



Title:	Acceptance of Statewide Carp Management Effectiveness Results	
Resolution number:	25-057	
Prepared by:	Name: Jill Sweet Phone: 952-930-1986 jsweet@minnehahacreek.org	
Reviewed by:	Name/Title: Brian Beck, Research and Monitoring Program Manager	
Recommended action:	Accept the findings of the Statewide Carp Management Effectiveness Assessment	
Schedule:	N/A	
Budget considerations:	N/A	
Past Board action:	Res # 17-036	Title: Authorization to request funding from the Lessard Sams Outdoor Heritage Council
	Res # 23-070	Title: Authorization to Execute a Memorandum of Understanding (MOU) to Evaluate the Effectiveness of Carp Management as a Watershed Management Strategy in Partnership with the MPCA and DNR
	Res # 24-006	Title: Authorization to Execute a Contract with the University of Minnesota to Evaluate the Effectiveness of Carp Management as a Watershed Management Strategy

Summary:

Common Carp Context at MCWD

In September 2017, the Lessard Sams Outdoor Heritage Council (LSOHC) recommended the Six-Mile Creek-Halsted Bay (SMCHB) Habitat Restoration Project for \$567,000 to the Minnesota State Legislature. The funding bill was approved, and the grant period began on July 1, 2018.

The project took a comprehensive approach to managing common carp in the SMCHB Subwatershed, based on the University of Minnesota's SMCHB carp assessment (2014-2017). This assessment developed a carp population census for each waterbody, identified migration patterns, and located reproduction areas. To address the carp population, the University researchers collaborated with District staff to develop a management plan, which received funding through the LSOHC grant.

MCWD successfully executed the LSOHC grant between 2018 and 2022 by implementing a three-pronged management strategy in the SMCHB Subwatershed that addressed carp migration and recruitment to reduce carp biomass. Now in the maintenance phase, the project focuses on three primary objectives:

1. Assessing water quality and vegetation response to carp management through field data collection;
2. Maintaining infrastructure and continuing to control carp biomass to ensure continued success;
3. Communicating MCWD's carp story with project partners and other interested public agencies.

MCWD's carp management approach successfully reduced carp to or near biomass goals in the majority of the Subwatershed's lakes. However, successful removal did not lead to consistent water quality and aquatic vegetation improvements systemwide.

Industry Need for Carp Effectiveness Assessment

In November 2023, MCWD staff engaged with the Minnesota Pollution Control Agency (MPCA) and the Minnesota Department of Natural Resources (DNR), since they also have a role in carp management. MCWD and its state partners discussed the nuanced results from the District's SMCHB carp management program and recognized no comprehensive assessment has been conducted on the numerous carp management projects that have been implemented throughout the State of Minnesota over the past 10 years. These discussions highlighted the need to better understand the variables that may affect carp management effectiveness and the impact of carp management on vegetation conditions and water quality.

University of Minnesota Analysis: Evaluating the Effectiveness of Common Carp Management in Minnesota

After engaging in discussions with its partners, MCWD staff partnered with University of Minnesota researchers to study statewide carp management efforts and understand how carp management impacts carp biomass, water quality, and aquatic vegetation in different types of lakes and lake ecosystems. The project began in 2024 with data discovery, compilation, and analysis. A partner team — including staff from the MPCA and DNR — has met quarterly to review initial findings and guide the direction of the analysis. Input from local lake managers and carp industry consultants has also been integrated throughout the process.

Findings and Interpretation

The statewide analysis found that carp management frequently produced positive, but variable, outcomes for water quality, with more pronounced effects in shallow systems. On average, lakes saw a total phosphorus reduction of 22 µg/L following carp management. These improvements can be meaningful in lakes near State water quality standards, where modest reductions may shift conditions toward meeting goals. Seasonal differences were also observed, with carp exerting greater influence on water clarity in the spring, while late-season conditions seem to be more strongly controlled by internal nutrient cycling.

Vegetation outcomes were more mixed. While some lakes experienced slight increases in plant richness and floristic quality, overall frequency of occurrence often showed little measurable change. In some cases, concurrent management practices such as herbicide treatments may be complicating interpretation of results, highlighting the difficulty of isolating carp effects.

Factors Driving Success or Limiting Outcomes

Projects that achieved large proportional reductions in carp biomass consistently demonstrated stronger improvements in phosphorus and chlorophyll-a concentrations, underscoring the importance of intensity of removal. System type also matters with shallow, nutrient-rich lakes responding more than deeper systems, possibly reflecting carp's greater influence in littoral areas. Conversely, projects in lakes with high internal phosphorus loading often saw temporary gains in clarity erased by mid- to late-summer algal blooms.

Taken together, the analysis confirmed that carp management is not a stand-alone solution. Instead, it is most effective when paired with other lake and watershed management tools. The strongest and most lasting outcomes were observed where carp removal was integrated with complementary strategies such as watershed nutrient reduction, internal load management (e.g., alum treatments), and connectivity barriers that prevent reinvasion.

Recommendations and Next Steps

Staff recommend that the Board formally accept the findings of the statewide carp management effectiveness analysis at the October 9, 2025 meeting. Doing so will memorialize the work and learnings from the assessment and conclude the scope of the current assessment with the University of Minnesota. The results will also be incorporated into a forthcoming lake management framework, which will describe the District's overall strategy for lake restoration through an integrated approach that addresses both watershed nutrient loading and in-lake stressors. Finally, staff have developed an outreach plan to communicate these findings through professional conferences, factsheets, and publications to ensure lessons learned are shared broadly across the state and integrated into future management strategies.

Supporting documents (list attachments):

- Attachment 1: University of Minnesota Technical Report



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RESOLUTION

Resolution number: 25-057

Title: Acceptance of Statewide Carp Management Effectiveness Results

- WHEREAS, The field of water resources has long hypothesized that benthivores, including common carp, negatively impact aquatic vegetation communities in lakes, drive sediment resuspension, and degrade water quality;
- WHEREAS, New research in the early 2010's provided a more quantitative relationship between common carp and aquatic vegetation health, establishing strategies for carp management with 100kg/ha as a critical threshold for carp biomass management targets;
- WHEREAS, Working in partnership with Dr. Peter Sorenson and other leading University of Minnesota researchers, the District conducted a carp diagnostic study between 2014 and 2017 to quantify carp populations and clarify migratory patterns within the Six Mile Creek-Halsted Bay (SMCHB) Subwatershed – a 27-square mile, 14-lake, focal geography for watershed restoration tributary to Lake Minnetonka;
- WHEREAS, Using the diagnostic data and management strategy developed by the University's Minnesota Aquatic Invasive Species Research Center (MAISRC), the District secured \$567,000 in legislative funding through the Lessard Sams Outdoor Heritage Council in 2018 to implement a systems-scale carp management program within the SMCHB subwatershed from 2018 to 2023. At the time of implementation, this was one of Minnesota's largest carp management efforts;
- WHEREAS, With this work concluding, and many of the management targets for carp population having been met, the District is interested in evaluating the efficacy of this effort, to bring increased focus to where and when it, and other watershed managers, may best apply carp management, and to better understand its impact on water quality and aquatic vegetation;
- WHEREAS, In 2023, the District has allocated \$75,000 of its levied funds to analyze the outcomes of its carp management program;
- WHEREAS, The Minnesota Pollution Control Agency (MPCA) and the Minnesota Department of Natural Resources (DNR) both have an interest and a role in understanding the ecosystem response to carp management, and therefore the District has entered into an MOU with these agencies to outline opportunities to collaboratively study the impact of common carp management on lake ecology to inform how each organization approaches carp management in the future;
- WHEREAS, On January 11, 2024, the Board of Managers authorized a contract with the University of Minnesota (UMn) to analyze the effectiveness of carp management as a watershed management strategy on data from across Minnesota to meet the shared objectives of the District, MPCA, and DNR;
- WHEREAS, An overview of the assessment's findings were provided at the April 10, 2025 Operations and Program Committee;

WHEREAS, Findings and insights gained from the assessment are comprehensively documented in the technical report titled "Minnesota Carp Management Effectiveness Assessment: A technical report on statewide carp management as a lake restoration strategy" (October 6, 2025).

NOW, THEREFORE, BE IT RESOLVED that the District Board of Managers hereby accepts the Minnesota Carp Management Effectiveness Assessment Technical Report to acknowledge the assessment's completion and memorialize the report's findings.

Resolution Number 25-057 was moved by Manager _____, seconded by Manager _____. Motion to adopt the resolution ___ ayes, ___ nays, ___ abstentions. Date: 10/9/2025

Secretary Date: _____

Attachment 1: University of Minnesota Technical Report



Minnesota Carp Management Effectiveness Assessment

*A technical report on statewide carp management
as a lake restoration strategy.*

Prepared by Jake R. Walsh¹, Jill Sweet², Daniel J. Larkin¹, and Brian Beck²

October 2025



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1. University of Minnesota – Twin Cities Department of Fisheries, Wildlife, and Conservation Biology
2. Minnehaha Creek Watershed District

Executive Summary

Common carp are often cited as a driver of poor ecological conditions in many Minnesota lakes, and lake managers throughout the state have implemented carp management projects over the past decade to reduce their negative effects. Some project evaluations demonstrate carp management can improve water quality and aquatic vegetation; however, the benefits vary, indicating carp removal does not produce consistent improvements in all lake systems.

While individual evaluations exist, no statewide assessment of implemented projects has been conducted to inform when and where carp management can be an effective restoration strategy. To better understand the factors influencing successful outcomes, the Minnesota Department of Natural Resources, the Minnesota Pollution Control Agency, and the Minnehaha Creek Watershed District partnered with the Minnesota Aquatic Invasive Species Research Center to compile the first statewide carp management dataset. Carp, water quality, and aquatic vegetation data from projects across the state were analyzed, with the goal of setting data-driven expectations and guidance for future management.

Continuing to collect, centralize, and analyze lake management and response data will remain important following this assessment. Of the 90 lakes with carp removals in this study, only 15 had pre- and post-management data for all response variables. Managers should invest in monitoring before, during, and after management, to accurately evaluate success and support continued understanding of the effects of carp in diverse lake systems.

Overall, this study's results demonstrate carp management can yield positive but often marginal water quality outcomes and more nuanced aquatic vegetation responses. Study lakes experienced an average total phosphorus (TP) reduction of 22 µg/L following carp management, which is meaningful for lakes with lower TP concentrations, but it is less impactful for lakes starting above 80 µg/L. On average, vegetation diversity increased, but carp removal did not result in consistent improvements to overall plant coverage.

The results suggest shallow lakes already near State water quality standards are better candidates for carp management than deeper or heavily impaired lakes. Large improvements are unlikely in highly impaired systems, but smaller-scale changes could benefit shallow lakes close to meeting standards. Seasonal differences are also likely, as carp displayed a stronger effect on spring water quality. The results suggest managing summer water quality may require strategies that directly address nutrient loading.

This study showcases carp management alone is not a silver bullet and should be implemented as part of an integrated management approach. The most successful projects were often accompanied by other restoration strategies, such as watershed nutrient reduction and internal load management. Accordingly, managers should consider a lake's historic and existing conditions to determine whether carp removal will meaningfully improve water quality and aquatic vegetation.

Carp management is one tool to improve a lake system, but it should not be the only tool utilized. Lakes are inherently complex systems, and as such, **comprehensive restoration relies on strategic, data-informed prioritization of multiple management strategies.**

Project Partnership and Team

Funded by the Minnehaha Creek Watershed District (MCWD), and in partnership with the Minnesota Department of Natural Resources (MNDNR) and the Minnesota Pollution Control Agency (MPCA), this work was conducted by University of Minnesota researchers (UMN; Jake Walsh and Daniel Larkin) and MCWD staff (Jill Sweet and Brian Beck). The work was done in collaboration with staff from the MNDNR (Brian Nerbonne) and the MPCA (Jeff Strom, Amy Timm, and Allison Gamble).

A Need for a Statewide Analysis

From 2014-2023, MCWD conducted carp management efforts in its Six Mile Creek-Halsted Bay Subwatershed, as part of a regional habitat and water quality restoration program. MCWD's carp management approach successfully reduced carp to or near biomass goals in the majority of the Subwatershed's lakes. However, successful removal did not lead to consistent water quality and aquatic vegetation improvements systemwide.

In 2023, MCWD began engaging with the MNDNR and MPCA, as state agencies that play a role in carp management, to discuss its program's variable and nuanced results. These discussions highlighted the need to better understand the factors that impact carp management effectiveness, including lake morphometry, the magnitude of pre-management degradation, and hydrology and other watershed characteristics.

Since no statewide assessment of carp management efforts had been conducted, the MNDNR, the MPCA, and MCWD partnered with UMN researchers to collect data from carp management projects throughout the state and create a comprehensive, statewide database. Data on carp population and biomass, water quality, aquatic vegetation, and watershed characteristics and lake management were collected. The project team then analyzed the data to further understand complex factors that impact the effectiveness of carp management as a lake restoration strategy in various lake ecosystems.

This report includes the results of this partnership's analysis, which is the first statewide study of carp management effectiveness in Minnesota.



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Project Overview

This report includes the findings of a research project, conducted from April 2024 through July 2025, that evaluated the effectiveness of carp management as a lake restoration strategy in Minnesota by synthesizing data from 90 lakes with carp management efforts.

The project was developed in response to variable water quality and aquatic plant community responses to successful carp biomass reductions in the Six Mile Creek-Halsted Bay Subwatershed (Dauphinais et al. 2016; Sweet and Beck 2024). These variable results have also appeared in similar anecdotes of carp management projects statewide. To address this variability, the project team assembled carp management, water quality, aquatic plant community, and lake and watershed data for lakes across Minnesota. At this broader spatial scale, the project team identified three research questions to guide an effectiveness analysis.

Research Questions

1. How variable are lake responses to carp management?
2. What drives the variability in lake responses to carp management?
3. What are the important ecological relationships in carp managed lakes?

Photo Credit: Dave Hansen, Minnesota Aquatic Invasive Species Center



The goals of addressing these questions were to help set data-driven expectations for lake managers and stakeholders, as well as provide insight into the factors that influence success, **to better determine and prioritize lakes for carp management projects.**

The results of this project have been made available in this final report and a factsheet, both available on [the MAISRC webpage](#). All data and R code have been published and made publicly available through the Data Repository for the University of Minnesota, “DRUM” (Walsh et al. 2025).

Background

Lake Management Context and Assumptions

Invasive common carp are known to disturb lake sediments and dislodge aquatic plants, which can alter the ecological makeup of lakes and adversely affect water quality.

Water resource managers use a conceptual model of lake ecological interactions that includes both direct and indirect effects of carp on water and floristic quality (Figure 1). Direct effects in this conceptual model include the negative effects of carp on water clarity via resuspending sediment and on macrophytes via dislodging plants, as well as the positive effect on nutrient concentrations in lakes via resuspending nutrients buried in lake sediments. Indirect effects of carp are thought to be mediated through their effects on water clarity: declining clarity can negatively affect macrophyte growth and diversity, and increasing nutrients can fuel algal growth that negatively affects clarity and, in turn, macrophyte growth and diversity (indirect paths in Figure 1).

Conceptual Model of the Direct and Indirect Effect of Carp in Lakes

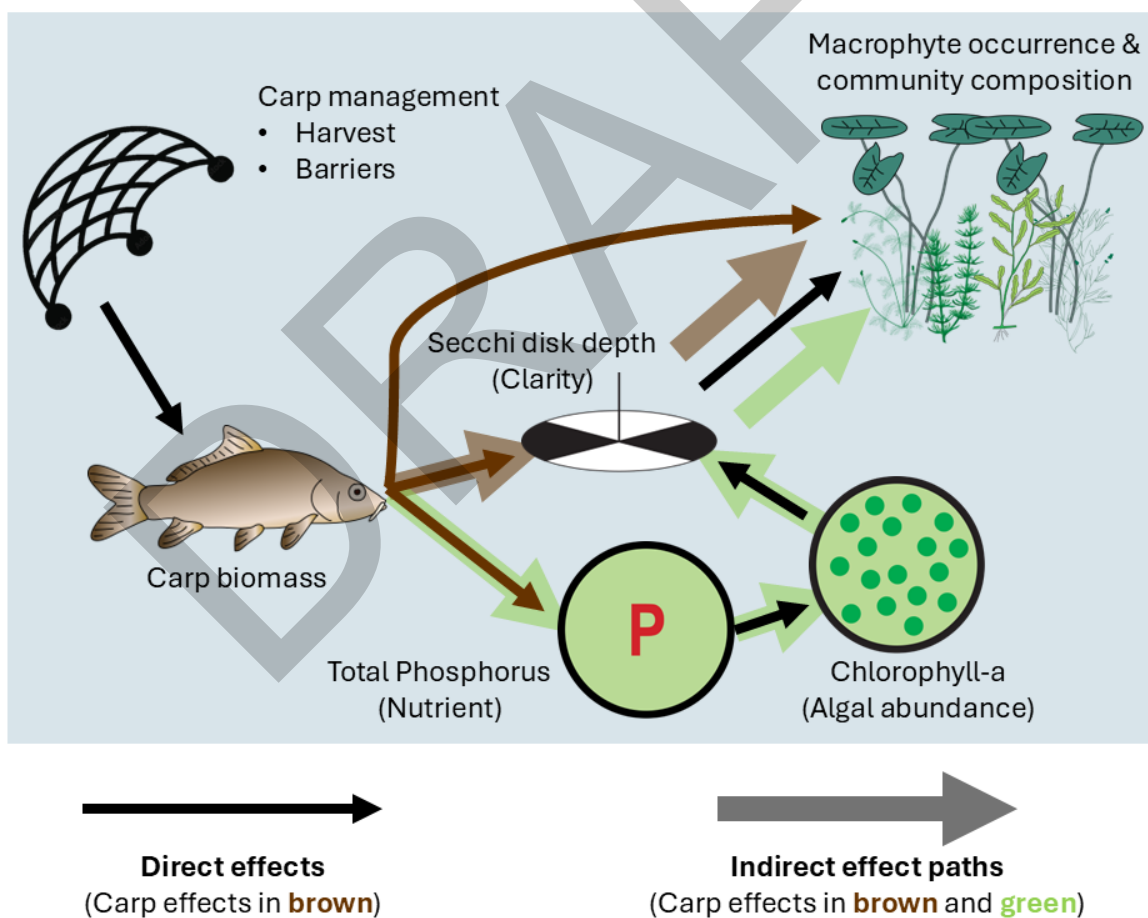


Figure 1. Conceptual model of the direct and indirect effects of carp in lakes. Arrows represent hypothesized direct effects (small solid arrows) and indirect effect paths (large transparent arrows). Carp has both direct (small solid brown arrows) and indirect effects on clarity (large transparent green arrow path) and macrophytes (large transparent green and brown arrow paths).

Thus, common carp management is often viewed as an effective tool to improve water or floristic quality, especially in degraded or impaired lakes. However, it is important to test this conceptual model by analyzing pre- and post-management data in diverse lake ecosystems.

Past analyses and anecdotes of observed lake responses to carp management demonstrate the assumed benefits of successful management, based on this conceptual model, are variable (Figure 2). Observed lake responses are also currently difficult to predict, as they depend on more than just carp removal, and have been most often evaluated in shallow, unstratified lakes from which results may not be generalizable to deeper lakes (Bajer and Sorensen 2015).

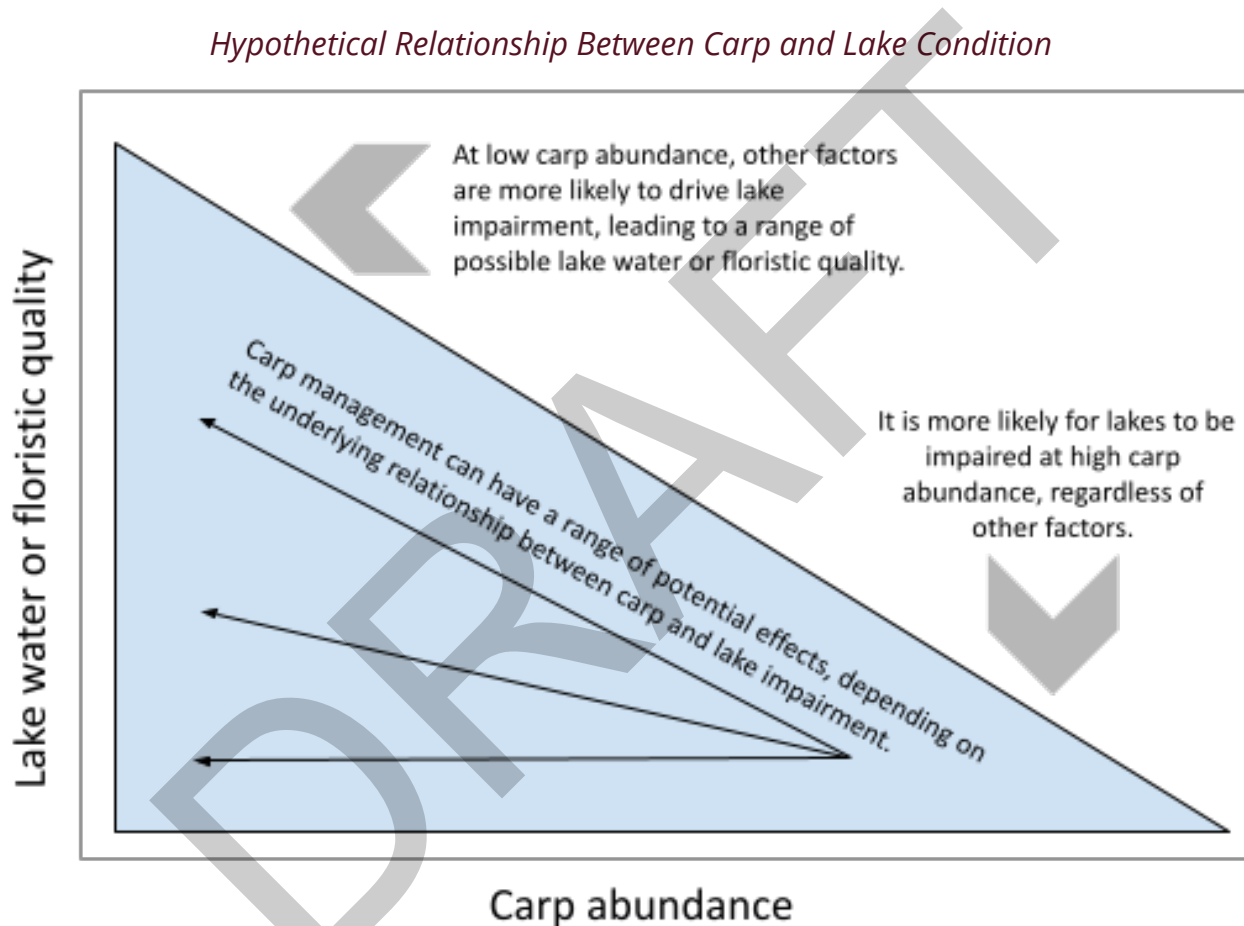


Figure 2. Hypothetical relationship between carp and lake condition. The blue-shaded triangle represents the range of potential lake conditions under increasing carp abundance and arrows represent the potential management outcomes of reducing carp abundance.

Evaluating Carp Management Efforts

Evaluating the effects of most lake management strategies is challenging, given the social, political, and ecological complexity and natural variability of lakes (Cianci-Gaskill et al. 2024), which is especially true for shallow lakes (Abell et al. 2022). As such, evaluating the success of carp management and its effects in impaired lakes is complex (Figure 3).

Conceptual Diagram of Lake Management for Water and Floristic Quality

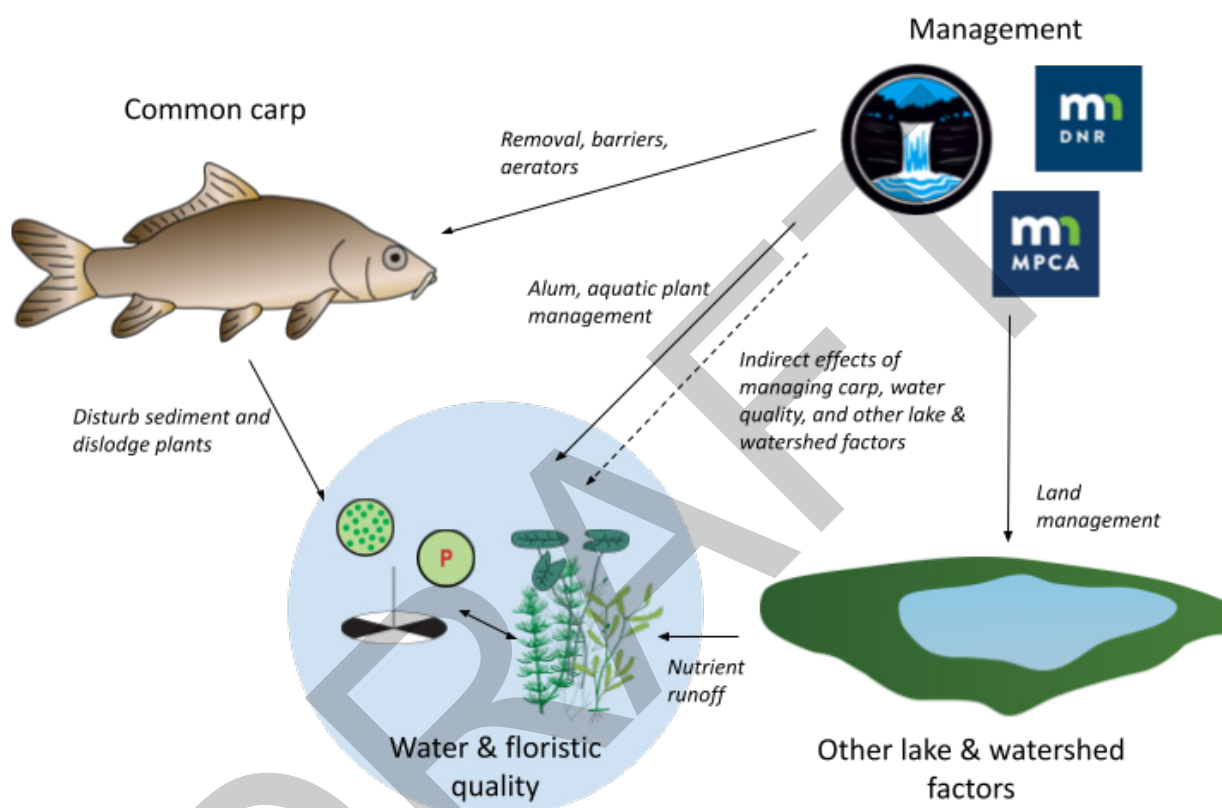


Figure 3. Conceptual diagram of lake management for water and floristic quality. Arrows represent effects.

Evaluations of carp management often focus on biomass reduction goals, whereby success is defined as reducing biomass below a threshold (e.g., < 100 kg/ha; Bajer et al. 2009). It is commonly assumed that reaching a specific biomass threshold will result in improved water and floristic quality, which is typically the overall goal with carp management efforts.

However, post-management data have demonstrated that successfully reaching a biomass threshold does not necessarily lead to meaningful ecosystem improvements in every lake, and in some cases, certain lakes can maintain acceptable water and floristic quality when their carp biomass exceeds 100 kg/ha. Since lakes are complex systems with high degrees of variability, meaningful improvements toward restoration are also dependent on context-specific interactions between watershed characteristics, lake processes, climatic variability, and other management strategies.

The underlying complexity of such interactions leads to a range of potential carp management outcomes. For example, the Minnehaha Creek Watershed District (MCWD) conducted carp

management in 14 lakes in the Six Mile Creek-Halsted Bay (SMCHB) Subwatershed, to improve water and floristic quality (Dauphinais et al. 2016). MCWD found floristic quality was low in SMCHB lakes with high carp biomass, as expected, but variable in lakes with low carp biomass (Figure 4 depicts Figure 3-8 from the [technical report](#) Sweet and Beck 2024).

These findings suggest existing water clarity could be a mediating factor in the ability of carp management to improve floristic quality, which is consistent with the intent of floristic quality as an indicator of water quality (Swink and Wilhelm 1994; Radomski and Perleberg 2012). In this example, MCWD's analysis demonstrated lakes with watershed or internal loading issues continued to experience poor water clarity, even if carp biomass was below or near the management threshold, suggesting management strategies beyond carp removal would be necessary to effectively improve and restore these lakes.

Relationship Between Carp Biomass, Floristic Quality, and Water Clarity in SMCHB Lakes

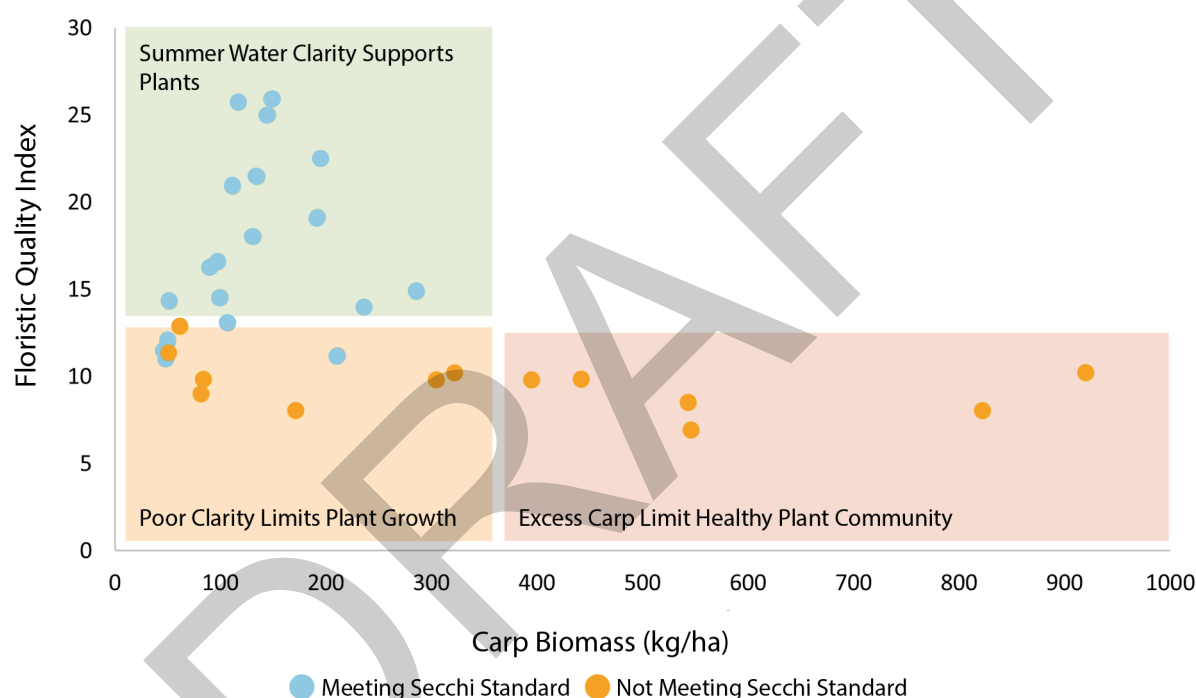


Figure 4. Relationship between carp biomass (kg/ha), floristic quality, and water clarity (Secchi disk depth standard of 1.4 m for 7 of the 8 plotted lakes deeper than 15 feet, and 1.0 m for the lake shallower than 15 feet) in SMCHB lakes is plotted in Figure 3-11 from "Six Mile Creek-Halsted Bay Habitat Restoration: A technical report on restoration efforts through common carp management" (Sweet and Beck 2024).

Project Objectives

The high degree of variability in observed lake responses to carp management, along with the need to test assumptions regarding carp ecology and management, underpinned project research objectives, which included:

1. Quantify the variability in lake responses to carp management
2. Explore drivers of the variability in lake responses to carp management
3. Quantify ecological relationships in carp managed lakes

Approach

Overview

The project team compiled available statewide carp management, water quality, and macrophyte data into one dataset—a first of its kind in Minnesota—and used it to evaluate lake responses to carp management. The dataset spanned both pre- and post-management time periods, which allowed the project team to quantify lake responses (and variability in those responses) to carp management, potential lake response drivers, and test the industry's underlying assumptions regarding ecological relationships in carp managed lakes.

Data was summarized at the lake-year level (April – September) as well as by season (“early season”, April – June, and “late season”, July – September), and analyses were conducted during these time periods. All available data were included in the final dataset, even if some variables were missing for a given lake-year. Data analysis was conducted using the statistical program R (R Core Team 2023). The following subsections further describe this approach.

Data Collation and Preparation

Carp

The project team worked with local management organizations to collate carp population estimate and removal data. Carp surveys for population estimates included average catch per unit effort, average length (mm) and weight (kg), population estimates, biomass density estimates (kg/ha; hereafter, “biomass”), and survey method (which included electrofishing, box nets, and mark-recapture for population estimates). While some survey methods are



Boat electrofishing is conducted for adult carp monitoring in 2023. Credit: Riley Purgatory Bluff Creek Watershed District

likely more accurate than others (e.g., mark-recapture), all population density and biomass estimates were included for calculating annual averages. Biomass density (kg/ha) was used as the primary measure of carp population size in each lake.

Carp removal data included total captured individuals, average length and weight of captured individuals, biomass removed, biomass density removed (kg/ha), and methodological details such as removal method (which included box nets and electrofishing) and effort (e.g., number and duration of set nets). East (MNDOW_10004402) and West (MNDOW_10004401) Auburn Lake have separate biomass estimates, but combined removal estimates (Auburn Lake; MNDOW_10004400). The removal estimates were scaled by the proportion of carp biomass in each lake (56% in East Auburn, 44% in West Auburn) as there were separate estimates for water quality and macrophyte variables. Biomass density removed (kg/ha) was used as the primary measure of carp removal in each lake.



Benton Lake box net removal from October 8, 2017. Credit: Carver County Water Management Organization

To account for long-term harvest pressure and its effect on carp biomass, the project team developed an index of relative historical harvest intensity for use in evaluating the relationship between harvest and carp biomass (Figure 5).



Commercial netters completing a seine on Upper Prior Lake. Credit: Prior Lake Spring Lake Watershed District

The goal in developing the index was to account for two key factors related to historical harvest intensity: 1) that harvest in a given year would have the highest effect on biomass in the following year and a decreasing effect on biomass in subsequent years and 2) that the index would include a measure of pressure where harvest would be relative to standing biomass density in a given year (Equation 1).

$$\text{Harvest Index}_t = \frac{\text{Historical Harvest}_t}{\text{Biomass Density}_t}$$

$$\text{Historical Harvest}_t = \sum_i^t W_i \times \text{Biomass Density Removed}_i$$

$$W_i = \begin{cases} 0 & \text{If } i = t \text{ and a winter harvest or kill did not occur in } t \\ 1 & \text{If } i = t \text{ and a winter harvest or kill occurred in } t \\ 1 & \text{Otherwise,} \\ \frac{1}{t-i} & \text{inverse weighting by time since year } i \end{cases}$$

Equation 1. Calculating Harvest Index for Carp Removal Histories

Where $Harvest Index_t$ in a given lake in year t is a unitless measure of inverse time weighted historical harvest intensity, $Historical Harvest_t$ (kg/ha), relative to current observed biomass density, $Biomass Density_t$ (kg/ha). So, a harvest index value of 2 would indicate that the total, inverse time weighted historical harvest intensity was twice the current biomass density, and 0.5 would be half the current biomass density.

$Historical Harvest_t$ is calculated as the total inverse time weighted historical harvest density from the first year of the observation window, $Year_1$ (here, $Year_1 = 10$ years before the first removal effort in that lake) to year t . To obtain $Historical Harvest_t$, $Biomass Density Removed_i$ is weighted by W_i and the product is summed. $Biomass Density Removed_i$ prior to the first removal year was set to zero. W_i is the inverse of time since year i ($t - i$). When $i = t$ and $1/(i - t)$ is undefined, $W_i = 0$ unless a winter harvest or kill of carp occurred in the winter immediately preceding year t , in which case $W_i = 1$. In this way, removals in the same year have no effect on $Historical Harvest_t$ unless a winter removal or kill occurred in that year, the preceding year ($t - i = 1$) has the strongest effect on $Historical Harvest_t$ ($W_i = 1/1$), and each year before ($t - i = 2, 3, \dots t - Year_1$) has increasingly weaker effects on $Historical Harvest_t$ ($W_i = 1/2, 1/3, \dots 1/(t - Year_1)$).

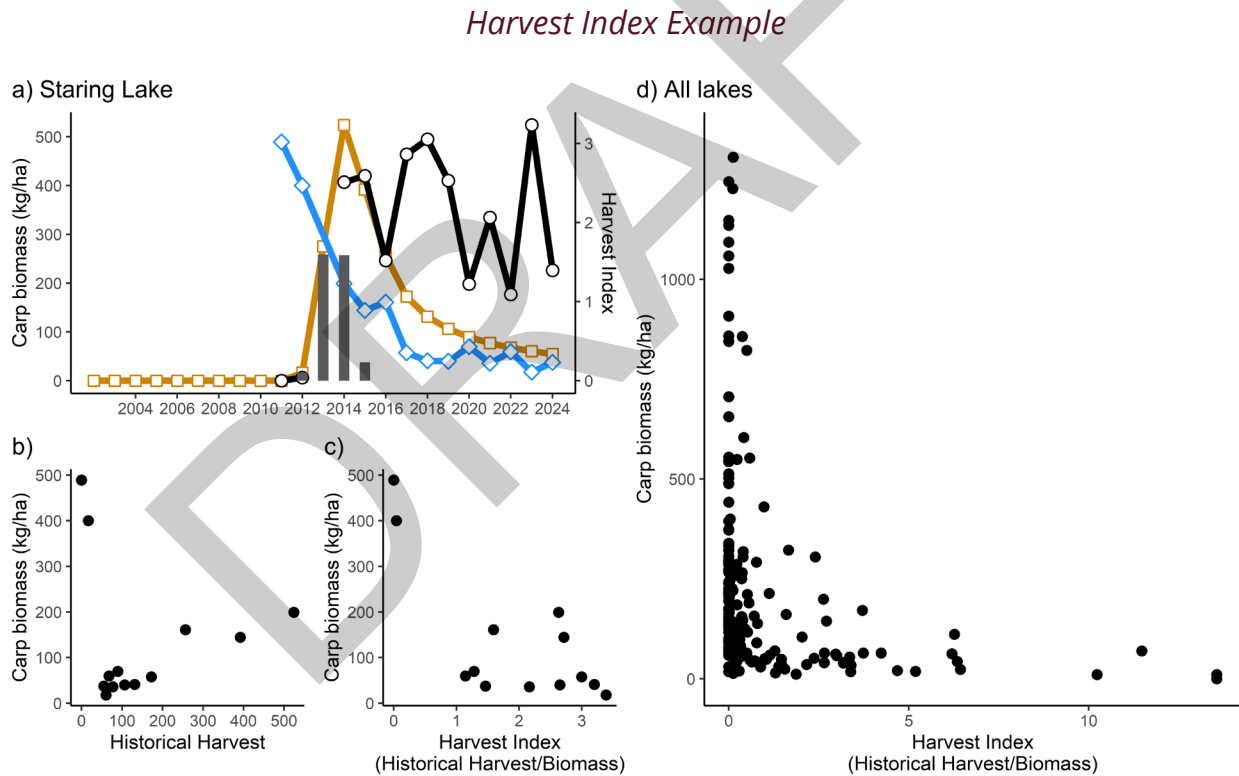
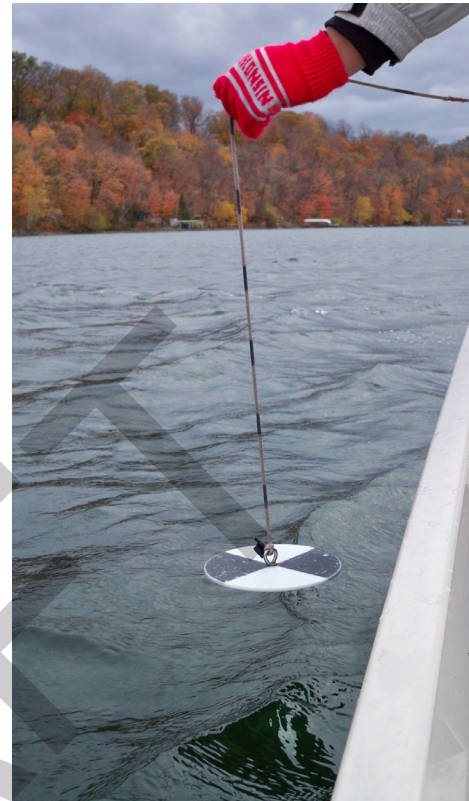


Figure 5. Harvest index example in Staring Lake (a, b, c) and harvest index data from all lakes (d). a) Observed carp biomass density (kg/ha; $Biomass Density_t$; light blue line and diamonds), annual biomass density removed (kg/ha; dark grey vertical bars), inverse time weighted historical harvest (kg/ha; $Historical Harvest_t$; dark orange line and squares), and harvest index (right y-axis; $Harvest Index_t$; black line and circles) are plotted over time in Staring Lake (MNDOW_27007800). b) The relationship between inverse time weighted historical harvest and carp biomass density in Staring. c) The relationship between the harvest index and carp biomass density in Staring. d) The relationship between the harvest index and carp biomass density in all lakes.

Water Quality

Water quality data was provided by the Minnesota Pollution Control Agency (MPCA), which included total phosphorus concentration (mg/L; surface waters, ≤ 3 m), chlorophyll-a concentration (ug/L; surface waters, ≤ 3 m), and Secchi disk depth (m) data from 1990 through 2023 from May through September. Change in TP was converted to ug/L to increase ease of interpretation as changes in concentrations were occasionally small. The MPCA uses the Environmental Quality Information System ([EQuIS](#)) to store and manage water quality data collected by state, county, city, watershed, and federal agencies, and citizen volunteers. All negative chlorophyll-a concentrations were censored up to 1 ug/L or 0.5 ug/L (reporting limit standards for different data sources). Roughly 15% of the chlorophyll-a dataset required some kind of cleaning by MPCA staff. Secchi disk depths that were represented as actual zeroes (versus a marker for not being able to sample, <1% of the data) were censored up to the generally minimum measurable Secchi depth of 0.1 m. The LAGOS-NE research platform (Soranno et al. 2017; Stachelek et al. 2023) was used to fill in gaps in water quality data through 2012, though note that MPCA was a primary contributor to the LAGOS-NE data collation effort for Minnesota lakes, so this only provided a few additional pre-management data points.



A Secchi disk is used to measure water clarity. Credit: Minnehaha Creek Watershed District

Water quality variables were averaged across the open water season (April – September) and early (April – June) and late (July – September) seasons to the lake-year level. There are likely relatively few April measurements included in these averages, based on the available data.

To ground data in management-relevant values, state water quality standards for deep (typically $\geq 15'$) and shallow (typically $< 15'$) North Central Hardwood Forest ecoregion aquatic recreational use (Class 2B) lakes were used for comparison. The majority of the carp-managed lakes in this database are located in this ecoregion. For deep lakes, these standards are under 40 ug/L TP, under 14 ug/L chlorophyll-a, and over 1.4 m Secchi disk depth, and for shallow lakes, under 60 ug/L TP, under 20 ug/L chlorophyll-a, and over 1.0 m Secchi disk depth (Acquah et al. 2024).

Macrophytes

Macrophyte data were obtained through the Minnesota Aquatic Invasive Species Center (MAISRC) “PI Charter app” database (Bajcz et al. 2024). These data are a collection of point-intercept (PI) surveys from managers, contractors, citizens, and researchers across Minnesota. PI surveys are a common, standardized approach to sampling lake macrophyte communities. PI surveys are composed of a grid of sampling points across a lake where surveyors toss and retrieve a rake to identify and score the abundance of different macrophyte species retrieved on the rake head (Madsen 1999).

These PI surveys were used to estimate macrophyte frequency of occurrence in the littoral zone for all submersed macrophytes (e.g., the frequency of any submersed macrophyte occurring on a rake toss), native/nonnative submersed macrophytes, and for all individual taxa. Macrophyte community richness and floristic quality were calculated using macrophyte taxa identified to the species level. Floristic quality can be measured by a “floristic quality index” calculated as the product of average conservatism (a subjective value ranging from 0 to 10, where higher values represent species more likely to occur in an “undisturbed” or “pre-colonial” landscape) of all macrophyte species in the survey and the square root of the number of species in the survey (Swink and Wilhelm 1994).

This index has been shown to be relevant for using macrophytes as indicators of biotic integrity in Minnesota lakes (Radomski and Perleberg 2012). Macrophyte variables were averaged across the open water season (April – September) and early (April – June) and late (July – September) seasons to the lake-year level.



*(above and below) Staff conducting plant surveys.
Credit: Minnehaha Creek Watershed District*



Lake and Watershed Characteristics and Management

Additional information regarding lake and watershed characteristics and the management of both was provided by the MNDNR and MPCA and again supplemented with LAGOS-NE research platform data (Soranno et al. 2017; Stachelek et al. 2023). Lake characteristic data included morphology (maximum and mean depth, lake area, lake perimeter, shoreline development index, Osgood index (Osgood 2005), percent littoral area), location (latitude, longitude, elevation), hydrology (water residence time), and external load estimates (phosphorus loading). Lake management data included impairment status, the year of alum treatments, and water quality management planning (e.g., “TMDL”, total maximum daily load projects). Watershed characteristics included watershed area and watershed area to lake area ratio.

Information about aquatic habitat connectivity for managed lakes, including the presence of barriers that would likely impede carp movement, was also collected. Barriers included existing and newly constructed barriers such as dams and weirs that were constructed with a goal of obstructing carp passage. The presence of barriers was used to estimate potamodromous dendritic connectivity before and after management, according to the methods outlined in Cote et al. (2009). The dendritic connectivity index (DCI) was calculated in both absolute and relative terms. Raw DCI scores allow for comparisons between watersheds in absolute terms, while the standardized relative DCI scores allow for clearer comparisons of connectivity within a watershed.



*An electric guidance system directs carp into a fenced in area, where they are aggregated and then removed.
Credit: Rice Creek Watershed District*

Data Coverage Across and Between Datasets

The project team collated 90 lakes with carp removal data, 86 of which had carp biomass data, including 32 lakes with carp biomass estimated before and after (“pre/post”) a removal. Of those 32 lakes, 23 lakes (72%) had pre/post water quality data and 16 lakes (50%) had macrophyte PI survey data.

Fifteen lakes (47%) had full pre/post management data for biomass, water quality, and late season macrophyte data (Table 1). All lakes are mapped in Figure 6, and lakes with pre/post data of any kind are listed in Table 2 and Table 3.

Figure 6. A map of study lakes includes all lakes with carp removal data (black points in inset map of Minnesota, colored points in zoomed map). Colored points indicate pre- and post-carp management data availability for carp biomass, water quality, and macrophyte response variables (“Full” in purple circles = data available for all response variables, “Partial” in blue squares = data available for carp biomass and either water quality or macrophyte data, “Limited” in green triangles = data available for just one category, and “None” in X shapes = no pre/post data available).

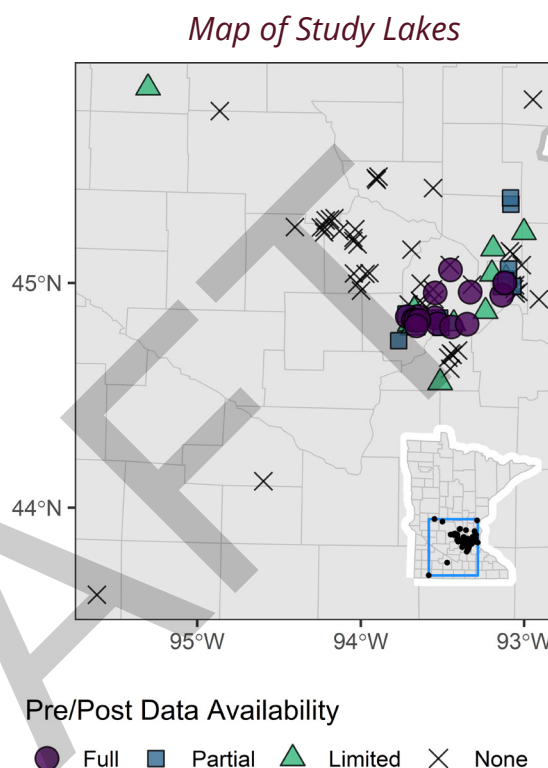


Table 1. Data Coverage Across Datasets

Dataset	Number of Lakes	Number of Lake-Years	Number of Lakes with Pre/Post Data
Carp Removal	90	831	--
Carp Biomass	86	270	32
Water Quality	63	520	28 (23)
Macrophyte	40	184	18 (16)
Carp Biomass, Water Quality & Macrophyte	33	151	15

Table 1. Data coverage across data sets. The number of lakes is the count of unique DOW IDs that have data for each dataset, the number of lake years is the count of unique DOW ID and year pairs that have data for each dataset, and the number of lakes with pre/post data is the count of unique DOW IDs that have data both before and after a carp removal. Numbers in parentheses are the number of lakes with carp biomass and either water quality or macrophyte data.

Table 2. Lakes with Pre/Post Data

ID	Lake	County	Pre/Post Data Available	Area (Acres)	Mean Depth (ft)	Max Depth (ft)	Watershed Area (Acres)	WA:LA
02003400	Martin	Anoka	CB, WQ*	232	8.7	17.0	24656	106
02077300	Sunrise	Anoka	CB	85				
10000200	Riley	Carver	CB, WQ	296	20.2	49.0	5380	18
10000600	Lotus	Carver	CB, WQ	245	9.9	28.9	1069	4
10000700	Lucy	Carver	CB, WQ, Mac	88	7.4	21.0	1002	11
10001300	Susan	Carver	CB, WQ, Mac	88	9.7	17.0	206	2
10004100	Zumbra/ Sunny	Carver	CB, WQ, Mac	271	11.6	57.8	536	2
10004200	Parley	Carver	CB, WQ, Mac	258	6.3	18.0	12861	50
10004401	West Auburn	Carver	CB, WQ, Mac	144	24.9	85.0	8031	56
10004402	East Auburn	Carver	CB, WQ, Mac	146	8.9	33.7	8031	55
10004500	Steiger	Carver	CB, WQ, Mac	166	13.0	36.8	826	5
10004800	Wassermann	Carver	CB, WQ, Mac	170	9.9	40.9	2880	17
10005300	Piersons	Carver	CB	267	17.8	40.0	1183	4
10006900	Benton	Carver	CB, WQ	49	~2	~7	2,242	46
21008100	Winona	Douglas	CB	211	4.4	7.0	1,636	9
27001900	Nokomis	Hennepin	CB	201	13.6	32.8	2948	15
27003501	Sweeney	Hennepin	CB, WQ, Mac	68	11.9	25.0	2077	31
27007800	Staring	Hennepin	CB, WQ, Mac	167	6.6	16.0	15314	92
27011800	Fish Lake	Hennepin	CB, WQ, Mac	229	20.3	49.9	1,616	7
27013309	Halsted	Hennepin	WQ	561	13.2	32.0		
27016000	Long	Hennepin	CB, WQ, Mac	285	13.7	35.0	6757	24
27099700	PCRA	Hennepin	CB					
27104501	Normandale	Hennepin	CB, WQ*, Mac	112	4.2	10.0	21,556	192
30000900	Typo	Isanti	CB, WQ	298	2.7	6.0	12074	40
62000700	Gervais	Ramsey	WQ, Mac	235	19.1	41.4	31879	136
62003802	West Vadnais	Ramsey	CB, WQ	212	5.7	9.0	15097	71
62004600	Pleasant	Ramsey	CB, WQ	607	16.8	57.7	8212	14
62004800	Bennett	Ramsey	WQ, Mac	29		9.0	772	27
62005500	Como	Ramsey	CB, WQ, Mac	71	6.4	16.0	1820	26

Table 2. Lakes with Pre/Post Data								
ID	Lake	County	Pre/Post Data Available	Area (Acres)	Mean Depth (ft)	Max Depth (ft)	Watershed Area (Acres)	WA:LA
62005600	Owasso	Ramsey	CB, WQ, Mac	375	10.9	37.0	3010	8
62006700	Long	Ramsey	CB	173	11.1	24.0	113738	659
62008200	Wabasso	Ramsey	CB, WQ**	43	18.9	72.9	3284	77
70009100	Cedar	Scott	WQ	788	6.9	15.1	2,472	3
82016300	Clear	Washington	WQ	429	11.3	28.0	2636	6
			Mean	219	11.6	30.6	10778	62
			Std. Dev.	163	5.1	19.0	21249	122
			Med.	187	11.0	28.9	3147	25
			Min.	29	2.7	5.0	206	2
			Max.	788	24.9	85.0	113738	659
<i>Table 2. Lake and watershed information for lakes with pre/post data for any of the carp biomass, water quality, or macrophyte response metrics. For pre/post data availability, CB = carp biomass, WQ = water quality (*just Secchi depth, **just TP and chlorophyll-a), and Mac = macrophytes.</i>								

Evaluating Lake Responses to Carp Management

The project team evaluated lake responses to carp management using two methods. First, linear mixed effects models were fit to test the null hypothesis that, on average, the response variable did not change with management (Equation 2). The mixed effects approach allowed the team to 1) use the full dataset of lake-years where pre and post time periods could be identified and 2) account for multiple lake years within a given lake pre or post time period by including a random intercept effect for lake (MNDOW_ID).

$$\begin{aligned} \text{Response Variable}_{i,t} &\sim N(\mu_{i,t}, \sigma_{i,t}^2) \\ E(\text{Response Variable}_{i,t}) &= \mu_{i,t} \\ \text{var}(\text{Response Variable}_{i,t}) &= \sigma_{i,t}^2 \\ \mu_{i,t} &= B_0 + B \times \text{PeriodPost}_t + \text{Lake}_i \\ \text{Lake}_i &= N(0, \sigma_{\text{Lake}}^2) \end{aligned}$$

Equation 2. Linear Mixed Effects Model for Average Lake Response

The mean value of the response variable for lake i in year t ($\mu_{i,t}$) is a linear function of PeriodPost_t where B_0 is the intercept (i.e., average of the response variable for PeriodPre) and B is the effect of PeriodPost (i.e., the average difference between PeriodPost and PeriodPre). The response variable is assumed to be normally distributed with variance $\sigma_{i,t}^2$ and the random intercept Lake_i is normally distributed with mean zero and variance σ_{Lake}^2 . The significance of B is then the formal test for whether the response variable changed with management ($\alpha=0.05$).

The second method to evaluate lake responses was by calculating pre- and post-removal averages for each lake and subtracting the pre average from the post average, which yielded a distribution of change values to observe the variability in lake responses to carp removal. Boxplots were used to evaluate these distributions, alongside the B coefficient estimates from the mixed effects model.

Exploring Drivers of Lake Responses to Carp Management

Using the values of observed change for each lake with removal, potential drivers of those changes were evaluated, which could include variables related to lake characteristics (e.g., mean depth, lake area, and impairment status), watershed characteristics (e.g., watershed-to-lake area ratio, phosphorus loading, land use, and land cover), or management (e.g., carp management details and alum treatments). Given the limited number of lakes with pre/post data (Table 1), this analysis is exploratory over a relatively small number of drivers. The following linear model was used to explore potential drivers of lake responses to management (Equation 3):

$$\begin{aligned}
 \text{Change}_i &\sim N(\mu_i, \sigma_i^2) \\
 E(\text{Change}_i) &= \mu_i \\
 \text{var}(\text{Change}_i) &= \sigma_i^2 \\
 \mu_i &= B_0 + B_{\text{alum}} + B_{\% \text{ reduction}} \times \% \text{ Reduction in Biomass}_i + B_{\text{pre biomass}} \times \text{Pre Biomass}_i \\
 &\quad + B_{\text{mean depth}} \times \text{Mean Lake Depth}_i
 \end{aligned}$$

Equation 3. General Model Format to Evaluate Drivers of Lake Responses

Where the change in a response variable in a lake i (Change_i) is a function of the percent reduction in biomass density in that lake ($\% \text{ Reduction in Biomass}_i$), the biomass density before management in that lake (Pre Biomass_i), the mean depth of that lake (Mean Lake Depth_i), and the natural log of the lake area of that lake ($\log(\text{Lake Area}_i)$). Alum treatments in study lakes were accounted for using a dummy variable for whether a treatment occurred during carp management (B_{alum}).

The model was fit as a linear model with mean, μ , and normally distributed error with standard deviation, σ_i^2 . Coefficients (B) can be interpreted as increasing ($+B$) or decreasing ($-B$) the change in the response variable. So, for variables where the expectation or goal is a decrease (e.g., TP, chlorophyll-a), a negative coefficient would indicate management was more successful and a positive coefficient less successful as the driver increases. For variables where the goal is an increase (e.g., Secchi depth, macrophyte richness, and submersed FOO), a positive coefficient would indicate management was more successful and a negative coefficient less successful as the driver increases.

Quantifying Ecological Relationships in Managed Lakes

Piecewise structural equation modeling (SEM) was used to explore and test ecological relationships in carp managed lakes (Lefcheck 2016; Lefcheck et al. 2024). The simplified relationships outlined in Figure 1 were chosen based on data availability and causal hypotheses often used by lake managers in carp management, thus important relationships may be missing (e.g., the influence of carp on total suspended solids and the influence of total suspended solids on water clarity).

SEMs leverage a series of linked models to represent these relationships statistically. Because multiple models are linked, variables can serve as both drivers and responses. Generally, SEMs are evaluated globally, where the fitted model is the model that best fits the variance-covariance relationship of all the models. By fitting models locally (i.e., each model individually), piecewise SEMs provided two key advantages over traditional approaches for this study's purposes. First, they allowed for the use of hierarchical structures of non-independent points (e.g., multiple observations within a single lake, which can be accounted for with a random intercept for lake). Second, they allowed for the use of the full dataset, including points where there are observations of one variable but not another. For example, water quality data was generally more available than macrophyte data (Table 1). Piecewise SEMs allowed for the use of all the water quality data to estimate drivers of water quality (so long as macrophyte data were not a predictor of water quality), rather than only those observations with concurrent macrophyte data points. This second benefit comes with a key caveat: Individual models within our piecewise SEMs were often fit with different subsets of the dataset (e.g., relationships to water quality were estimated on a broader subset of lake-years than relationships to macrophytes).

The relationships in Figure 4 were represented with the following series of linear mixed effects models (Bates et al. 2015) using the *piecewiseSEM* packages in R (Lefcheck et al. 2024). All models were fit with the same statistical form in Equation 4, and specific driver-response relationships are outlined in Equation 5. Two piecewise SEMs were fit for each model formulation in Equation 5: 1) lake-year averages across the early season (April – June), and 2) lake-year averages across the late season (July – September).

$$\begin{aligned} \text{Response Variable}_{i,t} &\sim N(\mu_{i,t}, \sigma_{i,t}^2) \\ E(\text{Response Variable}_{i,t}) &= \mu_{i,t} \\ \text{var}(\text{Response Variable}_{i,t}) &= \sigma_{i,t}^2 \\ \mu_{i,t} &= B_0 + B_j \times \text{Drivers}_{j,i,t} + \text{Lake}_i \\ \text{Lake}_i &= N(0, \sigma_{\text{Lake}}^2) \end{aligned}$$

Equation 4. Piecewise SEM Individual Model Structure

The mean value of the response variable for lake i in year t ($\mu_{i,t}$) is a linear function of a matrix of drivers $Drivers_{j,i,t}$ where B_j is a vector of coefficients representing the effect of each driver on the response variable. The response variable is assumed to be normally distributed with variance $\sigma_{i,t}^2$ and the random intercept $Lake_i$ is normally distributed with mean zero and variance σ_{Lake}^2 . Response variables included carp biomass density (kg/ha; $Biomass\ Density_{i,t}$), total phosphorus concentration (mg/L, surface waters; $TP_{i,t}$), chlorophyll-a concentration (ug/L, surface waters; $Chla_{i,t}$), Secchi disk depth (m; $Secchi_{i,t}$), and the frequency of submersed plant occurrence in the lake littoral zone (FOO; $FOO_S_{i,t}$) (Equation 5). Each of these variables also served as drivers for other response variables according to Figure 1 and Equation 5.

$$\begin{aligned}
 Biomass\ Density_{i,t} &\sim Harvest\ Index_{i,t} + Lake_i \\
 TP_{i,t} &\sim Biomass\ Density_{i,t} + Lake_i \\
 Chla_{i,t} &\sim TP_{i,t} + Lake_i \\
 Secchi_{i,t} &\sim Chla_{i,t} + Biomass\ Density_{i,t} + Lake_i \\
 FOO_S_{i,t} &\sim Secchi_{i,t} + Biomass\ Density_{i,t} + Lake_i
 \end{aligned}$$

Equation 5. Individual Piecewise SEM Formulations for Focal (Figure 1) Variables and Drivers

Models were also fit using different taxonomic divisions for submersed macrophytes, where carp biomass still affected all taxonomic groups. These additional models included native and nonnative taxa where nonnative FOO was included as a driver of native FOO, and native, curlyleaf pondweed, and Eurasian water milfoil where the FOO of the two nonnative macrophytes were included as drivers of native FOO.

Direct and indirect effect coefficients (B_j in Equation 4) that quantify the strength and direction of the arrows in Figure 1 were estimated using bootstrapping (10,000 iterations) in the package *semEff* in R. Coefficients are presented both as raw (e.g., a change in 1 mg/L of TP leads to a change in B m in $Secchi$) and standardized (e.g., a change in 1 standard deviation of TP leads to a change in B standard deviations in $Secchi$) effects. Raw effects are readily interpretable, especially in the context of lake management goals, while standardized effects allow for comparison of the relative strength of the effect across variables.

Results

Lakes with Carp Management Summaries

Carp management varied by duration, intensity, and barrier use (Table 3), and 86% of projects occurred in lakes with pre-management biomass densities of at least 100 kg/ha. The average biomass density removed each year was positively associated with pre-management biomass density (coefficient=0.09, SE=0.04, $p=0.03$), but this relationship explained relatively little variation ($R^2=0.12$). Connectivity, as measured by DCI, was reduced the most in lakes with barriers used in management. Some lakes with low pre-DCI scores may have had an existing man-made or natural obstruction to carp and might not have required construction of a barrier. Otherwise, management approaches were context-dependent without clear patterns in the relationships between management duration, intensity, and barrier use.

Table 3. Lake Management Data for Lakes with Pre/Post Data

ID	Lake	Alum Trt.	Last Pre Year	First Post Year	Pre Biom. Dens. (kg/ha)	Harvest Years	Avg. Biom. Dens. Removed (kg/ha/y)	Avg. Harvest Index	Carp Barrier	Pre DCI Rel.	Change in DCI Rel.
02003400	Mart	No	2020	2022	265	4	40	0.06	NA		
02077300	Sunr	No	2019	2020	95	2	8	0.08	No	2.60	0.00
10000200	Rile	Yes	2009	2010	133	2	71	7.16	No	0.03	0.00
10000600	Lotu	Yes	2012	2014	61	2	13	0.10	Yes	0.01	0.00
10000700	Lucy	No	2010	2011	70	1	96	4.68	No	0.03	0.00
10001300	Susa	Pre	2008	2009	307	2	97	1.56	No	0.03	0.00
10004100	Z/S	No	2019	2021	173	2	4	0.00	Yes	2.69	-2.33
10004200	Parl	No	2021	2022	619	4	239	1.78	Yes	24.45	-23.93
10004401	WAub	No	2018	2019	272	3	7	0.04	Yes	2.69	-2.33
10004402	EAub	No	2021	2022	201	3	9	0.04	Yes	2.69	-2.33
10004500	Stei	No	2018	2019	143	1	45		Yes	2.69	-2.33
10004800	Wass	Yes	2017	2018	464	2	92	2.97	Yes	2.69	-2.40
10005300	Pier	No	2023	2024	125	2	17	0.11	Yes	2.69	-2.40
10006900	Bent	No	2021	2022	651	5	170	0.29	Yes	15.58	-15.53
21008100	Wino	No	2022	2023	1120	2	104	0.02	Yes	NA	NA
27001900	Noko	No	2017	2023	310	1	36	0.00	No	0.06	0.00
27003501	Swee	Yes	2020	2021	227	1	54	0.00	No	1.07	0.00
27007800	Star	No	2013	2014	445	4	142	0.89	Yes	0.73	-0.73
27011800	Fish	Yes	2018	2021	322	1	29		NA		
27013309	Hals	No	2019	2020	1133	1	23	0.00	No	24.45	-3.27
27016000	Long	Pre	2021	2022	564	2	40	0.07	No	24.45	-3.27
27099700	PCRA	No	2020	2023	158	11	47	1.04	Yes	0.73	-0.04
27104501	Norm	Pre	2020	2021	191	5	32	0.27	No	0.27	0.00
30000900	Typo	No	2019	2021	503	3	13	0.05	No		

Table 3. Lake Management Data for Lakes with Pre/Post Data

ID	Lake	Alum Trt.	Last Pre Year	First Post Year	Pre Biom. Dens. (kg/ha)	Harvest Years	Avg. Biom. Dens. Removed (kg/ha/y)	Avg. Harvest Index	Carp Barrier	Pre DCI Rel.	Change in DCI Rel.
62000700	Gerv	No	2011	2012		9	14		No	15.81	0.00
62003802	WVad	No	2020	2023	30	1	5	0.00	Yes	15.81	-15.21
62004600	Plea	No	2022	2023	180	2	7	0.02	Yes	15.81	-11.13
62004800	Benn	No	2020	2021	114	3	26	0.03	Yes	15.81	-15.76
62005500	Como	Pre	2021	2022	294	2	3	0.15	No	0.00	0.00
62005600	Owas	No	2019	2020	116	7	11	0.12	Yes	15.81	-15.73
62006700	Long	No	2021	2022	492	7	203	0.86	Yes	83.97	-82.84
62008200	Waba	No	2019	2023	34	5	37	8.01	Yes	15.81	-15.77
70009100	Ceda	No	2022	2023		1	8		No	0.25	0.00
82016300	Clea	No	2019	2020	101	1	16	0.00	No	0.73	0.02
		Mean	2018	2020	308	3.0588	52	1.01		9.68	-7.24
		SD	3.72	3.866	262	2.388	59	2.03		16.16	15.55
		Med.	2019	2021	227	2	31	0.09		2.69	-2.33
		Min.	2009	2010	30	1	3	0.00		0.00	-82.84
		Max.	2023	2024	1133	11	239	8.01		83.97	0.02

Table 3. Lake management data for lakes with pre/post carp, water quality, or macrophyte data. DCI = Dendritic Connectivity Index. See Table 2 for full lake names. "Alum trt." is "Yes" for all lakes treated with alum during or after carp management, "Pre" for lakes treated with alum before management, and "No" for lakes that do not appear in the MPCA alum treatment database. "Carp Barrier" refers to whether carp barriers were installed during the management time period expressly for the purpose of blocking carp.

Lake Responses to Carp Management

Generally, lake responses to carp management matched expectations for carp biomass and water quality: Carp biomass, TP, and chlorophyll-a decreased, while Secchi depth, macrophyte richness, and floristic quality increased. However, these responses were highly variable by lake (Figure 7).

Changes in macrophyte frequency of occurrence (FOO) were also highly variable by lake and did not change significantly on average (Figure 7). Post-hoc analyses suggest the lack of a response in macrophyte FOO metrics could be related to 1) an overall negative relationship between pre-management FOO and change in FOO (Coefficient = -0.59, SE = 0.23, $p = 0.02$; linear model of Change in FOO ~ Pre-removal FOO with Gaussian normal error), where change would be less detectable at high pre-management FOO (as is common in many eutrophic lakes), and 2) relatively highly interannual variability in lake macrophyte FOO (SD = 0.11) (Appendix 1).

While there were large improvements to water quality in some lakes (e.g., two lakes decreased over 0.09 mg/L in TP and three lakes increased over 1 m in Secchi depth), most water quality and macrophyte responses were relatively small (Figure 7).

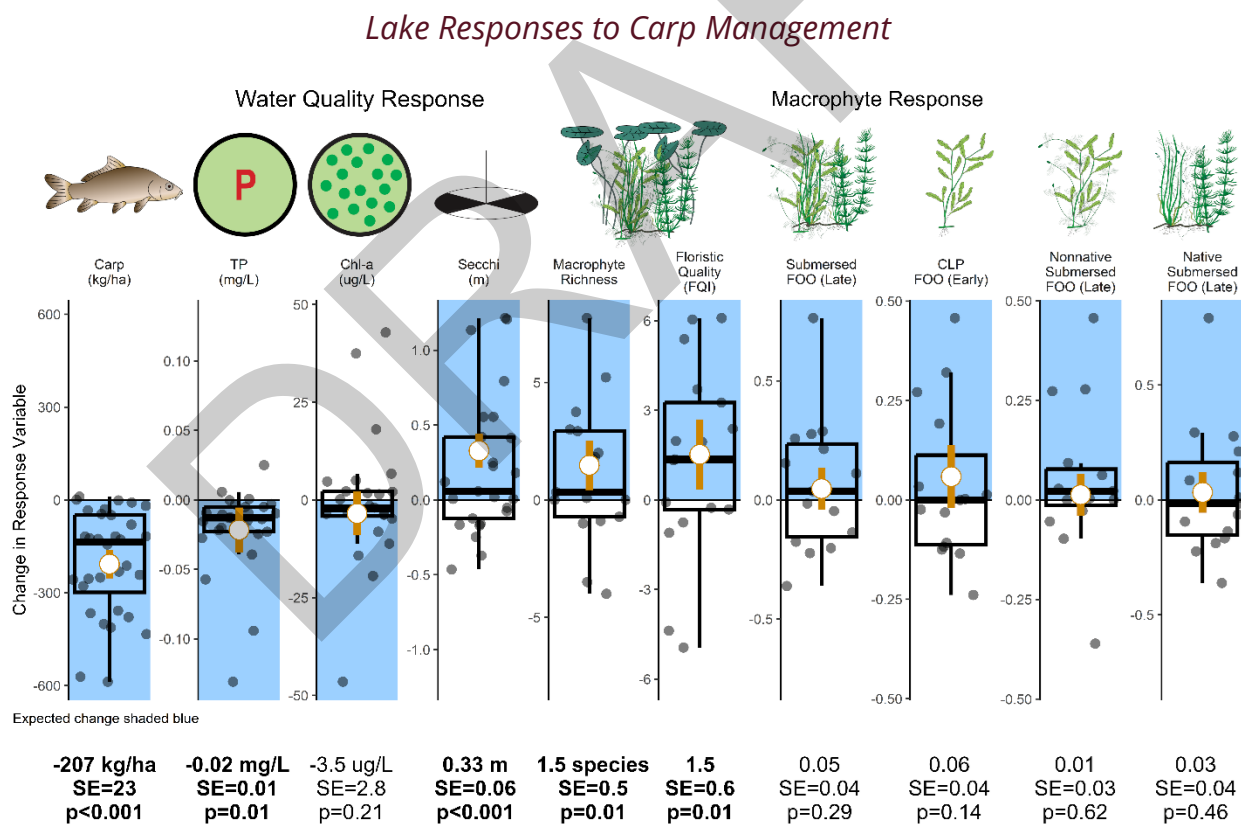


Figure 7. Lake responses to carp management are plotted as grey points behind box plots of that distribution and the estimates and 95% confidence intervals for average change in each variable are plotted in dark orange (estimated from the model in Equation 2). This estimated average change, standard error, and p -values (testing if the average change differs from zero) is also listed under each panel where bolded values are significant at $\alpha=0.05$ and italicized values at $\alpha=0.10$.

The median relative decrease in TP was 20%, and half of all lakes (the 25th percentile to the 75th percentile) fell within an 11% and 31% decrease. The median relative decrease in chlorophyll-a was small (9%) and variable, and half of all lakes fell within a 15% increase and a 59% decrease. The median relative increase in Secchi disk depth was also small (7%), and half of all lakes fell within an 8% decrease and a 33% increase.

As with absolute changes in macrophyte metrics, relative changes were small and variable. The median relative increase in macrophyte richness was 3.8%, and half of all lakes fell within a 10% decrease and a 50% increase. The median relative increase in floristic quality was 8%, and half of all lakes fell within a 3% decrease and 29% increase.

DRAFT

Drivers of Lake Responses to Carp Management

While the ability to explore drivers of lake responses to carp management using the models outlined in Equation 3 was limited to 15 lakes with full pre- and post-management data, preliminary results of a small number of drivers support anecdotes from discussions within the project team and other water resource managers (Table 4).

After accounting for the presence of alum treatments (which positively influenced Secchi depth, macrophyte richness, and floristic quality), management was more successful for TP and chlorophyll-a with larger relative reductions in carp biomass, more successful for chlorophyll-a with lower pre-removal carp biomass, and marginally more successful for chlorophyll-a in shallower lakes (Table 4).

Table 4. Drivers of Lake Responses						
				Driver Coefficients		
Response	B ₀	B _{alum}	Management Goal	B _{% reduction}	B _{pre biomass}	B _{mean depth}
TP (ug/L)	-35 (25)	5.1 (19)	Decrease	-0.47 (0.21)	0.03 (0.05)	2.6 (1.5)
Chl-a (ug/L)	-14 (9.0)	-7.2 (6.9)	Decrease	-0.24 (0.08)	0.06 (0.02)	1.1 (0.55)
Secchi depth (m)	0.23 (0.30)	0.65 (0.24)	Increase	0.00 (0.00)	0.00 (0.00)	0.00 (0.02)
Macr. Richness	2.3 (2.2)	4.3 (2.2)	Increase	-0.01 (0.03)	0.00 (0.00)	-0.09 (0.15)
FQI	2.1 (1.9)	3.7 (1.8)	Increase	-0.03 (0.02)	0.00 (0.00)	0.05 (0.13)
Subm. FOO (late)	-0.20 (0.17)	0.26 (0.16)	Increase	0.00 (0.00)	0.00 (0.00)	0.00 (0.01)
Table 4. Drivers of lake responses ("Response") are estimated from the models outlined in Equation 3 and model coefficients are represented below with standard errors in parentheses. Bolded coefficients are significantly different from zero at $\alpha=0.05$, and italicized coefficients at $\alpha=0.10$. Management goals are included to help interpret model coefficients, whereby a negative coefficient for a response variable where the goal is "decrease" is more successful as it represents a stronger decrease (as would be a positive coefficient for an "increase" goal) and a positive coefficient for a "decrease" goal is less successful as it represents a weaker decrease (as would be a negative coefficient for an increase goal). Management goals are meant to help with coefficient interpretation and do not represent all stakeholder goals.						

The most successful management projects generally reflect the importance of harvest intensity for TP (e.g., positive outliers in Figure 7).

The lakes with the two largest decreases in TP (-0.10 mg/L in Susan Lake, Carver County; -0.09 mg/L in Como Lake, Ramsey County) experienced highly successful carp removals (-82% and -95% biomass density, respectively).

These lakes were also treated with alum before carp removal management ("Pre" in Table 3).

Clarity, macrophyte richness, and floristic quality responded more positively when alum treatments occurred during or after carp management, though there were few alum treated lakes (N=4). Drivers were unrelated to response magnitude for both Secchi depth and macrophyte richness.

Ecological Relationships in Managed Lakes

On average, SEM coefficients were consistent with hypothesized ecological relationships (Figure 8). However, the models explained relatively small fractions of variation in response variables ($R^2_{\text{biomass}} = 0.05$, $R^2_{\text{TP}} = 0.03$, $R^2_{\text{chl-a}} = 0.05$, $R^2_{\text{Secchi}} = 0.26$, $R^2_{\text{FOO}_S} = 0.30$). The effect of the harvest index on carp biomass density was negative. Carp biomass had a relatively strong negative direct effect on submersed macrophyte FOO in both seasons, a negative effect on Secchi depth in the early (April – June) season, and a positive effect on TP in both seasons ("late" = July – September). The positive effect of carp on TP was stronger in the early season model. TP had a positive effect on chlorophyll-a in both seasons. Chlorophyll-a had a negative effect on Secchi depth in both seasons, but this effect was much stronger in the late season model. Secchi depth had a relatively strong positive effect on submersed macrophyte FOO in both seasons. Indirect effects of carp biomass on Secchi depth and submersed macrophyte FOO were small or insignificant in both models (Figure 8d). While the negative indirect effects

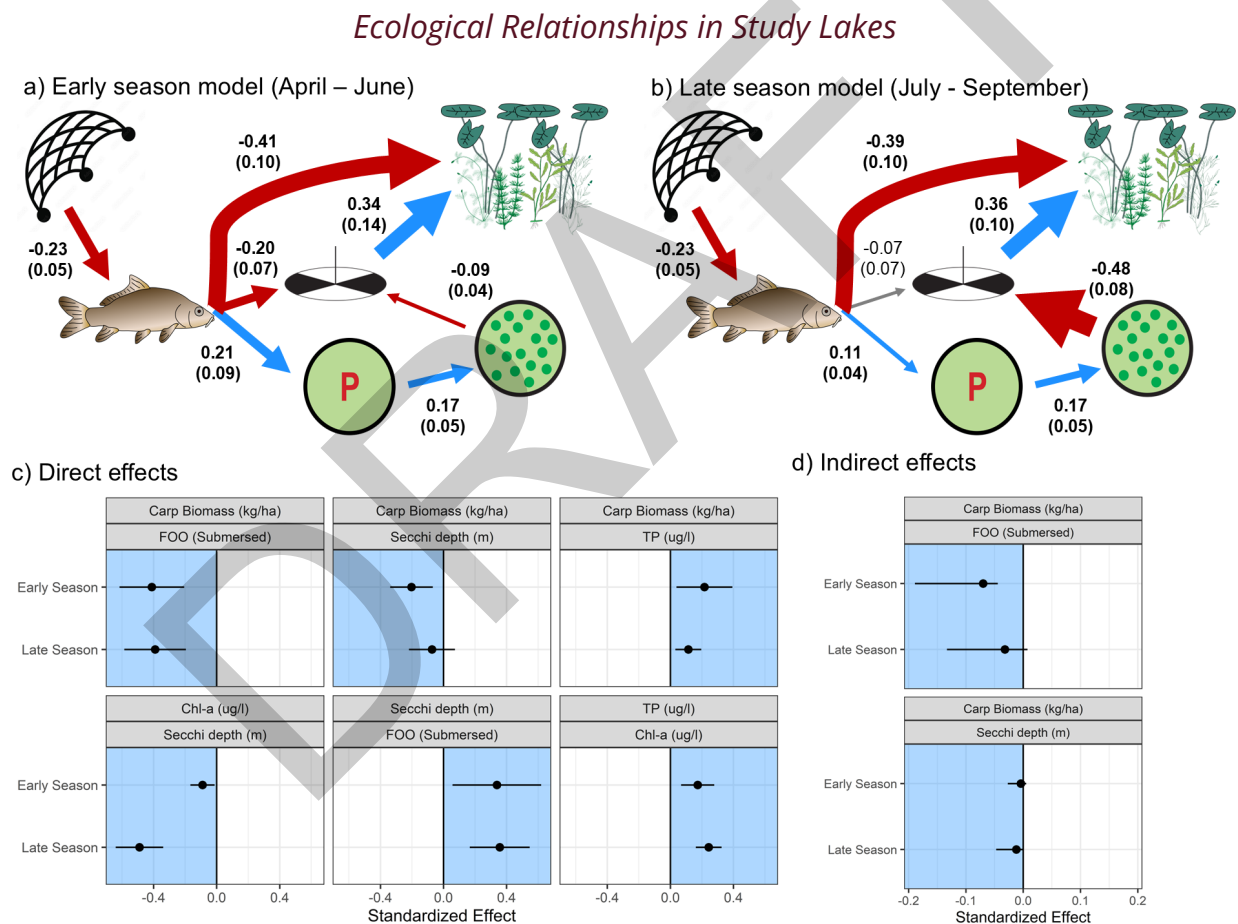


Figure 8. Ecological relationships in study lakes are represented by paths (a, path diagram for the early [April – June] season model; b, path diagram for the late [July – September] season model; dark red = negative effect, blue = positive effect, and grey = no effect, with arrow size scaled by effect size; effect size is also listed next to each arrow with standard error in parentheses) and with coefficient and 95% confidence intervals for interpreting significance (c, direct effects; d, indirect effects; panel title interpreted as the effect of the top strip on the bottom strip; early and late season models along the y-axis, and the standardized effect along the x-axis with blue shaded areas represented the expected effect).

of carp biomass on FOO in the early season and on Secchi depth in the late season were statistically significant, their magnitudes were much smaller than direct effects (-0.07 and -0.01, respectively).

Providing raw, unstandardized effect sizes (as opposed to the standardized effect sizes in Figure 8) can help ground coefficients in a variable's natural units. Unstandardized effects were used to compare SEM results with observed changes in response variables by multiplying each carp coefficient by -198 kg/ha, the average reduction in carp biomass density. The estimated direct effect of this reduction on TP and Secchi depth was small relative to observed change, and more certain relative to observed change for submersed macrophyte FOO (Table 5).

Table 5. Direct Effect of a -207 kg/ha Change in Carp Biomass				
	Early (April - June)		Late (July - September)	
Response Variable	SEM Response (95% CI)	Obs. Change	SEM Response (95% CI)	Obs. Change
TP (ug/L)	-12 (-23, -2.2)	-24 (-42, -6.3)	-7.0 (-12, -1.9)	-16 (-28, -3.0)
Secchi Depth (m)	0.19 (0.06, 0.31)	0.34 (0.16, 0.52)	0.04 (-0.04, 0.12)	0.28 (0.17, 0.40)
FOO_S	0.08 (0.04, 0.12)	0.08 (0.00, 0.16)	0.08 (0.04, 0.12)	0.05 (-0.04, 0.13)
<i>Table 5. Direct effect of a -198 kg/ha change in carp biomass on response variables (TP = total phosphorus in ug/L, Secchi Depth = Secchi disk depth in m, and FOO_S = submersed macrophyte occurrence in the littoral zone) estimated from the early (April - June) and late (July - September) season structural equation models (SEM Response) and compared to estimated average change (Obs. Change) using mixed effects models outlined in Equation 2.</i>				

To test for differing relationships between carp biomass and different submersed macrophyte taxa, two additional models were fit: the first splitting submersed macrophyte FOO into native and nonnative taxa, and the second splitting submersed macrophyte FOO into Eurasian watermilfoil, curlyleaf pondweed, and native taxa. Both models included an additional direct effect of nonnative taxa on native taxa.

These models revealed consistent negative effects of carp biomass on submersed native FOO, but insignificant effects on nonnative taxa FOO in both seasons. Eurasian watermilfoil had a significant positive effect on submersed native FOO in the early season model, but otherwise nonnative taxa FOO had no effect on native FOO (Table 6).

Table 6. Structural Equation Model Coefficients for More Resolved Macrophyte Taxonomic Groupings			
Model	Relationship	Early (Apr-Jun) Coefficient (SE)	Late (July-Sept) Coefficient (95% CI)
Native, Nonnative	Carp → Native	-0.27 (0.09)	-0.34 (0.09)
	Carp → Nonnative	-0.16 (0.16)	-0.16 (0.16)
	Nonnative → Native	0.17 (0.10)	0.11 (0.11)
Native, EWM, CLP	Carp → Native	-0.26 (0.09)	-0.37 (0.09)
	Carp → EWM	-0.09 (0.09)	-0.10 (0.10)
	Carp → CLP	-0.11 (0.11)	-0.26 (0.00)
	EWM → Native	0.28 (0.11)	0.15 (0.10)
	CLP → Native	0.08 (0.09)	-0.09 (0.11)
<i>Table 6. Structural equation model coefficients for more resolved taxonomic groupings where submersed macrophyte FOO was split into native and nonnative submersed FOO, and native submersed, Eurasian watermilfoil, and curlyleaf pondweed FOO in two additional models with structures that include direct carp biomass effects on each taxonomic group and direct effects of nonnative on native FOO but otherwise follow Equation 5.</i>			

Post-hoc tests of directed separation were conducted to explore potential missing pathways in the SEMs (Table 7). Failed independence claims between TP and Secchi depth, and TP and submersed macrophyte FOO were notable for low p-values in both models. Adding these to the early season model reveals a marginally significant, weak negative effect of TP on Secchi depth (-0.09, $p=0.06$) and an uncertain effect on FOO (-0.46, $p=0.14$). Adding these to the late season model reveals a significant negative effect of TP on Secchi depth (-0.17, $p=0.02$) and a significant strong negative effect on FOO (-0.59, $p=0.01$).

Table 7. Tests of Directed Separation for SEMs		
Independence Claim	p-value Early (Apr-Jun)	p-value Late (Jul-Sep)
TP ~ Harvest Index	0.98	0.45
Secchi ~ Harvest Index	0.10	0.00
FOO_S ~ Harvest Index	0.84	0.21
Chl-a ~ Harvest Index	0.87	0.39
Chl-a ~ Carp Biomass	0.47	0.03
Secchi ~ TP	0.06	0.02
FOO_S ~ TP	0.14	0.01
Chl-a ~ FOO_S	0.05	0.19
<i>Table 7. Tests of directed separation for SEMs (early and late season) are presented with p-values and significance at $\alpha=0.05$ (bold) and $\alpha=0.10$ (italic). Unmodeled relationships used for directed separation tests are listed as "Independence Claims".</i>		

Discussion

The project team evaluated lake responses to common carp management, the drivers of those responses, and the ecological assumptions behind them. On average, carp biomass decreased and water quality and macrophyte diversity improved as expected, but the magnitude of these changes varied widely across lakes.

Despite this variability, most relationships between drivers and responses aligned with ecological hypotheses: carp management appeared to have the strongest effects on early season (April–June) water quality, while late season (July–September) water quality was likely influenced by other factors such as input of legacy phosphorus from sediment. Structural equation models (SEMs) also suggested relationships were dominated by direct effects (e.g., carp directly reducing macrophyte FOO), rather than indirect effects (e.g., carp indirectly reducing macrophyte FOO through reduced clarity), though these models were somewhat limited in explanatory power (e.g., $R^2[\text{FOO}_S] = 0.31$) and may be missing ecological pathways.

Overall, the results suggest carp management can produce positive but variable water quality outcomes and more nuanced macrophyte responses.

Large improvements are unlikely in highly impaired lakes, but smaller-scale changes—such as a 22 µg/L TP reduction, the average observed response—could still provide meaningful benefits for lakes near State standards.

In the context of this high variability, the team developed a foundation for predictive modeling and highlighted preliminary considerations for project success (e.g., greater success with a greater reduction in carp biomass or greater success in shallower lakes), including potentially synergistic effects of multiple management strategies (e.g., concurrent alum treatments). Prediction of management outcomes could improve with more pre- and post-management data, a broader understanding of lake connectivity to carp spawning habitat, and consideration of potentially important missing variables such as total suspended solids, nitrogen, and nutrient loading dynamics. However, the underlying complexity, variability, and interconnectedness of lake socioecological systems will likely always contribute to uncertainty in generalizing carp management outcomes across lakes, seasons, and years, especially in observational experiments and studies such as these (Abell et al. 2022; Cianci-Gaskill et al. 2024).

Main Findings

Water Quality

On average, lake water quality improved when carp biomass was reduced, which follows with hypotheses regarding carp disrupting sediment and resuspending nutrients as well as with past studies (e.g., Bajer and Sorensen 2015). However, large positive outcomes were only observed in a handful of lakes. These lakes tended to have relatively large reductions in carp biomass density with management, which positively influenced TP and chlorophyll-a outcomes. While more data could resolve some of this uncertainty and even support more predictive models, these early results suggest lake water quality responses to common carp removal will be complex, reflecting the complexity of lake ecosystems and results from past multi-lake studies of carp removals (e.g., Sweet and Beck 2024) and lake water quality management (Strom et al. 2024).

This study also highlights seasonal complexity in drivers of water quality. Carp biomass had a strong negative effect on clarity in the early (April – June) season SEM, but weak effects in summer (July – September) when the effect of chlorophyll-a on clarity was strong and negative. This could reflect seasonal changes in carp activity (e.g., early season spawning) and drivers of water quality (e.g., high internal nutrient loading in the late season).

Carp biomass had a strong negative effect on water clarity in the early season. However, it had weak effects in the late season, when the effect of chlorophyll-a on clarity was strong and negative.

This demonstrates seasonal differences and complexity in drivers of water quality.

Also, carp only weakly affected clarity indirectly through the TP-chlorophyll-a-Secchi pathway. Indeed, the low explanatory power of the models (R^2 from 0.03 to 0.30, and $R^2 = 0.26$ for Secchi depth) suggests while average patterns that match hypotheses were observed, the strength, direction, and overall topology (e.g., nodes and arrows in Figure 3 and Figure 1) of the drivers of water quality and macrophytes is complex and likely variable over time and between lakes.

Understanding how water quality drivers vary across these dimensions would support integrated lake management (i.e., management that considers all the ecological aspects of a lake and its watershed).

Taking an Integrated Approach

MCWD found carp removal from Wassermann Lake improved clarity in the early season but did not change late season clarity. Following carp removal, MCWD conducted alum treatments, which has led to improvements in late season clarity (Sweet and Beck 2024).

This case, as well as this study's results, suggest carp removals may be most effective in improving water quality in spring and early summer, while other approaches such as alum treatments and external nutrient load reductions may be required for managing clarity in late summer and early fall.

Wassermann Lake alum treatment. Credit: Minnehaha Creek Watershed District



SEMs suggested the direct effects of carp biomass reduction were often smaller than observed changes in water quality: The direct effect on TP was roughly half the observed change in both seasons, roughly half the observed change in early season Secchi depth, and much smaller than the observed change in late season Secchi depth (Table 5). This difference could have both statistical and ecological implications for interpreting results.

SEM coefficients are modeled using hypothesized causal relationships, but they are still correlative estimates of variable effect sizes and should be interpreted with the same caution used for inferring causation from correlation, especially given the complex and interconnected nature of variables influencing lake water quality. Also, since models only explained a small portion of variation in response variables, SEM coefficients are only providing a piece of the full ecological picture in carp managed lakes.

As a result, differences between modeled and observed results could be due to unmodeled ecological interactions. For example, since the indirect effects of carp biomass were predicted to be too small to account for the difference between predicted and observed change, this could imply that biomass does not fully capture the effect of carp on water quality or that other changes in the system (e.g., alum treatments or implementation of other nutrient management projects) could also be driving changes in water quality.

Preliminary results with a small sample size suggest integrated lake management—considering all ecological aspects of the system and using watershed nutrient load reduction (e.g., lakes with an approved TMDL plan, though these plans may not necessarily include external load reduction efforts), internal nutrient load reduction (e.g., alum treatments), and carp management—was associated with more successful outcomes (Table 4; Figure 9 re-summarizes responses alongside other management in lakes with pre/post data for all metrics). This result is consistent with past studies on water quality change in Minnesota (Strom et al. 2024).

Preliminary results suggest integrated lake management approaches were associated with more successful water quality outcomes.

For example, alum treatments are often conducted after carp biomass reductions, and this study found more positive outcomes in a small sample ($N = 4$) of alum treated lakes (Table 4). Yet, relatively little is known about how lake water quality and biological communities respond to multiple lake management activities. A similar study with more lakes with different combinations of strategies could be an important step toward conducting and evaluating lake management holistically in an integrated framework.

Lake Responses to Carp Management and Co-Occurrence of Other Management

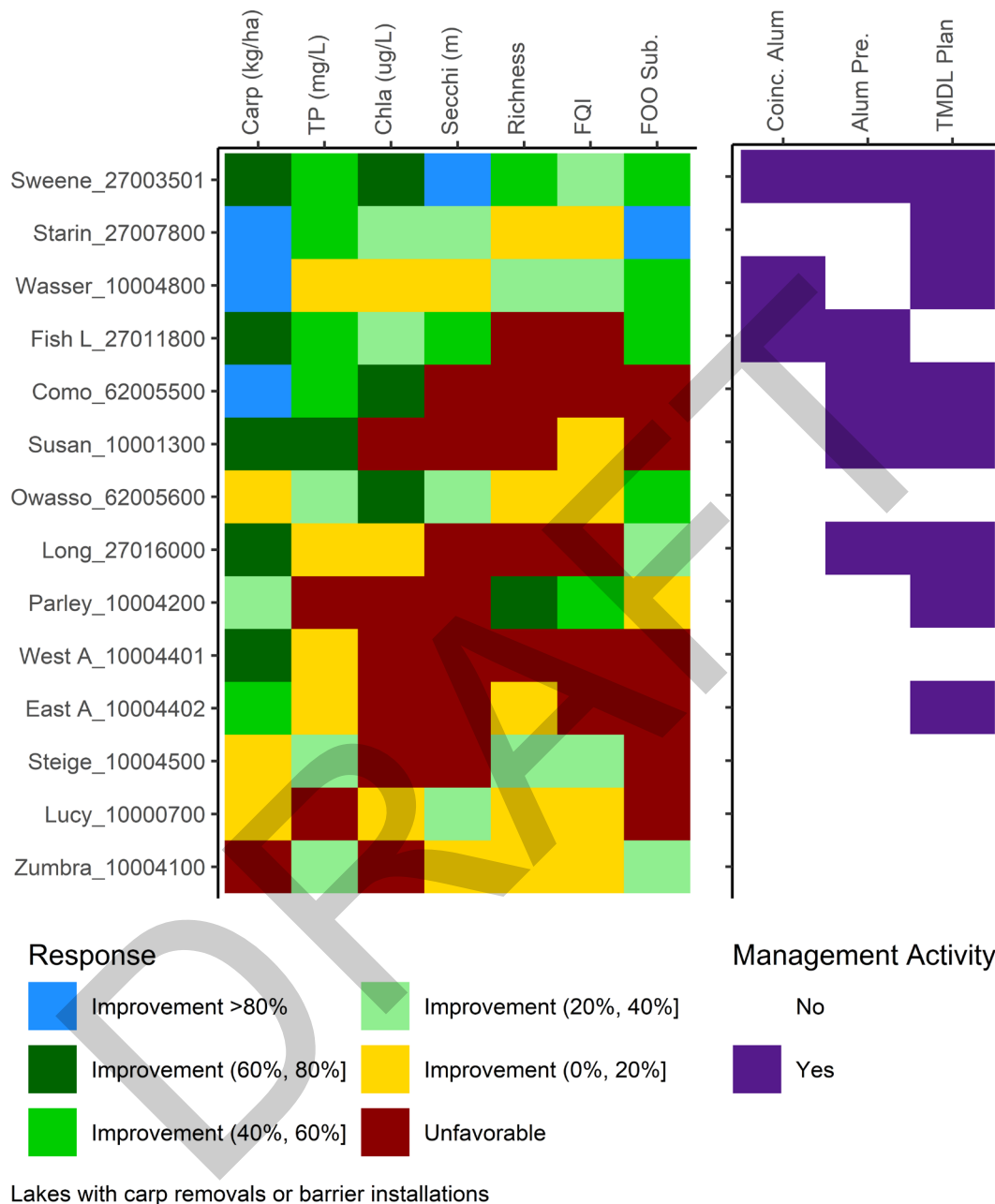


Figure 9. Lake responses to carp management and co-occurrence of other management are plotted using filled colored boxes. Lakes are organized by their overall (carp, water quality, and macrophyte community) response along the y-axis. Lake responses (relative percent change in target variables along the x-axis) are more successful with cooler colors (blue and darker greens), less successful with warmer colors (lighter greens and yellow), and unsuccessful with red (i.e., percent change was in an unfavorable direction). Other management activities include "Coinc. Alum" for lakes with coincident alum treatments during or after carp management, "Alum Pre." for lakes with alum treatments before carp management, and "TMDL Plan" for lakes with MPCA approved total maximum daily load plans (does not necessarily imply that external loading reductions have occurred), which can include a range of internal and external water quality management projects (purple indicates these activities occurred, white indicates they did not).

Macrophytes and Floristic Quality

On average, macrophyte diversity increased by 1.5 species and floristic quality increased by 1.5 with management. However, there were no consistent changes in macrophyte FOO, which contrasted with relationships estimated from SEMs, where carp biomass had a significant negative direct effect on macrophyte abundance.

On average, macrophyte diversity and floristic quality increased with carp management.

However, management did not result in consistent changes in macrophyte frequency of occurrence.

Many of the raw effect sizes of the SEMs were small (e.g., SEM prediction of +0.08 FOO with the observed reduction in carp biomass, roughly equal to the uncertain observed changes) and within the average annual variation of FOO in lakes ($SD=0.11$), which could make detecting average change in FOO challenging (Appendix 1). This was especially true for the indirect effects of carp on FOO via water clarity, which were estimated to be very small (Figure 8d) and suggest carp may have a stronger effect on submersed macrophyte directly (e.g., dislodging plants) than indirectly (e.g., reducing clarity by resuspending sediment and nutrients).

Other factors could lead to similar discrepancies between observed change and modeled relationships. For example, increasing FOO is generally anticipated with carp management and can be considered a nuisance, especially with increasing nonnative FOO (Lathrop et al. 2013; Bartodziej et al. 2017). Managing aquatic plants in response to carp management could weaken FOO responses observed here.

Contextualizing Results for Carp Management

Common carp management is often implemented to make progress toward meeting State standards for TP, chlorophyll-a, and Secchi depth. Similar targets have also been developed for carp biomass, macrophyte richness, and floristic quality (Bajer et al. 2009; Radomski and Perleberg 2012). These targets provide relevant context for our results. To explore this context further, the data was scaled to be centered to the State standards and bounded by the worst and best lakes for each metric, where meeting a standard is a scaled value of 1, meeting or below the average of the bottom 5% is a value of 0, and meeting or exceeding the average of the top 5% is a value of 2 (Appendix 2). Subtracting the pre-management average scaled value from the post-management average scaled value provides a measure of how a variable in a lake moved toward or away from a standard with management.

On average, carp biomass moved 0.47 (SE=0.04) points toward the standard, TP moved 0.22 (SE=0.03), chlorophyll-a moved 0.14 (SE=0.03), Secchi depth moved 0.15 (SE=0.03), macrophyte richness moved 0.15 (SE=0.05), and floristic quality moved 0.12 (SE=0.05) (Figure 10). So, if a lake was near the State TP standard with a pre-management scaled value of 0.78, then the average response of 0.22 would bring it to the standard. Considering that 75% of lakes had a scaled TP value of 0.75 or higher, this change would be meaningful in most cases (i.e., the 25th percentile was 0.75 and the 75th percentile was 1.1, which spans 50% of all lakes). Lake Secchi depth responses were smaller when scaled to the State standard (0.15 points toward the standard versus a raw change of +0.3 m). Even so, 50% of lakes had a scaled Secchi value of 0.91 or higher, so the average increase of 0.15 points would be meaningful in most lakes.

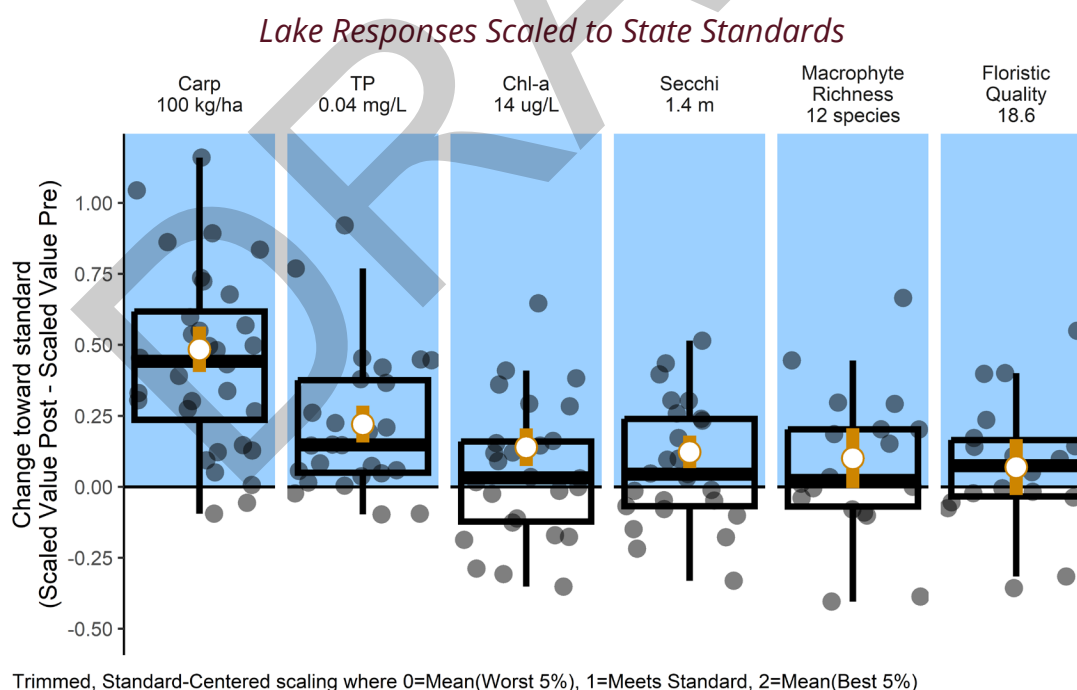


Figure 10. Lake responses scaled to State standards are plotted as grey points behind box plots of that distribution and the estimates and 95% confidence intervals for average change in each variable are plotted in dark orange (estimated from the model in Equation 2). Pre/post scaled values are scaled using trimmed, standard-centered scaling, and the difference between pre and post is used as the change toward standard y-axis value.

Table 8. Comparing Results to State Standards and Pre-Management Conditions

Variable (Standard)	Data	Lake Pre-Management Conditions					Estimated Change
		10th	25th	Median	75th	90th	
TP (40 ug/L)	Raw	166	119	66	41	29	-22
	Scaled	0.62	0.75	0.94	1.1	1.6	+0.22
Chl-a (14 ug/L)	Raw	71	43	29	13	5.7	-3.5
	Scaled	0.54	0.77	0.88	1.2	1.6	+0.14
Secchi (1.4 m)	Raw	0.66	1.1	1.4	2.0	2.6	+0.33
	Scaled	0.33	0.74	0.91	1.2	1.4	+0.15
Richness (12 species)	Raw	4.0	4.6	7.1	11	14	+1.5
	Scaled	0.19	0.25	0.51	0.89	1.3	+0.15
FQI (18.6)	Raw	7.5	8.1	14	17	20	+1.5
	Scaled	0.20	0.25	0.67	0.89	1.3	+0.12

Table 8. Comparing results to deep lake State standards (listed below each variable row) and pre-management conditions (presented as both raw and scaled values in the "Data" column). Scaled values are centered on 1 (meets standard) and bounded by 0 (equal to or below the average of the bottom 5% of lakes) and 2 (equal or exceeding the average of the top 5% of lakes). The distributions of the raw and scaled values are from pre-management averages of all lakes (e.g., Median = variable in the 50th percentile of all lakes before carp management). Changes are estimated from the models in Equation 2 (e.g., orange open circles from Figure 7 and Figure 10).

Ultimately, managers will need to consider historical water and floristic quality conditions in their lake and the variability in the response of each metric (e.g., Figure 7, Figure 10) when using these results to help determine whether carp management could help them progress meaningfully toward goals and State standards (e.g., Table 8).

Managers will need to consider historical conditions in their lake to determine whether carp management could meaningfully improve water and floristic quality.

This study's results suggest lakes near State standards are likely better candidates for carp management, especially if other drivers have already been addressed.

Consistent with past studies finding that meaningful water quality improvements are most common for lakes near State standards (Strom et al. 2024), this study's results suggest lakes already near State standards are likely better targets for carp management than more impaired lakes, especially in cases where other drivers of impairments have already been addressed. For example, a 22 µg/L TP reduction will likely result in a more meaningful improvement in eutrophication response variables (chl-a and Secchi) in a lake that is starting at 60 µg/L compared to 200 µg/L.

Key Takeaways

Expect Limited and Variable Lake Responses

- **Water quality outcomes were often positive, but variable.** Smaller-scale improvements can be meaningful for lakes near State standards, which may be ideal targets for carp management.
- **Seasonal differences are likely.** Carp may have a stronger effect on water quality in the early season, while managing late season (July – September) water quality may require more direct nutrient management.

Invest in Monitoring to Evaluate Projects and Support Understanding

- Monitor response variables before, during, and after carp management. These data are valuable for evaluating project success and contribute to broader research.
- Monitoring data that sufficiently characterizes conditions before and after management is essential for variables with high year-to-year variability (e.g., macrophyte FOO). Understanding natural variability helps design monitoring programs with adequate power to detect management effects.
- This study focused on TP, chlorophyll-a, Secchi depth, and macrophyte occurrence. Future work should consider additional variables like total suspended solids, nitrogen, nutrient loading, and species-specific macrophyte data to better understand lake responses.

Future Directions

Progress Toward a Sustained State Carp Management Database

Synthesizing data on lake responses to carp management allowed for broader scale understanding than previous studies focusing on single lakes or lakes within a single district. This study's approach 1) provided support for carp management as a tool to manage water quality while also providing important context regarding variable lake responses to such management and 2) helped to verify the ecological relationships hypothesized to underpin the adverse effects of excess carp biomass. Additional data could improve capacity for predictive modeling to help set data-driven expectations and prioritization schemes for carp management projects. Many of the carp management projects included in this study are ongoing and post-management data will be collected in the coming years. Such work could help fill gaps in the data assembled here (Table 1).

In the near term, it will be important to consider the long-term sustainability of a centralized carp management database, including who should be responsible for hosting and maintaining it, how the lake management community can develop processes to support it with data and expertise, and whether a follow-up analysis with more data would be worthwhile to better inform carp management as a lake management tool. Such an analysis could also help to identify specific research questions that could be addressed with experimentation leveraging existing and planned carp management projects.

Exploring Underlying Complexity of Ecological Relationships

If aquatic plant management to address nuisance conditions is commonly conducted after carp removals, then observed changes in FOO could be smaller than expected based on the relationship between carp and macrophytes. In Minnesota, total macrophyte harvest is limited to 50% of the lake littoral area, and herbicidal application to 15% of the lake littoral area without special aquatic plant management ("APM" or, for invasive plants, "IAPM") permitting variances. Management at these scales—or even beyond with lake vegetation management plans that include carp management and a permitting variance—could influence results here. MAISRC Subproject 64 (led by Walsh) will collate, centralize, and make publicly available APM/IAPM permitting and management data. Exploring APM and IAPM with carp management (and potentially alum treatments) could be a valuable contribution to the project. Such an analysis could benefit APM/IAPM, especially since carp seem to have differential impacts on native and nonnative macrophytes here and elsewhere (Larkin et al. 2020).

In the SEMs, carp biomass had differential effects on native and nonnative macrophytes, which has been found in past studies (Larkin et al. 2020) and suggests more in-depth community analysis could be informative. In particular, the PI survey data used here includes more detailed taxonomic resolution and abundance estimates (i.e., rake ratings, sometimes biomass), which could improve understanding of whether some macrophyte species, especially those with high degrees of conservatism, recover with management. Continuing to collect and centralize point-intercept surveys will be important for such an analysis as these are still relatively rare in the dataset assembled here (the median lake has 3 post surveys and 11 pre surveys; Appendix 1). Point-intercept surveys can be cleaned, standardized, and centralized using the "Submissions" tab in the MAISRC PI Charter online app (https://university-of-minnesota.shinyapps.io/pi_charter/).

Potential missing pathways were also identified in the simplified model of carp management and ecology (Figure 1). Specifically, SEM post-hoc tests of directed separation suggested relationships between TP and Secchi and TP and FOO_S could be missing pathways. While TP does not directly affect Secchi depth, TP could represent TP in particulate matter such as suspended sediment or algae not fully captured by chlorophyll-a that do directly affect Secchi depth. Similarly, water column TP could also influence FOO indirectly via clarity as described or represent changes in lake biogeochemistry that might directly influence macrophytes. For example, excess nitrogen has been shown to limit plant growth in lake mesocosm experiments (González Sagrario et al. 2005), and carp removal can increase nitrogen removal in lakes (Ginger et al. 2017; Jeppesen et al. 2025). The MAISRC Lab to Lakes Initiative is evaluating lake responses to common carp management (lake response evaluation led by Walsh in MAISRC Subproject 65). In partnership with the UMN Finlay Lab, this work will include additional nitrogen and macrophyte sampling to explore this relationship further. The lake response evaluation will also include measuring total suspended solids and changes in lake sediments and could benefit from a better understanding of the role of total suspended solids in water and floristic quality responses. These data are relatively accessible (e.g., via MPCA) and an updated SEM analysis could provide valuable context for the Lab to Lakes Initiative in addition to answering lingering questions of this study.

Carp Habitat Connectivity

This study provided an approach and supporting dataset to investigate the role of aquatic habitat connectivity in carp management. Carp are dependent on connections between feeding and spawning habitats, and disrupting these connections with barriers is an important management strategy. A dendritic connectivity index (DCI) was calculated for each of the lakes before and after carp management. A key advantage of the index is that it depends on widely available geospatial data. As a result, the project team was able to calculate DCI for most of the study lakes, which decreased with barrier installation, often by nearly 100%. While there was limited statistical power to include DCI as a predictor in the management outcome analysis, such an analysis would be informative as this dataset expands.

Further, this study provides several examples of complex, interconnected lake systems that could provide valuable case studies for examining the role of connectivity and its management in driving carp management outcomes. Such an examination could 1) evaluate DCI to determine if it provides a meaningful and relevant representation of connectivity for carp movement and spawning and 2) determine whether additional connectivity and carp movement data should be collected with carp management projects, as well as whether these data could be standardized for synthetic study (e.g., score and weight connections by their importance as a potential spawning location). The DCI tool could also be used to evaluate and weigh the impact of barriers on native fish populations.

Considerations and Interpretations for Lake Managers

Defining Success for Carp Management

It is important to remember successful carp management is not solely defined by a large reduction in a lake's carp biomass. Successful lake restoration through carp management must be defined by the changes in a lake's water and/or floristic quality, following carp biomass reductions.

This study's results have demonstrated carp management can improve lake water quality, **but the benefits are most meaningful in shallow systems already near the State phosphorus standard**. Deeper lakes showed weaker responses, likely because carp influence a smaller portion of the lake.

On average, lakes saw a total phosphorus reduction of about 22 µg/L following carp management.

This is meaningful for lakes with initial total phosphorus concentrations of 50-70 µg/L, but it is less impactful for lakes starting well above 80 µg/L before management.

While these averages help define what success looks like, they also mask considerable variability across lakes, prompting an exploration of the factors behind that variability.

For aquatic plants, responses were mixed: **macrophyte richness and floristic quality increased slightly, but overall frequency of occurrence rarely showed clear change**. These changes to aquatic plants following carp management were inconsistent and variable across lakes, prompting considerations for further research.

Factors that Influenced Success

- Projects that achieved large proportional reductions in carp biomass saw the strongest improvements in phosphorus and chlorophyll-a.
- Shallow lakes may respond more than deep lakes, possibly reflecting carp's greater influence in littoral areas.
- These findings align with other studies showing the negative impacts from carp are most pronounced in shallow, nutrient-rich systems.

In short, **success depended on starting conditions and the intensity of removal**, with the largest gains occurring where both factors worked in favor of management.

Factors that Led to Poor Outcomes

- Some lakes showed little or no improvement, often due to conditions beyond carp control. In deeper lakes, carp effects may have been diluted relative to water volume.
- In systems with strong internal phosphorus loading, spring clarity gains from carp removal often disappeared by late summer as algae and nutrient release from sediments dominated.
- Incomplete removals or concurrent plant management efforts (e.g., herbicide treatments) may have further limited measurable vegetation recovery.

These cases highlight that **carp management alone is not a silver bullet and should be paired with other strategies**, where nutrient loading or depth constraints limit its effectiveness.

Lake Management Conclusions

Overall, carp management can be a valuable tool, but its outcomes depend on lake characteristics, project design, and additional management strategies.

Managers should **calibrate expectations to a lake's condition**: because positive results are often marginal, shallow lakes already near State standards are strong candidates, while deeper or heavily impaired systems will likely require broader nutrient control efforts.

The **most effective projects combine carp removal with integrated management approaches**—such as watershed nutrient reduction, internal load management (e.g., alum), and connectivity barriers—as lasting restoration requires more than a singular strategy (Strom et al. 2024).

Strategically Prioritizing Integrated Management

Lakes are complex, unique systems, and as such, there is no “one size fits all” management plan for restoration. Rather, a **data-driven prioritization of multiple, tailored strategies is important** to achieve lasting benefits. This typically begins with assessing a lake's external to internal nutrient loading ratio.

The underlying driver of in-lake issues, such as degraded ecology and poor water quality, is often caused by changes to the landscape that increase external nutrient loading (e.g., development, agriculture). If a significant proportion of a lake's nutrient loading comes from external sources, rather than internally, watershed nutrient reduction strategies should be prioritized (MPCA 2020).

“Unless external loading has been adequately addressed, in-lake treatment will have short-term benefits at best” (MPCA 2020).

Therefore, managers should consider in-lake strategies in the context of a comprehensive lake management plan that strategically incorporates methods to address both watershed and in-lake nutrient loading (MPCA 2020). **Once a lake system's underlying issues from external sources are addressed, in-lake management, including carp management, should be considered to maximize and sustain improvements.**

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Appendix 1: Detecting Change in Macrophyte Occurrence

We conducted two post-hoc analyses to explore the challenges associated with detecting change in macrophyte FOO: 1) we evaluated the relationship between change in FOO and pre-removal FOO and 2) we explored average within-lake interannual variability in FOO. The magnitude of the submersed FOO response was related to pre-carp removal FOO (Coefficient = -0.59, SE = 0.23, $p = 0.02$; linear model of Change in FOO ~ Pre-removal FOO with Gaussian normal error). As a result, detecting changes in FOO would be more likely in lakes with low pre-removal FOO. The average interannual variability in FOO was relatively high in the lakes surveyed (SD = 0.11) (Figure A1- 1). This relationship and underlying variability may make detecting changes in FOO challenging, especially in lakes with high pre-removal FOO where an increase in FOO would be estimated from an already high baseline.

To briefly demonstrate the relationship between statistical power and underlying variability, we visualized results of a power analysis for detecting differences between two means using a two-sample t-test (Figure A1- 1). It should be noted that this test assumes independence and years are temporally autocorrelated within pre- and post-carp removal groups. The test also assumes equal sample sizes and pre-removal data is more well-represented than post-removal data. So, we caution that these results are for illustration and should not be used to design macrophyte monitoring around a carp removal. The median lake had 11 years of pre-management data and 3 years of post-management data. Assuming a power of 0.8 and an alpha of 0.05, sample sizes of 11 and 3 are large enough to detect a change of 0.14 and 0.34 for a lake with average annual variability (SD=0.11) and large enough to detect a change of 0.28 and 0.68 for a lake with high annual variability (SD=0.22).

Underlying Variability in Submersed Macrophyte FOO Response

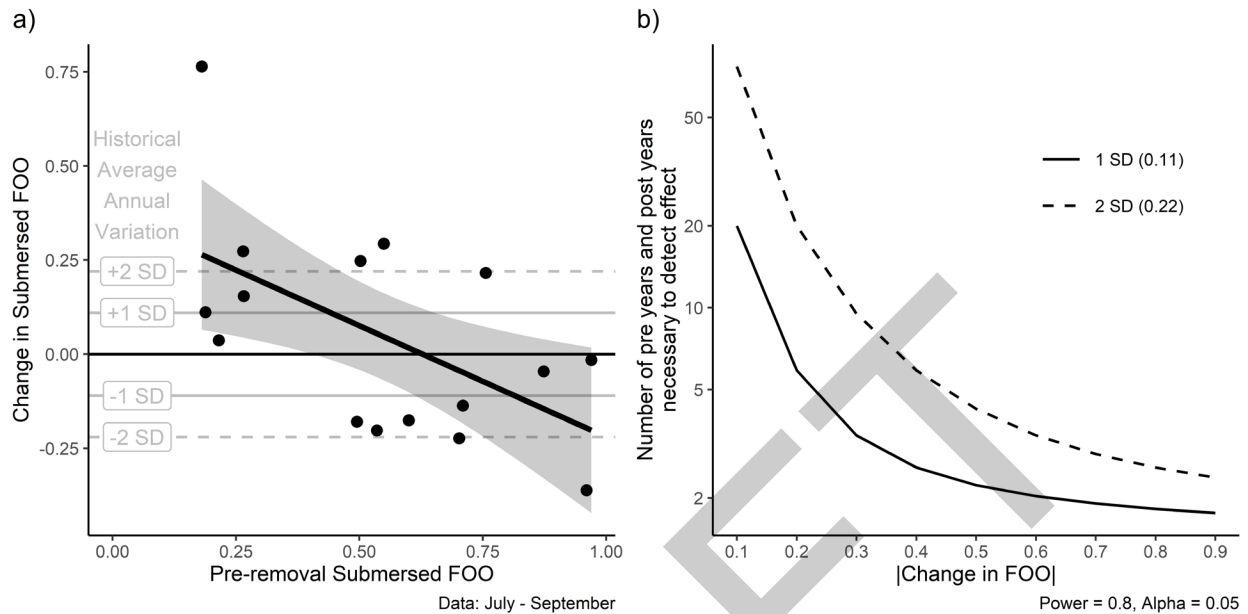


Figure A1-1. a) The underlying variability in submersed macrophyte FOO response can be partially explained by pre-carp removal submersed FOO where lake responses were highest when pre-FOO was lowest (black regression line with grey 95% CIs). Historical (pre-management) average annual variation across lakes is represented by grey solid (1 standard deviation = 0.11) and dashed (2 standard deviations = 0.22) lines. b) Results from a power analysis exploring the relationship between the data required to detect change (number of pre and post years on the y-axis) and the size of the change (absolute change in FOO on the x-axis) for a lake with average (solid line, 1 standard deviation) and exceptional (dashed line, 2 standard deviations) annual variability in FOO.

Appendix 2: Lake Responses Relative to State Standards

To contextualize lake responses in terms of State standards and other goals, we scaled response variables to standards. We used State standards for lakes in the region (MN Ecoregion “2B” or “North Central Hardwood Forest”; 40 ug/L TP, 14 ug/L chlorophyll-a, and 1.4 m Secchi depth) and similar goals for carp biomass (100 kg/ha; Bajer et al. 2009) and macrophyte richness and floristic quality (12 species and 18.6 FQI; Radomski and Perleberg 2012). We tested three different scaling methods: 1) “basic” scaling where 0 is the worst observed value for a given variable and 1 represents meeting or exceeding standards, 2) “trimmed” scaling where 0 is the average of the bottom 5% worst observed values (lake years) and 1 represents meeting or exceeding standards, and 3) “trimmed and standard-centered” scaling where 0 is the average of the bottom 5% worst observed values, 1 represents meeting the standard, and 2 is the average of the top 5% best observed values. The method of scaling has important implications for interpreting results (Figure A2- 1, Figure A2- 2). We selected the “trimmed and standard-centered” approach because the “basic” and “trimmed” approaches truncate a score such that lakes that exceed a standard count the same as those that meet it, while the “trimmed and standard-centered” approach allows such cases to take on a value between 1 and 2 (Figure A2- 1).

Effects of Data Scaling on Response Variables

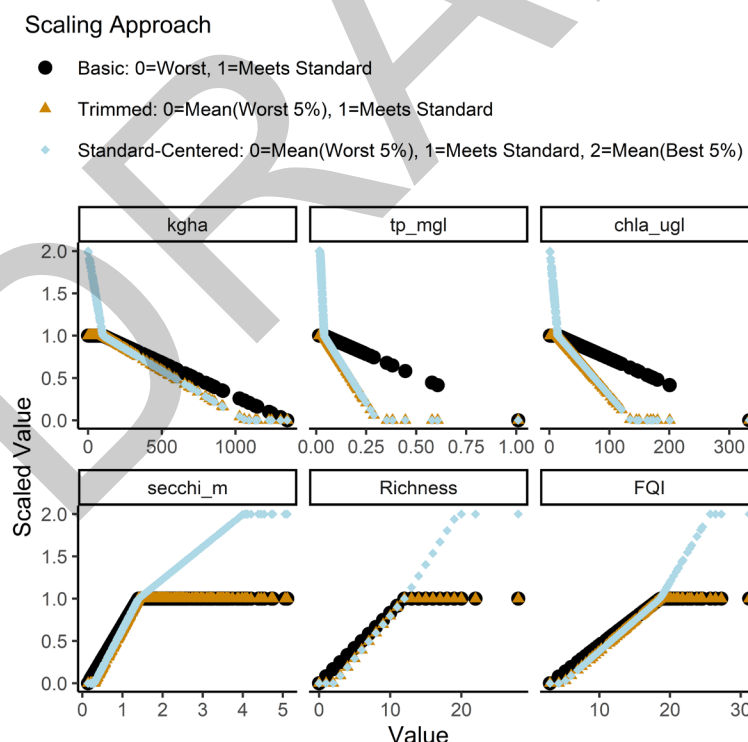
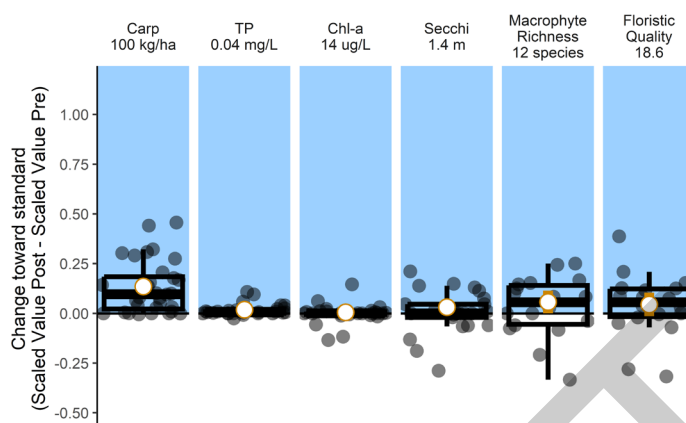


Figure A2-1. Effects of data scaling on response variables are shown by plotting the raw value (x-axis, units in panel strips) against the scaled value (y-axis). The scaling approach described in more detail in Appendix 1 is represented by differently colored and shaped points (Basic = black circles, Trimmed = dark orange triangles, and Standard-Centered = light blue diamonds).

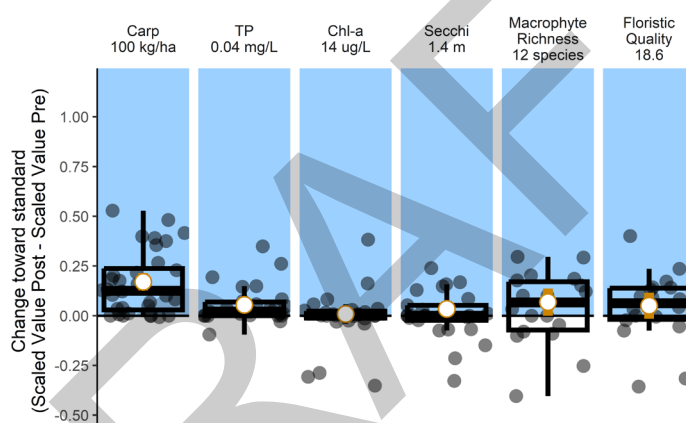
Figure 10 Results Plotted for Each Scaling Method

a) Basic scaling



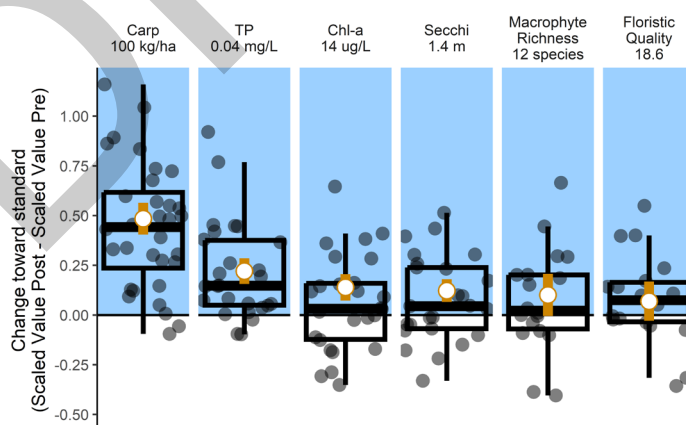
Basic scaling where 0=Worst, 1=Meets Standard

b) Trimmed scaling



Trimmed scaling where 0=Mean(Worst 5%), 1=Meets Standard

c) Trimmed and centered scaling



Trimmed, Standard-Centered scaling where 0=Mean(Worst 5%), 1=Meets Standard, 2=Mean(Best 5%)

Figure A2-2. Figure 10 results plotted for each scaling method. Lake responses scaled to State standards are plotted as grey points behind box plots of that distribution and the estimates and 95% confidence intervals for average change in each variable are plotted in dark orange (estimated from the model in Equation 2). Pre/post scaled values are scaled using each scaling method in the panel title described in detail in Appendix 2, and the difference between pre and post is used as the change toward standard y-axis value.