^{15}N$ and 0.1‰ for $\delta^{13}C$. Final delta

(δ) values were reported as ratios of $^{13}C:^{12}C$ and $^{15}N:^{14}N$ relative to international standards Vienna PeeDee Belemnite and Air for C and N, respectively (Peterson & Fry, 1987).

Previous research has shown that lipids have depleted $\delta^{13}C$ values relative to other types of tissues, causing problems in food web studies as differences in $\delta^{13}C$ for a given species could be due to differences in lipid content instead of differences in C source (Smyntek, Teece, Schulz, & Thackeray, 2007). Thus, we used equation 3 in Post et al. (2007) to lipid correct all $\delta^{13}C$ values in samples with C:N > 3.25. Hereafter all reference to $\delta^{13}C$ values represent lipid-corrected values. Representative baselines of pelagic and littoral energy sources are also necessary for application of mixing models to estimate reliance on littoral versus pelagic C, and to compare $\delta^{13}C$ values between lake ecosystems (Post, 2002). Recommendations often focus on using mussels for the pelagic baseline and snails for the littoral baseline as both are relatively long-lived and their diets comprise the respective carbon pools (Post, 2002). However, we failed to find adequate numbers of snails in Lake Carlos, perhaps due to heavy infestation by zebra mussels. Thus, we used the mean value of all littoral primary consumers analysed in each lake for the littoral C source in mixing models and baseline corrections (Table 1). Using mussels as the baseline for pelagic energy sources also proved problematic as $\delta^{13}C$ in mussels in Ida were more enriched than a number of individual fish samples, and 1.6‰ more enriched relative to zooplankton (mussel and zooplankton $\delta^{13}C$ were similar in Lake Carlos; Table 1). This indicates that mussels did not fully capture the isotopic signature of the pelagic food web in Lake Ida, perhaps due to zooplankton feeding in deeper pelagic water on $\delta^{13}C$-depleted seston (Francis et al., 2011; Vander Zanden & Rasmussen, 1999). Mussel $\delta^{13}C$ more enriched than individual fish samples would confound our mixing model estimates of reliance on littoral C (described below). Thus, we used the mean value of $\delta^{15}N$ and $\delta^{13}C$ of zooplankton as our pelagic baseline model so that $\delta^{15}N$ and $\delta^{13}C$ of pelagic and littoral energy sources bracket fish and invertebrate consumers in both lakes.

We used a three-pronged approach to assess impacts of zebra mussels on lake food webs. First, we tested whether baseline-corrected (BC) $\delta^{13}C$ values of three taxa of invertebrate secondary consumers (dragonflies, damselflies and water scorpions) and six groups of primary consumers (snails, caddisflies, *Hyalella azteca*, mayflies, midges from littoral habitats and midges from profundal habitats) differed between Lake Ida and Lake Carlos. BC $\delta^{13}C$ values were determined by subtracting the mean $\delta^{13}C$ value of zooplankton in each lake (Table 1) from the $\delta^{13}C$ value of each invertebrate sample. Given the reliance of zooplankton on pelagic energy sources (Post, 2002), BC $\delta^{13}C$ significantly higher than zero for macroinvertebrates indicates greater reliance on littoral energy (hereafter littoral C) relative to zooplankton, with the degree of reliance on littoral C positively related to BC $\delta^{13}C$. We then used *t* tests to determine whether BC $\delta^{13}C$ values differed between lakes for each taxonomic group.

In our second approach, we used mixing models to test whether the reliance on littoral C differed between fish species in Lake Carlos versus Lake Ida. We estimated the trophic position of each fish and the proportion of C ultimately derived from littoral aquatic invertebrates based on mixing models from Post (2002). Proportion of littoral C (α) was estimated by: $\alpha = (\delta^{13}C_{pelagic\ base} - \delta^{13}C_{secondary\ consumer} + \Delta t_{sc})/(\delta^{13}C_{pelagic\ base} - \delta^{13}C_{littoral\ base})$, where $\delta^{13}C_{pelagic\ base}$ is the average $\delta^{13}C$ of zooplankton, $\delta^{13}C_{secondary\ consumer}$ is the $\delta^{13}C$ of each individual fish, Δ is the trophic fractionation of $\delta^{13}C$ (set to 0.39‰; Post, 2002), t_{sc} is trophic position of each individual fish, and $\delta^{13}C_{littoral\ base}$ is the $\delta^{13}C$ of littoral invertebrate primary consumers. Trophic position of each fish was estimated as: trophic position = $\lambda + (\delta^{15}N_{secondary\ consumer} - [\delta^{15}N_{littoral\ base} \times \alpha + \delta^{15}N_{pelagic\ base} \times (1 - \alpha)])/\Delta_N$, where λ is the trophic position of littoral aquatic invertebrate primary consumers, $\delta^{15}N_{secondary\ consumer}$ is the $\delta^{15}N$ of individual fish, $\delta^{15}N_{littoral\ base}$ is the average $\delta^{15}N$ of littoral aquatic invertebrates primary consumers, $\delta^{15}N_{pelagic\ base}$ is the mean $\delta^{15}N$ for zooplankton and Δ_N is the trophic fractionation of $\delta^{15}N$ (set to 3.4 ‰; Post, 2002). We set λ equal to one so results for fish are expressed as trophic position above invertebrate primary consumers. Trophic position and α appear in both equations, so the two equations are fit iteratively until estimates stabilise (Post, 2002). Proportion littoral C and trophic position were estimated for each individual fish using the above mixing models, and we then used ANCOVA to test for significant effects of fish length and lake on proportion littoral C and trophic position of each species of fish.

Our third approach was focused on community-level analyses of fish. First, we estimated the isotopic niche space of each fish species in each lake using sample size-corrected standard ellipse area (SEAc) proposed by Jackson et al. (2011). The SEAc is a descriptive measure of a bivariate distribution, analogous to the standard deviation of a univariate distribution (Batschelet, 1981). In this analysis the *y* axis of niche space consisted of the trophic position of each fish and the *x* axis the proportion littoral C in diets for each fish as estimated by the mixing models described above. Thus, larger scores on the *y* axis reflect higher trophic positions, while larger scores on the *x* axis indicate greater reliance on littoral energy. We assessed differences in community niche structure between lakes by comparing species' SEAc ellipse sizes and locations on the trophic position and littoral C axes between lakes. We also estimated the trophic range, range of littoral C reliance and SEAc for the entire fish community in both lakes using the Bayesian framework described by Jackson et al. (2011). Similar to the SEAc described above for individual species, these metrics estimate the range of littoral C use (*x* axis), range of trophic positions (*y* axis), and size of the SEAc (using both axes) for the entire fish community. We used the resulting credible intervals to assess whether these three community metrics differed between lakes. Finally, McMeans et al. (2016) proposed that fish in higher trophic positions feed across multiple trophic levels and in both pelagic and littoral habitats, and that anthropogenic disturbances can reduce integration by forcing fish to feed at higher trophic levels and specialise on either pelagic or littoral energy sources. We tested this prediction by assessing whether littoral C in diets was positively related to trophic position of fish, and whether presence of zebra mussels increased reliance on littoral C. This analysis tested for significant effects of fish species, trophic position, lake and trophic position–lake interaction on littoral C in diets of individual fish.

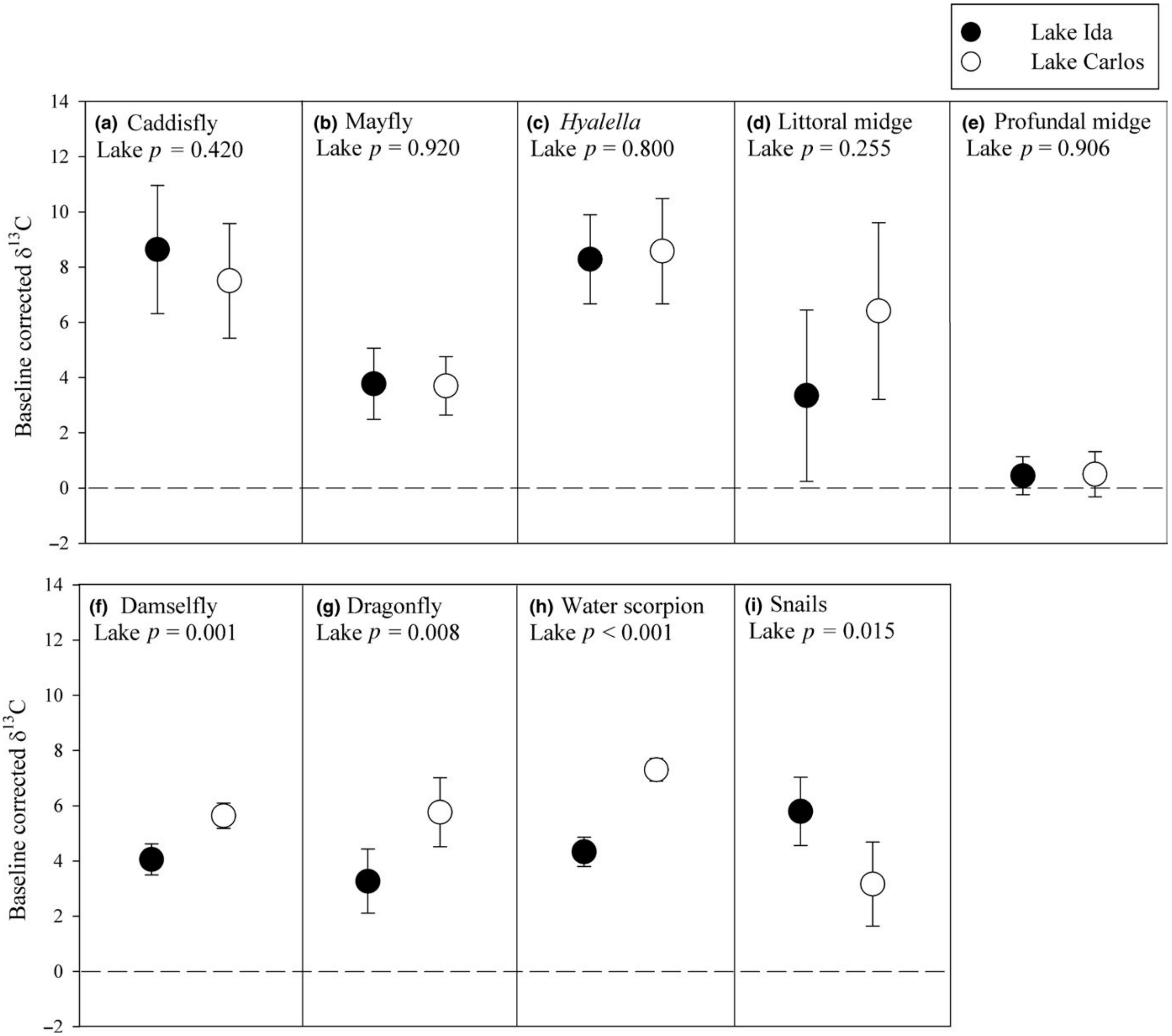

FIGURE 2 Mean baseline corrected $\delta^{13}C$ for nine taxonomic groups of aquatic invertebrates in Lake Ida and Lake Carlos (±95% confidence intervals). Baseline corrected $\delta^{13}C$ are the difference between average zooplankton $\delta^{13}C$ and each littoral macroinvertebrate (macroinvertebrate $\delta^{13}C$ – $\bar{x}$ zooplankton $\delta^{13}C$). Thus, a baseline corrected $\delta^{13}C$ of zero indicates similar reliance on pelagic C as zooplankton, while higher positive numbers indicate increasing higher reliance on littoral C

Though fish species was included in our analysis, we focus on the effects of lake and trophic position on littoral C given our interest in community-scale patterns.

3 | RESULTS

In both lakes, confidence intervals showed that BC $\delta^{13}C$ for caddisflies, mayflies, *Hyalella* and littoral midges were significantly higher than zero, indicating greater reliance on littoral C compared to zooplankton (Figure 2a–d). No differences were detected between lakes, indicating similar reliance on littoral C between systems for these taxa. Confidence intervals for profundal midges did not differ significantly from zero, indicating a reliance on pelagic C similar to zooplankton, and no differences were detected between lakes (Figure 2e). In contrast, all three groups of secondary invertebrate consumers (damselflies, dragonflies and water scorpions) had higher reliance on littoral energy relative to zooplankton, and in each group the reliance on littoral energy was significantly higher in Lake Carlos compared to Lake Ida (Fig 2f–h). Finally, snails also relied more heavily on littoral C compared to zooplankton, and reliance was higher in Ida compared to Carlos, the reverse of the pattern observed in secondary consumers (Figure 2i).

Mixing model estimates of proportion of littoral C in fish diets were similar to results for BC $\delta^{13}C$ in invertebrate secondary consumers in that 10 of 11 species of fish had a higher reliance on littoral C in Lake Carlos compared to Lake Ida. Black crappie (*Pomoxis*

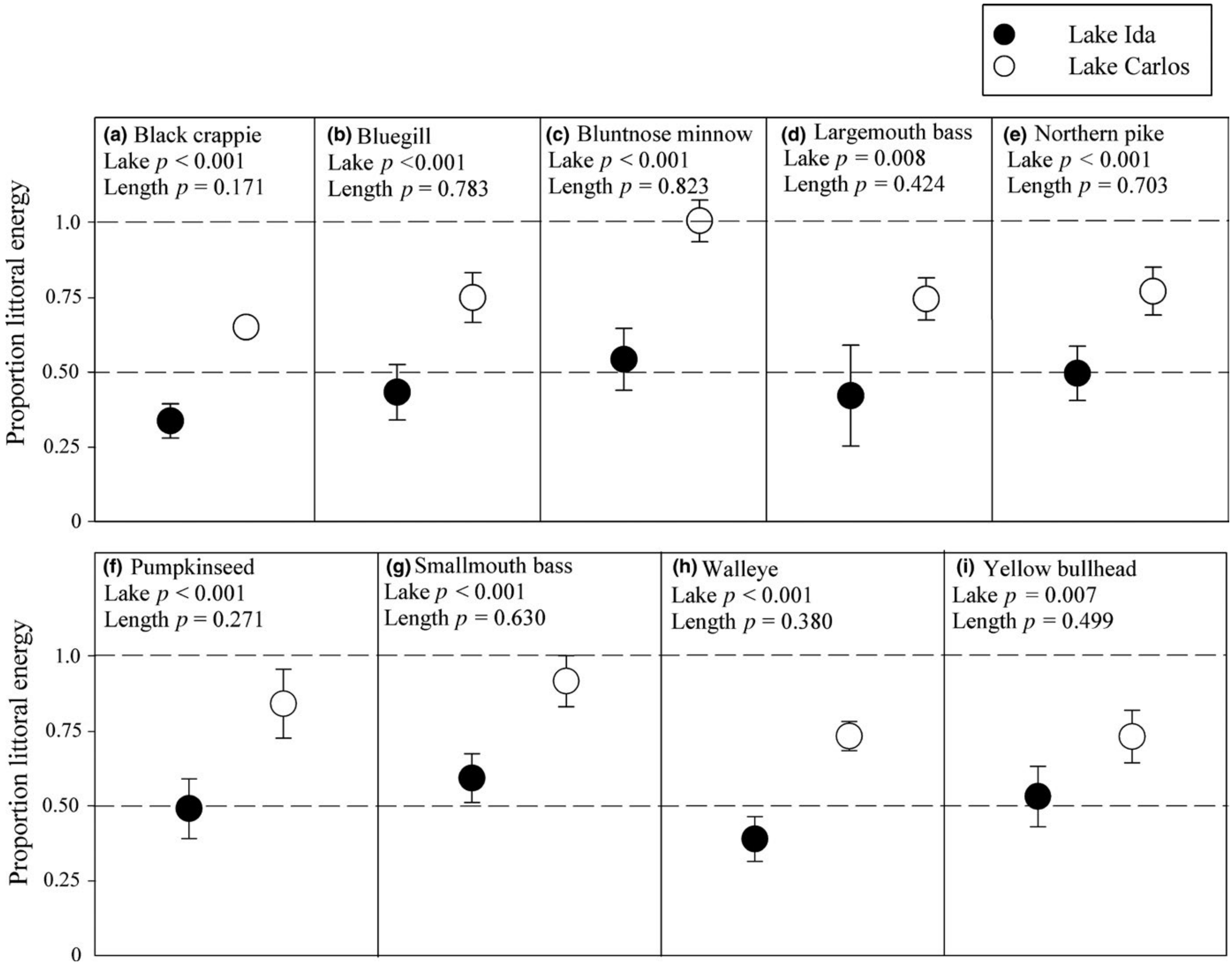

FIGURE 3 Mean proportion littoral carbon in tissue of nine species of fish in Lake Carlos and Lake Ida as estimated from isotope mixing models (±95% confidence intervals). A value of 0.50 indicates equal amounts of pelagic and littoral carbon in fish tissue

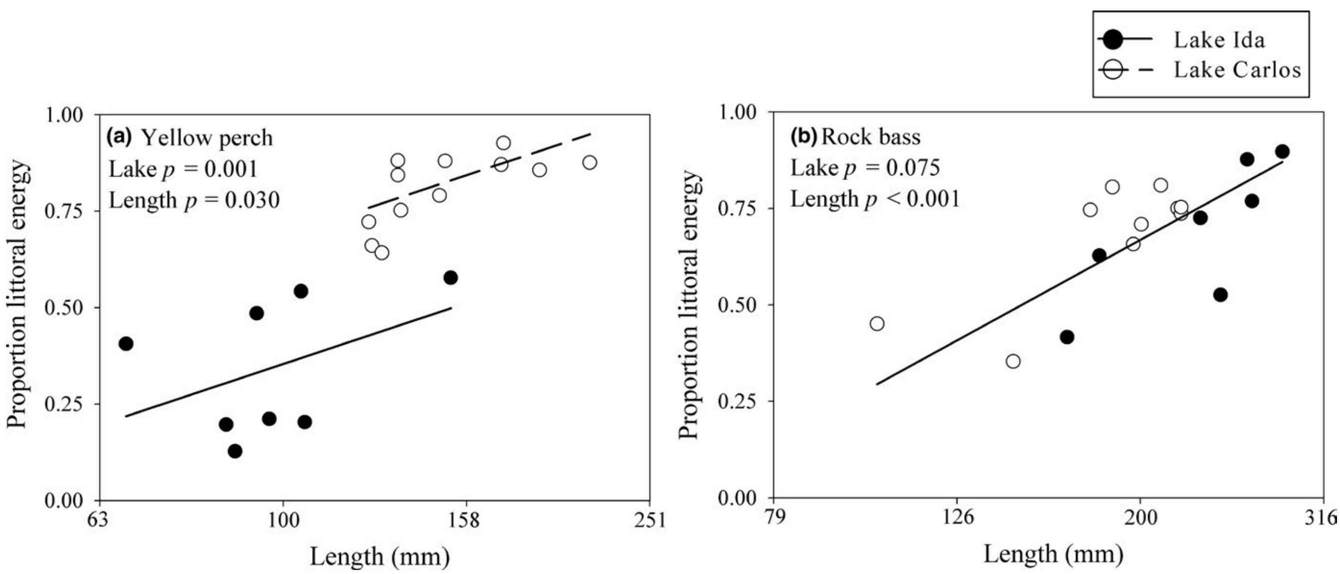

FIGURE 4 Proportion littoral carbon in dorsal muscle tissue of two species of fish in Lake Carlos and Lake Ida as a function of fish length. Values were estimated via isotope mixing models, and a value of 0.50 indicates equal amounts of pelagic and littoral carbon in fish tissue

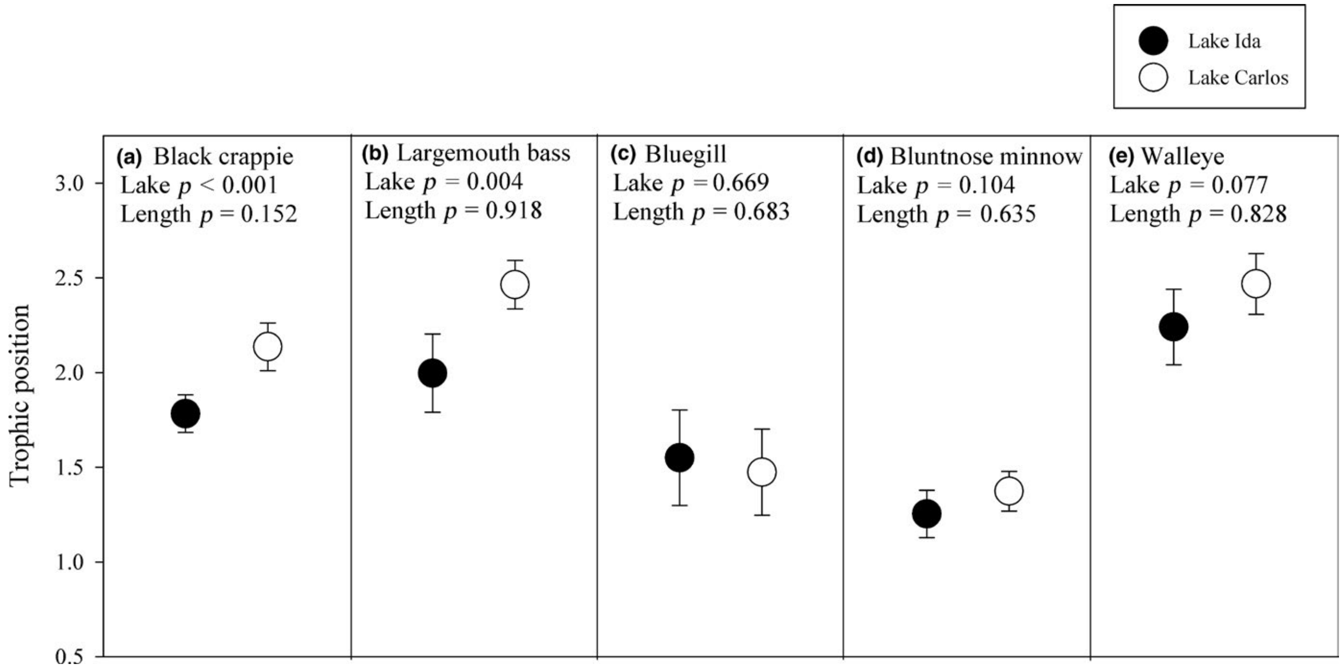

FIGURE 5 Mean trophic position above primary consumer for five species of fish in Lake Carlos and Lake Ida (±95% confidence intervals). Values were estimated from isotope mixing models, and a value of 1.0 indicates fish feed only on primary consumers

nigromaculatus, Centrarchidae), bluegill, bluntnose minnow, largemouth bass (*Micropterus salmoides*, Centrarchidae), northern pike (*Esox lucius*, Esocidae), pumpkinseed (*Lepomis gibbosus*, Centrarchidae), smallmouth bass (*Micropterus dolomieu*, Centrarchidae), walleye and yellow bullhead (*Ameiurus natalus*, Ictaluridae) all had higher proportions of littoral C in their diets in Lake Carlos compared to Lake Ida, while fish length did not influence proportion of littoral C in any of these species (Figure 3a–i). Yellow perch showed higher reliance on littoral C as fish length increased, and also higher littoral C reliance in Lake Carlos compared to Lake Ida (Figure 4a). Lastly, rock bass (*Ambloplites rupestris*, Centrarchidae) showed a positive relationship between proportion of littoral C and fish length but was the only species that did not differ between lakes in reliance on littoral C (Figure 4b).

Analysis of trophic positions as estimated from mixing models showed that black crappie and largemouth bass had higher trophic positions in Lake Carlos relative to Lake Ida, but these species showed no relationship between fish length and trophic position (Figure 5a, b). Bluegill, bluntnose minnow and walleye trophic positions did not differ between lakes or show a relationship with fish length (Figure 5c–e). The most common result was higher trophic position of fish in Lake Carlos and trophic position increasing with fish length in both lakes, as was observed for northern pike, smallmouth bass, yellow bullhead and yellow perch (Fig 6a–d). Finally, pumpkinseed and rock bass trophic position did not differ between lakes but did increase with fish size for both species, although results for rock bass were influenced by two data points (Figure 6e, f).

Results for isotopic niche SEAc ellipses showed that all species of fish excluding rock bass had niches more reliant on littoral C in Lake Carlos compared to Lake Ida (Figure 7), as rock bass was the only species whose SEAc ellipses overlapped between lakes. Differences in trophic position were largely consistent with parametric tests of trophic position, with SEAc ellipses of some fish species showing no overlap on the *y* axis between the two lakes (e.g., yellow perch and smallmouth bass), while other species had considerable overlap indicating no difference in trophic position between lakes (e.g., rock bass and pumpkinseed). In contrast to species-level results, we found no differences between lakes in community-scale estimates of niche space. Estimates of trophic range, range of littoral C reliance and SEAc total niche space were similar between lakes and all had widely overlapping credible intervals (Figure 8). Finally, trophic position, lake, and species all showed significant relationships with proportion littoral C in fish diets (all $p < .001$), but we detected no lake–trophic position interaction ($p = .352$; Figure 9). The overall pattern was higher reliance on littoral C in Lake Carlos at a given trophic level, as well as a shift to trophic levels higher than those observed in Lake Ida. The net result was fish at the highest trophic levels integrated more diverse energy sources in Lake Ida than in Lake Carlos. For example, predicted values for proportion of littoral C in diet for smallmouth bass were 64% in Lake Ida compared to 98% in Lake Carlos.

4 | DISCUSSION

Our results indicate multiple differences in trophic structure and pathways of energy flow between a lake heavily colonised with zebra mussels and a reference lake lacking a high-density zebra mussel population. Relative to reference Lake Ida, all three sampled Lake Carlos invertebrate secondary consumers were more reliant

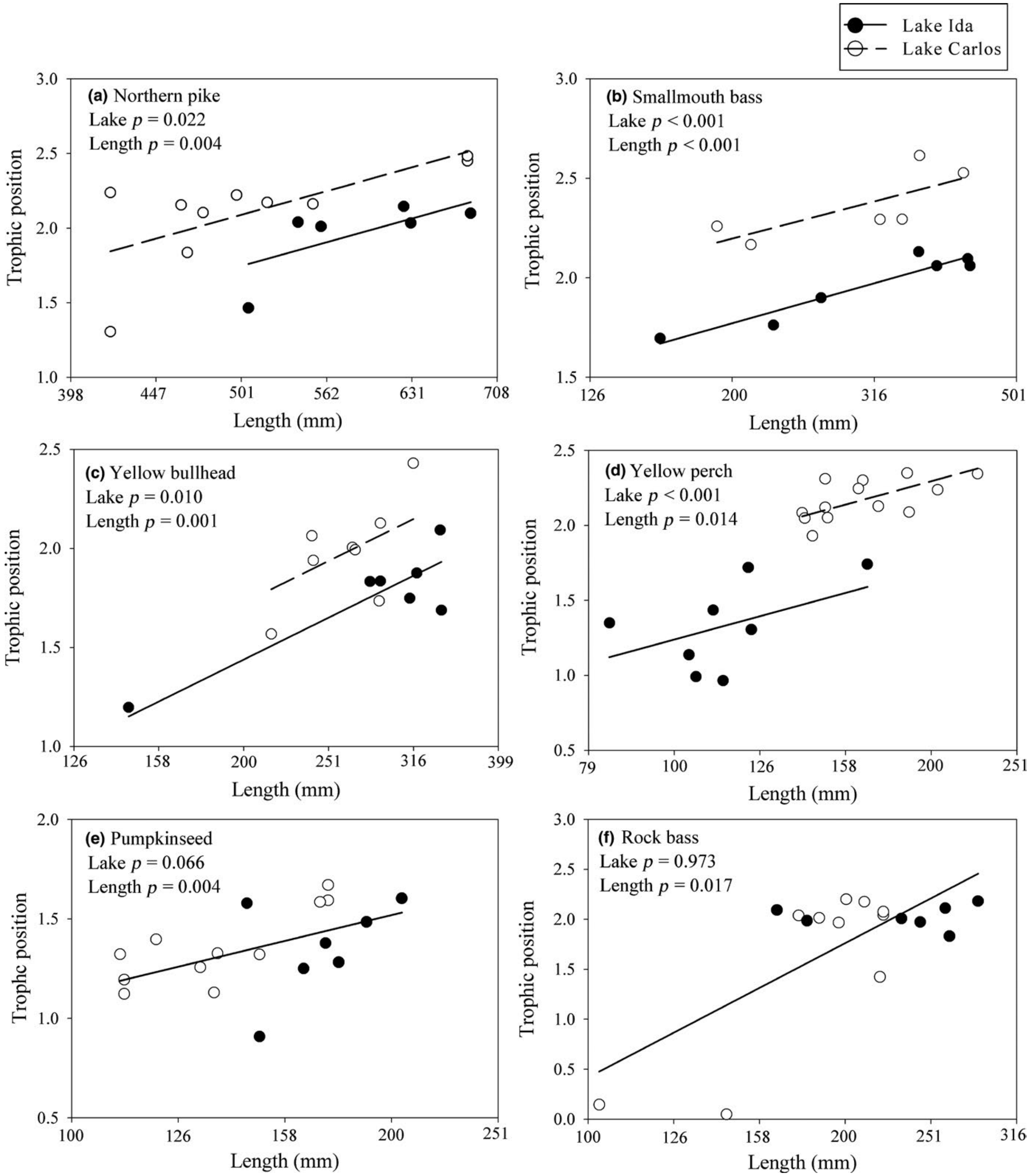

FIGURE 6 Trophic position above primary consumers for six species of fish in Lake Carlos and Lake Ida as a function of fish length. Values were estimated from isotope mixing models, and a value of 1.0 indicates fish feed only on primary consumers

on littoral C, 10 of 11 fish species were more reliant on littoral C, 7 of 11 fish species fed at higher trophic levels, and the overall fish community showed a significant shift in their isotopic niche towards higher reliance on littoral C and increased trophic position. Taken together, these results indicate that impacts of zebra mussels on energy flow in lakes are pervasive and influence both invertebrate and fish communities. Although impacts on aquatic invertebrates were limited to predators, effects on the fish community included species from all major functional guilds of planktivores, benthivores and piscivores. The fact that all impacted

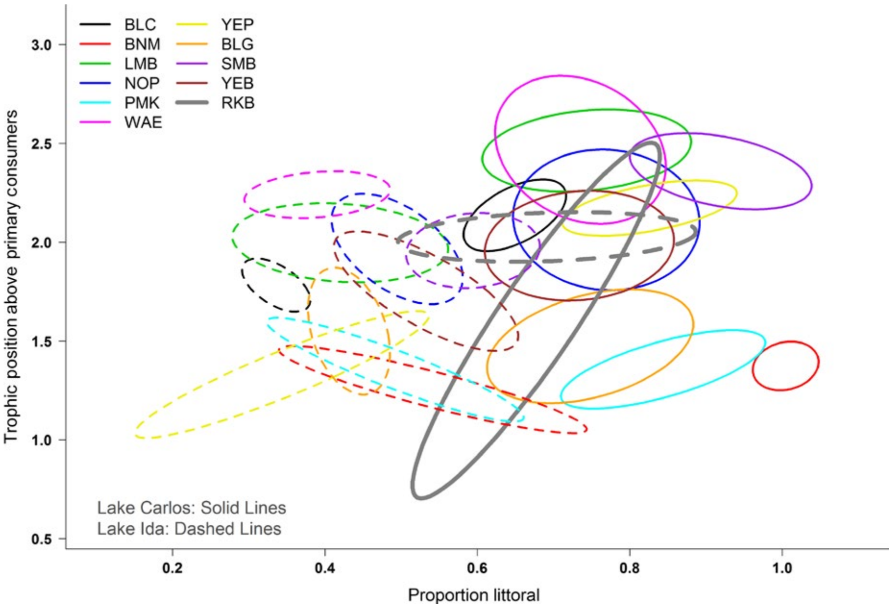

FIGURE 7 Isotopic niche ellipses for 11 species of fish in Lake Carlos and Lake Ida. Ellipses constitute sample size-corrected standard ellipse area for each fish species in each lake. The *y* axis is trophic level above primary consumers and the *x* axis is the proportion of littoral C, with values for both axes estimated with mixing models. Species are defined as follows: BLC: black crappie; BNM: bluntnose minnow; LMB: largemouth bass; NOP: northern pike; PMK: pumpkinseed; WAE: walleye; YEP: yellow perch; BLG: bluegill; SMB: smallmouth bass; YEB: yellow bullhead; RKB: rock bass

species in Lake Carlos increased their reliance on littoral C suggests the potential for increased interspecific resource competition, which may result in shifts in community structure of both aquatic invertebrates and fish based on a species' ability to exploit littoral energy sources. The most likely cause for the differences between lakes is the documented reduction in abundance of phytoplankton and zooplankton following the increase in zebra mussel abundance in Lake Carlos. These impacts are well-described in many studies (Higgins & Vander Zanden, 2010; Noonburg, Shuter, & Abrams, 2003), and we believe they are likely to be the cause for the differences we detected between food webs in lakes Ida and Carlos.

Our results showed that all invertebrate secondary consumers we sampled had higher reliance on littoral C in Lake Carlos, while one primary consumer (snails) relied more heavily on littoral C in Lake Ida and five other primary consumers did not differ between lakes. We suspect that the differences between lakes in use of littoral C by secondary invertebrate consumers is driven by higher consumption of zooplankton in Lake Ida, as damselflies, dragonflies, and water scorpions are all known to consume zooplankton prey (Blois & Cloarec, 1983; Heads, 1986; Johansson, 1993). In Lake Carlos, lower zooplankton abundance forced these groups to rely more heavily on littoral prey such as midges and amphipods.

Some invertebrate groups did not show higher reliance on littoral C in Lake Carlos than in Lake Ida. The absence of differences in reliance on littoral C for caddisflies, mayflies, *Hyalella*, or littoral midges is probably due to these primary consumers being highly dependent on periphyton and benthic algae as an energy source regardless of phytoplankton abundance (reviewed in Thorp & Covich, 2009). Thus, their reliance on littoral C in Lake Carlos did not increase following zebra mussel colonisation as they were already feeding heavily on littoral C sources. We also found no difference in littoral C reliance between lakes for profundal midges. Profundal midges rely on rain of seston material from the pelagic habitat (Jónasson, 2004), and this is

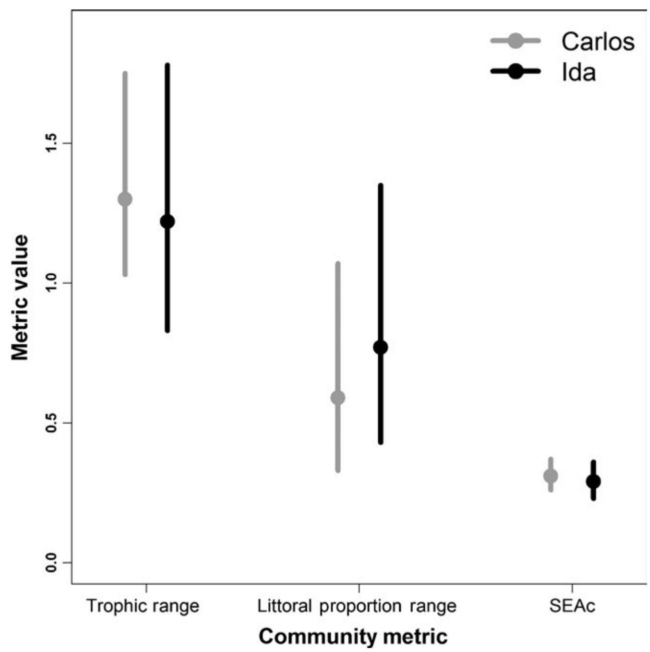

FIGURE 8 Estimated community-scale metrics of isotopic niche size (±95% credible intervals). Trophic range is the estimated range of trophic levels, littoral proportion range is the estimated range of littoral C in diets, and SEAc is the standardised ellipse area based on trophic level and littoral C range of individual fish in each lake. Trophic level and littoral C in diets were estimated for each fish with mixing models

also indicated in our study by profundal midges in both lakes having BC $\delta^{13}C$ values similar to zooplankton (as indicated by BC $\delta^{13}C$ values not different from zero in either lake; Figure 2e). Chlorophyll-*a* values were much higher in Lake Ida (11.8 μg L^{-1}) than in Lake Carlos (3.4 μg L^{-1}) during this study, indicating much higher seston abundance in Lake Ida. No difference in reliance on littoral C between lakes for profundal midges, despite much less seston in Carlos, is

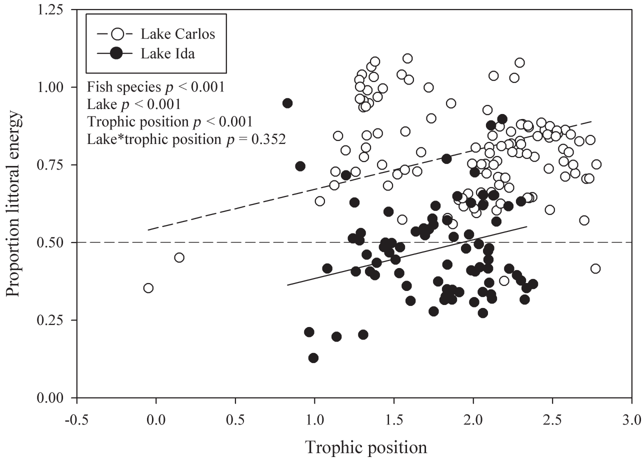

FIGURE 9 Effects of trophic position, lake and fish species on proportion littoral C in diets. Regression lines are not shown for individual fish in order to simplify the figure. Trophic position and littoral C were estimated for each fish using mixing models

probably driven by the inability of profundal midges to access near-shore benthic production enriched in δ^{13}C relative to seston (Hecky & Hesslein, 1995), as these animals remain confined to deep-water habitats and use existing depleted δ^{13}C sources. Less seston coupled with an inability to exploit near-shore benthic production may lead to reduced densities of profundal midges in Lake Carlos. Although anecdotal, it took approximately 10-fold more sampling effort to collect sufficient numbers of profundal midges in Carlos compared to Ida, suggesting a large difference in density. Finally, snails were the only taxonomic groups among all fish and invertebrates analysed to show higher reliance on littoral C in Lake Ida relative to Lake Carlos. This was a surprising result given the high reliance of snails on littoral C (Post, 2002). However, snails can be physically displaced by zebra mussels (Wisenden & Bailey, 1995), and so it is possible that altered habitat use in Lake Carlos forced snails to feed on resources more depleted in δ^{13}C.

Our results also showed reliance on littoral C was higher in Lake Carlos for almost all fish tested. We observed differences in a wide variety of fish types from the two lakes, as we found differences in planktivores, benthivores and piscivores, as well as littoral-oriented species (e.g., bluegill, pumpkinseed, smallmouth bass and largemouth bass) and pelagic-oriented species (e.g., black crappie, yellow perch and walleye). Moreover, the effect size for littoral C use was large; averaged across the 11 species that differed between lakes, littoral C use was 1.5-fold higher in Lake Carlos. The pervasive increase in littoral C in nearly all fish species tested was likely driven by increased consumption of littoral invertebrates by both invertebrate consumers (as discussed above) and fish at all trophic levels, but especially by fish in lower trophic levels with high rates of invertebrate consumption. For example, estimates of trophic position for the bluntnose minnow indicated that this species fed heavily on invertebrates in both lakes, but its reliance on littoral C increased from 54% in Lake Ida to nearly 100% in Lake Carlos. Higher reliance on littoral C in lower trophic levels was then subsequently passed to higher trophic levels, resulting in the nearly ubiquitous increase in littoral C in the fish community. Even though many species had higher reliance on littoral C in zebra mussel-colonised Lake Carlos, the implications are probably greatest for yellow perch and walleye given their more pelagic nature (Irwin et al., 2016). It seems likely that these two species may be least suited to do well under a scenario of increased interspecific resource competition for littoral energy sources. The net result could be reduced abundance of walleye and perch (and other pelagic-orientated fish) coupled with increased abundance of littoral-associated species such as sunfish and smallmouth bass. Similar shifts from pelagic to littoral-associated fish have been observed in other lakes colonised by zebra mussels (Irwin et al., 2016) and in lakes with increased water clarity driven by reduced nutrient loading and zebra mussels (Robillard & Fox, 2006).

The isotopic niche analysis also indicated an increased reliance on littoral energy sources for the fish community impacted by zebra mussels, as all species excluding rock bass showed a higher reliance on littoral C in Lake Carlos relative to Lake Ida. This analysis also provides potential insight as to why we failed to detect differences in littoral C use between lakes for rock bass, as the SEAc ellipses in Lake Carlos for this species showed the greatest combined range on the x and y axes (Figure 7). This suggests C source and trophic position of rock bass in Lake Carlos were highly variable, making it more difficult to detect differences between lakes. The pattern of ellipses at the community scale also visually demonstrates the potential for increased interspecific competition for littoral resources in Lake Carlos, as the ellipses are clustered near to 80% reliance on littoral C in Carlos while clustering closer to 40% littoral C in Ida, reflecting a more balanced use of littoral and pelagic C across many species.

The niche analysis also visualises two groups of fish in terms of differences in trophic position between lakes. The first group is more planktivorous, and show no difference between lakes (e.g., bluegill, pumpkinseed and bluntnose minnow). The second group is more piscivorous and shows a shift upward in trophic position in Lake Carlos (e.g., yellow perch, largemouth bass, smallmouth bass etc.). These results are highly consistent with results of testing for significant differences in trophic position between lakes using mixing models. This raises the question of why trophic shifts upwards were more commonly seen in piscivorous fish than planktivorous in Lake Carlos, especially given that increased reliance on littoral C was nearly ubiquitous in both planktivorous and piscivorous fish in that system. It is possible that the trophic shift upwards in piscivores but not planktivores is driven by increased competition for littoral invertebrate prey in Lake Carlos. Piscivorous fish in Carlos may be responding to increased competition for littoral invertebrates by increasing consumption on prey fish, resulting in the observed trophic shifts upwards in that system. Planktivorous fish, in contrast, lack the morphological adaptations to feed effectively on fish prey, causing the trophic position of these species to be similar between lakes. Although we were unable to document specific mechanisms, the combined results of increased reliance on littoral energy and shifts upward in trophic position indicate that predator–prey relationships within the fish community and pathways of energy flow differ substantially between these two lakes. In contrast to our species-level analysis, we failed to find any differences in the size of isotopic niche space at the scale of the entire fish community. In general, the fish community in Lake Carlos shifted up and to the right in Figure 9 (and was perhaps slightly parabolic), but the overall size and range of energy use and trophic position remained unchanged. However, despite similar ranges of C use between lakes, interspecific competition for energy is likely to be higher in Lake Carlos given the much higher reliance on littoral C at the community scale. Although the general pattern was a shift up and to the right for Carlos fish in Figure 9, there also appears to be a more parabolic relationship in Carlos compared to Ida.

Recent work has shown that integration of energy sources increases with trophic position in food webs (McMeans et al., 2016; Rooney, McCann, Gellner, & Moore, 2006). Our results for Ida show the same pattern, as % littoral C in diets was 56% for fish in the highest trophic levels compared to 38% in the lowest trophic levels. In Lake Carlos, the upwards shift in both trophic level and reliance on littoral C caused fish in the lowest and highest trophic levels to increase reliance on littoral C to 67% and 89% respectively. Thus, it appears that zebra mussels reduced the ability of top predators to integrate energy flow between pelagic and littoral food webs, with integration shifting to lower levels of the food web. The implications of this shift in energy integration are unknown, but our results support the hypothesis that invasive species may reduce the ability of higher trophic levels to integrate sources of energy in food webs (Vander Zanden, Casselman, & Rasmussen, 1999; Vander Zanden, Olden, Thorne, & Mandrak, 2004). Reduced food web integration by large, mobile fish high in the food web may reduce the adaptive capacity of the ecosystem to respond to other stressors and environmental change (McMeans et al., 2016; Rooney et al., 2006).

Increased reliance on littoral energy and trophic shifts in piscivorous fish may result in shifts in the structure of both aquatic invertebrate and fish communities in Lake Carlos. Phytoplankton biomass decreased substantially in Lake Carlos following zebra mussel colonisation, but it is possible that primary production did not decrease due to a compensatory increase in mass-specific production rates of phytoplankton due to an improved light environment (Idrisi et al., 2001). If this were true, the ability of phytoplankton to support the lake food web may have remained largely unchanged. However, the consistent increase in reliance on littoral C among fish and invertebrate predators indicates that this is not the case, and the ability of phytoplankton to support the lake food web has decreased. It is also possible that overall lake primary production has remained relatively consistent despite reduced phytoplankton abundance due to increased abundance and production of littoral and benthic primary producers following the increase in water clarity (Higgins & Vander Zanden, 2010). If total primary production does stay consistent, and the food web can shift to increased reliance on littoral sources, it is plausible that lake-wide biomass of invertebrates and fish could also stay relatively consistent from pre- to post-zebra mussel infestation. Even though overall abundance could remain consistent, the species composition could shift towards invertebrate and fish species better suited to utilise littoral energy sources.

Despite weaknesses in our study design, including lack of replicate lakes and a lack of isotope data for Lake Carlos prior to colonisation by zebra mussels forcing us to use a *space for time* experimental design, we feel that several lines of evidence indicate that the observed differences are due to zebra mussels. First, littoral area was 5% larger in Lake Ida, yet the consistent pattern was higher reliance on littoral C by invertebrates and fish in Lake Carlos despite a smaller littoral area. Second, the lakes are in close proximity, they are in the same catchment and have similar physical characteristics and trophic status. Third, several other studies have documented $\delta^{13}C$ enrichment in lake food webs following zebra mussel infestation (Fera et al., 2017; Rennie et al., 2013; Turschak et al., 2014). Though previous studies have documented enriched $\delta^{13}C$ values in lake food webs post zebra mussels, our study builds on this past work by using mixing models to document the actual amount reliance on littoral C increases as well as significant effects on trophic positions in lake food webs. Another potential limitation in our study is the use of zooplankton for our pelagic baseline, given their potential seasonal variability (Post, 2002). We feel our results are robust, however, as using mussels for the pelagic baseline produced similar results, with the main differences being slightly higher estimates of pelagic C for fish and invertebrates in Lake Ida. Thus, relative to using mussels, our zooplankton baselines generated similar (though slightly conservative) estimates of the difference in pelagic versus littoral energy use between lakes Ida and Carlos.

In conclusion, our results indicate that zebra mussel infestation can cause large changes in pathways of energy flow in mesotrophic temperate lakes, with higher reliance on littoral C by both invertebrate secondary consumers and fish from multiple guilds, and can also result in piscivorous fish feeding at higher trophic levels. What is unknown is whether these changes will result in reduced abundance of fish or shifts in fish community structure. These patterns have implications for fisheries management and human recreation activities, as increased reliance on littoral energy could shift fish communities from balanced assemblages of pelagic- and littoral-orientated species to predominance of littoral-adapted species.

ACKNOWLEDGMENTS

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ETHICS STATEMENT

The Minnesota Department of Natural Resources has the authority to regulate, manage, and undertake the scientific collection of fish in the waters of the state. Collection of fish for this study was completed under that authority and all guidelines and approved procedures were followed, including humane euthanasia and the release of unneeded live fish back into the lake. Live native mussels were collected under special permit number 20807 for the taking and possession of mussels.

CONFLICT OF INTEREST

The authors of this manuscript have no conflict of interest to declare.

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