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Research Addendum for Peer Review

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Abstract - Minnesota's shallow lakes provide numerous valuable ecosystem services and habitat for native species along with direct human benefits including clean water, recreational opportunities, and carbon sequestration. Unfortunately, water and habitat quality of Minnesota's shallow lakes have deteriorated dramatically during the past century. Conversion from native upland covers, widespread wetland drainage and surface-water consolidation to facilitate agricultural and urban/residential development have been implicated as major causes for these changes. We propose to study approximately 140 shallow lakes in 5 ecological regions of Minnesota to 1) identify major factors leading to deterioration, 2) evaluate results of specific lake restoration approaches, including cost-effectiveness of various combinations of lake management strategies, and 3) assess the impacts of increased surface water connectivity on fish invasions and resulting habitat quality. Our efforts will include extensive sampling of shallow lakes to identify direct and indirect causes of deterioration, evaluation of approximately eight lakes currently undergoing rehabilitation, and economic analyses to determine which restoration strategies are likely to produce the greatest improvements in water quality and other lake characteristics per unit cost. Ultimately, our results will allow municipalities, state, county, and local governments, and private organizations to identify cost-effective approaches for maintaining and restoring ecological integrity of shallow lakes throughout Minnesota. Special attention will be directed towards development of regionally-specific recommendations for sustainable lake management.

Background - Minnesota has approximately 4,000 lakes characterized by mean depth $\leq$ 15 ft and surface area > 40 acres (Nicole Hansel-Welch, personal comm.) and many thousands of smaller waters technically classified as "prairie wetlands"; the latter are functionally indistinguishable from the larger analogues (Potthoff et al. 2008). Collectively, these shallow lakes represent an international resource, providing critical waterfowl habitat and ecological benefits within Minnesota and the Mississippi Flyway. Currently, only 40 of these lakes > 40 acres are formally designated for wildlife management, however many others are focus areas for various wildlife habitat and conservation practices. Due to concerns over wetland/lake water quality, seasonal duck abundance and habitat use, and hunter satisfaction, MN DNR recently proposed a collaborative plan to Recover Ducks, Wetlands, and Shallow Lakes (http://files.dnr.state.mn.us/outdoor_activities/hunting/waterfowl/duck_plan_highlights.pdf). This plan targets restoration of 1,800 shallow lakes in Minnesota. At the same time, restoration strategies for shallow lake managers remain limited and often ineffective; in addition, reliable data on baseline conditions of shallow lake characteristics and regional patterns of variability are often unavailable, especially for northern areas. This means that lake and wildlife managers are frequently unsure of the current status of lakes they manage, and whether ecological characteristics of these areas may be limiting use by waterfowl and other wildlife. In general, managers receive little technical guidance useful for management and restoration of these lakes, or for implementation of rules for managing increased development and other anthropogenic influences in these areas.

Ecological characteristics of shallow lakes, along with their suitability for ducks and other wetland wildlife species, result from integrated influences of within-site and landscape-mediated processes. Effects of key variables operate at multiple spatial scales, sometimes result from off-site influences, and no doubt vary regionally throughout the state. Ecologists have long held that prairie wetlands (including our "shallow lakes") are strongly influenced by gradients of hydrology (or hydrogeomorphic setting) and climate (especially precipitation) (Euliss et al. 2004). However, within boundaries established by hydrology and climate, biological interactions, especially wetland fish communities, also exert major structuring influences on communities and characteristics of prairie wetlands and shallow lakes (Hanson et al. 2005). This is not surprising given robust improvements known to follow removal of undesirable fishes from shallow Minnesota lakes such as Christina (Hanson and Butler 1994), and smaller wetlands (Zimmer et al. 2001).

As evidenced by whole-lake manipulations such as those summarized above, shallow lake food webs often differ dramatically in response to density and community structure of associated fish populations. Fish-mediated influences on invertebrate community structure and water transparency are often pronounced (Bendell and McNicol 1987; Zimmer et al. 2000, 2001). Recent studies in Minnesota's Prairie Pothole Region (PPR) documented the strong negative influences of fathead minnows on invertebrate populations (Zimmer et al. 2000, 2001, 2002). Consequent reductions in herbivorous zooplankton (resulting from fish predation) allowed increases in phytoplankton densities and turbidity consistent with predictions of the recent models of Scheffer et al. (1993) and Scheffer (1998). These models propose that shallow-water ecosystems exist in one of two alternative conditions, either a clear-water, macrophyte-dominated state, or a turbid-water, phytoplankton-dominated state (Scheffer et al. 1993). Minnesota PPR wetlands largely conform to a binomial distribution (clear or turbid), rather than a normal distribution of features along a theoretical continuum (Zimmer et al. 2001; Herwig et al. 2004; Zimmer et al. 2009).

Composition of fish assemblages may also mitigate the relative influence of fish on shallow lake communities, and may dictate the success of remediation efforts. For example, stocking of piscivorous fish often results in a reduction of planktivorous fish (especially soft-rayed minnows), which may indirectly increase water transparency (Walker and Applegate 1976; Spencer and King 1984; Herwig et al. 2004). Similarly, in small lakes in northern Wisconsin containing natural fish communities, piscivores (largemouth bass *Micropterus salmoides* or northern pike *Esox lucius*) and cyprinids often occupy unique and separate assemblages. This pattern is thought to reflect the elimination of minnows via predation, and further suggests that biotic interactions can be important in structuring fish assemblages (Tonn and Magnuson 1982; Rahel 1984). In contrast, populations of large-bodied benthivorous fish species (e.g., black bullhead *Ameiurus melas*, white sucker *Catostomus commersoni*, and common carp *Cyprinus carpio*) are often resistant to predation, and are frequently associated with high turbidity and loss of rooted aquatic plants (Hanson and Butler 1994; Braig and Johnson 2003; Parkos et al. 2003). Due to the important but very different influences of planktivorous and benthivorous fishes on water quality, and the potential for restoration success given different fish assemblages, managers would benefit from tools that linked fish assemblages to landscape features and environmental characteristics of shallow lakes themselves.

Many lake and wetland studies have reported that landscape setting directly influences characteristics of embedded waters. For example, the watershed position sets boundaries on a variety of physical, chemical, and biological attributes of both deep lakes (Kratz et al. 1997) and prairie wetlands (Euliss et al. 2004). These lake properties include potential responses to drought, predominant groundwater interactions, water chemistry and concentrations of dissolved constituents, and biological communities. Other landscape features that have been found to influence lake water quality are wetland extent in the lake watershed (Detenbeck et al. 1993; Prepas et al. 2001), and extent of agricultural land use, the latter being correlated with higher trophic state index in associated lakes (Detenbeck et al. 1993). In many cases, off-site influences probably interact with site-level wetland features and processes so that observed community characteristics reflect simultaneous influences operating within the local context of lake nutrient status (Scheffer et al. 1993; Bayley and Prather 2003; Jackson 2003), surface area (Hobæk et al. 2002), depth (Scheffer et al. 1993), and biological properties such as abundance of macrophytes (Scheffer et. al. 1993; Paukert and Willis 2003; Zimmer et al. 2003).

Our previous work (2005-06) confirmed that landscape characteristics can influence lake communities, interact with within-basin processes, and may be important determinants of shallow lake characteristics in Minnesota. These landscape effects are direct and indirect. For example, both presence of downstream fish sources and depth were useful for predicting fish presence/absence (Herwig et al. In review), and landscape control on distribution of fish species limited the ability of predatory fish to control prey fish and improve water quality conditions (Friederichs et al. In review). Proportion of agricultural lands in upstream lake watersheds interacted with fish mass in our best models and together these attributes were useful for predicting algal biomass in adjacent shallow lakes (Gorman et al. In prep.), and fish were also the best predictors of amphibian site occupancy and abundance in shallow lakes (Herwig et al. In Prep.). In addition, results from our previous study provided new insights that will help elucidate mechanisms associated with important in-lake processes such as identifying thresholds at which shallow lakes shift from turbid- to clear-water regimes, and clarifying roles of benthivorous fish in these well-known lake dynamics (Zimmer et al. 2009). Preliminary results from earlier work indicate that fish abundance and community structure exert major influences on shallow lake invertebrates, yet this relationship varies widely across ecological region. We are also comparing relative influences of within-site and landscape-scale characteristics on shallow lake invertebrate communities. Contributions from Sean Vaughn (Division of Waters, MDNR) and Robert Wright (Section of Wildlife, MDNR) provided new spatial analysis tools (delineating lake watershed boundaries, spatial analysis, etc.) that were not only critical for the recently-completed study, but will have direct application to questions and hypotheses posed in this current effort.

Major goals of our previous study were to develop conceptual and empirical models linking landscape features, environmental influences and wetland fish assemblages, to assess influences of these factors on the community characteristics in shallow lakes, and to clarify specific influences of within-lake processes that influence ecological characteristics of shallow lakes. An overarching finding of the prior work was that regional differences often constituted the largest source of variance in characteristics of shallow Minnesota lakes. This is not unexpected given findings of others studying deeper lakes (Carpenter et al. 2007), or perceptions of staff from the MDNR shallow lakes program indicating that baseline characteristics of shallow lakes differ dramatically across regions of the state (Nicole Hansel-Welch, pers. comm.). Regional differences not only contribute to major variability in obvious lake characteristics, but they probably influence extent and nature of lake responses to landscape constraints such as surface-water connectivity, as well as within-lake processes in regime responses to thresholds of phytoplankton and fish mass. For example, it is likely that combinations of increased benthivorous fish mass and/or decreased macrophytes will often induce regime shifts in prairie lakes, and these changes probably portend shifts to turbid-water states. However, we speculate that increased fish mass is much less likely to induce turbid-states in north-central Minnesota lakes, and turbid states may not even be possible in northern lakes where low ambient nutrient levels prevail. Additional work is needed to document extent and patterns of regional variation, and to assess how it influences key structuring mechanisms such as surface connectivity, fish community characteristics, stability of phytoplankton- and macrophyte-dominated states, and proportion of lakes in clear- vs. turbid-water states.

Hypotheses - Our overall, general working hypothesis is that 6 fundamental "drivers" are ultimately responsible for most of the variation in ecosystem characteristics of Minnesota shallow lakes: climate, ambient nutrient levels, fish abundance and community type, landscape features, land use, and morphometric features of individual lakes. These 6 factors, in turn, induce strong, predictable spatial gradients in shallow lake characteristics across the state of Minnesota. Thus, we expect shallow lakes will exhibit wide ranges of features (and responses to lake management) at a statewide scale as the influence of some drivers increase while others decrease. Additionally, inter-annual variability in precipitation and temperature will have strong influences on shallow lakes, and this inter-annual variability will also exhibit spatial patterns across the state. Thus, we hypothesize these 6 drivers generate predictable spatial and temporal patterns in shallow lakes across the state of Minnesota. Overall, we believe that understanding and predicting ecosystem characteristics of shallow lakes (fish, waterfowl, plant and invertebrate communities, water quality, carbon cycling, etc.), along with lake responses to rehabilitation efforts, requires understanding the influence of these drivers, as well as synergistic combinations of influences arising from two or more drivers. Within-lake interactions, such as those associated with fish, have strong influences on shallow lakes (Scheffer et al. 2006; Verant et al. 2007; Potthoff et al. 2008). However, we hypothesize that the types and strengths of these interactions are also a function of our 6 main drivers, such that within-lake interactions will also exhibit spatial and temporal patterns that can be predicted from these influences.

We believe it is also especially important to test hypotheses regarding stability regimes in shallow lakes. Previous work (Hanson and Butler 1994) suggests that shallow lakes in MN conform to general models of alternative states developed for European lakes (Scheffer et al. 1993, Scheffer 1998) and these relationships have recently been confirmed from our prior work on Minnesota lakes (Zimmer et al. 2009). However, in Minnesota, it is likely that regime dynamics and stability thresholds will vary along regional gradients. We expect that companion models may need to be developed that extend the concept of basin states to include patterns of variance in invertebrate communities and other lake characteristics. Resulting data and modeling outcomes from tests of our specific hypotheses will be synthesized and applied to address needs and provide results identified in our accompanying Work Plan. For example, results from all study lakes will be used to estimate the magnitude of major factors responsible for deterioration of shallow lakes within the 6 study regions. Comparisons among management outcomes on 8 Intensive lakes (Result 2) will allow generalizations about relative usefulness of these lake rehabilitation approaches. Using a combination of data and outcomes from Extensive and Intensive lakes, our economic analysis will compare cost-effectiveness of various management approaches and will provide guidelines useful for maximizing future lake restoration and management decisions, including suggestions as to how more cost-effective approaches vary across the state. Finally, all resulting data will be used to assess extent to which surface connectivity among surface waters influences ecological characteristics of shallow study lakes. We emphasize that our combination of specific hypothesis is necessary to address lake management needs identified in our proposal and work plan.

The following specific hypotheses are couched within general working hypothesis. Extent to which all specific hypotheses can be tested will be determined by characteristics and management plans of actual study lakes.

Specific hypothesis 1: Ambient nutrient levels will be highest in Windom (Figure 1), moderate in Twin Cities, and Elbow Lake, and lowest in Itasca and Red Lake, and this will have strong indirect effects on resident fish populations.
Explanation: Geological influences result in a natural gradient of phosphorus levels in lake sediments and topsoil within lake watersheds, with highest levels occurring in the southwestern part of the state and decreasing toward the northeast. Additionally, agriculture will be highest in Windom and Elbow Lake, and lowest in Itasca and Red Lake, while Twin Cities will be highest in extent of developed land. Winterkill effects will be most intense, but most variable in Windom due to fluctuating winter severity and high ambient nutrient levels (thus high biological oxygen demand in winter), whereas frequent, low intensity winterkills will occur throughout Red Lake and Itasca due to more consistent winter weather patterns.

Specific hypothesis 2: Spatial patterns in ambient nutrient levels, fish communities, and landscape features will cause spatial and temporal variability in proportional frequency of alternative states and stability of these regimes throughout Minnesota's shallow lakes.
Explanation: Windom will be dominated by stable turbid regimes, Red Lake and Itasca dominated by stable clear regimes, with a more equal frequency of regimes in Elbow Lake, and Twin Cities in the central part of the state. Furthermore, frequency of regime shifts will be highest in Elbow Lake, and Twin Cities, and lowest in Windom, Itasca, and Red Lake. High ambient nutrients and fish biomass will increase resilience and resistance of the turbid regime in Windom, while low nutrients and fish biomass promote resilience of clear regimes in Red Lake and Itasca.

Specific hypothesis 3: Functional influences of fish will decrease northward, along a spatial gradient from Windom to Red Lake.
Explanation: Dominance of benthivores will decrease along this same gradient, while planktivores increase. Concurrently, influence of piscivores on fish abundance will also increase along this gradient. Overall, species diversity of fish will peak at moderate level of ambient nutrient levels in Elbow Lake.

Specific hypothesis 4: Thresholds at which changes in fish biomass induce shifts between alternative regimes will vary across the state due to interactions between ambient nutrient levels and fish.
Explanation: Our previous work on shallow lakes in central Minnesota indicated that interannual proportional change in biomass of planktivores and benthivores is a threshold for regime shifts in shallow lakes (Zimmer et al. 2009). We predict similar thresholds for Elbow Lake, but lower biomass thresholds for Windom and Twin Cities, and higher thresholds in Itasca and Red Lake.

Specific hypothesis 5: Differences in landscapes features and land use among the 6 study areas will influence the relative importance of extinction and colonization as processes controlling distribution and abundance of fish in shallow lakes.
Explanation: High incidence of surface-water connectivity in Windom and Twin Cities will result in fish present in lakes, independent of lake depth and size, while a low prevalence of surface-water connectivity in Itasca and Red Lake will limit fish to deeper, larger lakes. Thus, long-term success in inducing regime shifts via biomanipulation may require installation of fish barriers in southern lakes, but not in the more isolated northern lakes.

Specific hypothesis 6: Benthivores and planktivores exert different relative influences on key characteristics of shallow lakes, with planktivores stabilizing turbid regimes, while benthivores both stabilize and induce shifts to the turbid regime.
Explanation: Planktivores stabilize a turbid regime, but do not induce shifts from clear to turbid regimes. Thus, we will not observe planktivore-only lakes shifting clear to turbid, but winterkill in planktivore lakes will cause a shift from turbid to clear. In contrast, benthivores stabilize turbid regimes and induce shifts to turbid regimes. Lakes with benthivores may shift clear to turbid, and winterkill in benthivore lakes will cause a shift from turbid to clear. We also hypothesize that influences will differ between the two dominant benthivore species in these systems: common carp and black bullhead. Carp distribution will be more limited, but will be more closely associated with turbid regimes.

Specific hypothesis 7: Shallow lake responses to biomanipulation will depend on ambient nutrient levels.
Explanation: Relative to high nutrient lakes (Windom), lakes with low nutrient levels (Itasca, Red Lake) will exhibit faster responses in water clarity and submerged macrophytes. The clear-water regime will also be more stable through time in low nutrient lakes, and more resistant to influences of subsequent recovery of planktivorous or benthivorous fish. We also predict that low nutrient lakes will require less reduction in fish mass for regime shifts (due to lower overall fish biomass), and the overall success rate will be higher in these systems.

Specific hypothesis 8: Water clarity and stability of clear-water regimes will be higher in *Chara* dominated lakes relative to lakes dominated by submerged angiosperms. We also predict a spatial gradient of *Chara* lakes, with highest occurrence in the Itasca-Red Lake and lowest in Windom.
Explanation: *Chara* species are very sensitive to changes in light intensity. They require high light intensity, and are expected to be more prevalent in clear lakes. Other submerged macrophytes are generally less sensitive to low light, thus are expected to decrease in abundance at higher critical turbidity thresholds than *Chara* spp.

Specific hypotheses 9: *Chara* species will become less abundant along the gradient from Itasca-Red Lake-Windom, while overall macrophyte biomass will increase along that gradient.
Explanation: *Chara* species are typically limited to relatively low-nutrient systems. Increasing nutrient availability along the Itasca-Red Lake-Windom gradient will thus decrease the relative abundance of *Chara* along that gradient. At the same time, higher nutrient availability will favor the biomass production of larger macrophytes, such as *Potamogeton* species.

Specific hypothesis 10: Efficacy of lake watershed restoration (e.g. converting row crop agriculture to native grasslands) and biomanipulation to reduce algal abundance will vary among study areas. Interactions between ambient nutrient levels, land use, and fish communities will make manipulations of fish more effective as you move toward the southwestern portion of the state, and management of lake watersheds more effective as you move north.
<u>Explanation:</u> Figure 2 (below) shows results from our previous study of high nutrient lakes near Elbow Lake, and low nutrient lakes west of Bemidji. Inset box show the ranges of fish biomass and agriculture in lake watersheds actually observed for the low nutrient lakes. The area below the

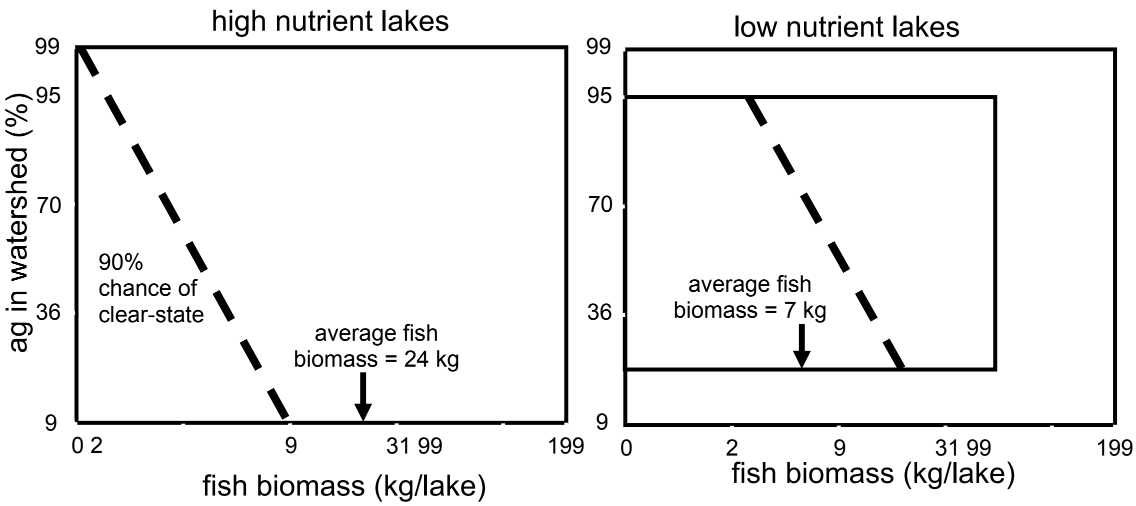

Figure 2. General relationships showing likelihood of achieving clear-water regimes under various combinations of extent agriculture (in lake watershed) and total fish biomass (per lake) in high and low nutrient lakes. Lakes falling left of dashed lines have a 90 % chance of being clear (based on unpublished data from K. Zimmer). Inset box for low nutrient lakes shows the actual range of agriculture in lake watershed and fish biomass observed in those lakes.

dashed line shows combinations of agriculture in the lake watershed and fish biomass (summed biomass of benthivores and planktivores) that allow a 90% chance of a lake being in a clear-water regime. Combinations above the line don't necessarily guarantee a turbid regime, but the probability of being clear declines as you move up and to the right the right from the dashed line. These results show that, in high nutrient lakes, efforts reducing agriculture result in a 90% chance of clearing lakes only if fish biomass is <9 kg. In contrast, reducing agriculture has potential to induce clear shifts in low nutrient lakes lakes with up to 25 kg of fish. Moreover, the average fish mass was higher than the 9 kg threshold for high nutrient lakes, while average mass was lower than the threshold for low nutrient lakes. These patterns indicate that lake watershed management will be more broadly applicable in low nutrient lakes. Eliminating fish should work in both areas, but improving water quality via fish reduction may also be more difficult in high nutrient lakes. For the upcoming study, we predict an even lower fish-mass threshold (for 90% chance of being clear) in Windom, where average fish biomass in shallow lakes is likely to be high. In contrast, Itasca and Red Lake should have higher fish thresholds, and lakes here should contain lower fish biomass due to lower productivity. Overall, this would indicate that restoration of lake watersheds contributing to shallow lakes is most effective in Itasca and Red Lake, fish and watershed management are both viable in Elbow Lake, while fish management is most effective in Windom and Twin Cities. Additionally, we predict the amount of fish reduction needed to generate 90% chance of being clear will be highest in Windom, and lowest in Red Lake.

Specific hypothesis 11: Feeding activities of exotic earthworms increase concentrations of orthophosphate and ammonia in lake watersheds, while reducing concentrations of dissolved organic carbon in soil. The net result is worms increase autochthonous production in shallow lakes by increasing nutrient loading from lake watersheds, while simultaneously reducing loading of allochthonous organic matter from the watershed.
Explanation: Exotic earthworms have been referred to as 'ecosystem engineers' due to their profound effects on soil properties (Frelich et al. 2006). They are capable of decreasing the organic layer horizon of soils, increasing the rates of carbon, nitrogen and phosphorus cycling as well as altering the aboveground plant composition (Frelich et al 2006; Suarez et al. 2004; Dominguez et al. 2004). Little work has examined the effects of earthworms on adjacent aquatic ecosystems but given their profound effects on biogeochemical dynamics in soils, it is also likely that they are having important effects on aquatic systems. Given the increased rates of soil metabolism and nutrient leaching, it is quite probable that earthworms mobilize nutrients for transport into lakes and rivers, facilitating the rates of eutrophication of water bodies where they are most abundant. Preliminary work in lakes at Itasca State Park suggest that lakes with increased worm abundance are more productive and less likely to be limited by phosphorus, perhaps suggesting that earthworms are increasing the availability of P in these lakes.

Below we describe our methods for research on both Extensive (128) and Intensive (8) lakes, the latter undergoing various management efforts to improve ecosystem characteristics. Similar field methods will be used in both the extensive and intensive aspects of this project, allowing us to use the data from the 128 lakes in our assessment of improvements in the 8 lake study.

Methodology-

Study Areas

A key goal of our study is to increase understanding of spatial patterns of shallow lake characteristics across Minnesota. Shallow lakes here occur across a wide range of lake watershed characteristics (agriculture and urban land uses, native cover types, etc.), phosphorus concentrations, and water transparency gradients. We propose to use an aquatic ecoregion approach for characterizing shallow lake features (sensu Heiskary et al. 1987). We plan to use classifications based on Omerik's (1987) Level III ecoregion delineations denoting areas of general similarity in the type, quality, and quantity of environmental resources. Under this approach we will establish a study area (or "study landscape"), each containing a cluster of study sites, within each of the five ecoregions that collectively encompass the vast majority of lakes and wetlands in Minnesota: Northern Minnesota Wetlands (NMW), Northern Lakes and Forests (NLF), Northern Glaciated Plains (NGP), Western Corn Belt Plains (WCP), and North Central Hardwood Forests (CHF). As previously mentioned, there are large gradients in in-lake phosphorus (P) and nitrogen concentrations across these ecoregions. For example, in a survey of 1,062 lakes, Heiskary et al. (1987) found median P concentrations of 23 ppb (NLF), 50 ppb (CHF), 121 ppb (WCP), and 177 ppb (NGP). No information was available for NMW, but we expect lower P concentrations here, perhaps intermediate between NLF and CHF. Cover types also vary widely, ranging from heavily forested, with some marshlands (NLF) to nearly level marsh, containing both boreal vegetation and expansive swamps (NMW), to principally cropland agriculture (WCP & NGP), to a mosaic of cover types, including forests, wetlands and lakes, cropland agriculture, pasture, grasses, and urban development (CHF) (Omerik 1987).

Our study will focus on 6 landscape areas distributed across five aquatic ecoregions within Minnesota as follows: (1) the NMW study area (hereafter "Red Lake") will be located within the boundaries of the Red Lake Indian Reservation in far northern Clearwater and west-central Beltrami counties, (2) the NLF study area (hereafter "Itasca") will be focused within and around Itasca State Park in south-eastern Clearwater County, (3) sites located in western portions of the Chippewa National Forest in far western Itasca County, (4) the NGP study landscape (hereafter "Elbow Lake") will be located in the southern portions of Grant County, extending into the northern and western margins of Stevens and Douglas counties, respectively (we have a long time series here, dating back the mid 1990's), (5) the WCP study area (hereafter "Windom") will be centered around Windom, MN, and thus roughly split between Cottonwood and Jackson counties, (6) the CHF study landscape (hereafter "Twin Cities") will be located in the Hennepin-Carver county metro area (Figure 1).

Our study landscapes are also positioned in several different major river watersheds. In some cases, study areas fall within two or more drainages. For example, Red Lake is entirely within the Red River drainage, Itasca is entirely within the Upper Mississippi River drainage, but Twin Cities is within both the Upper Mississippi River and Minnesota River drainages. Similarly, Windom is within the Minnesota River and Lower Mississippi River drainages, and Elbow Lake is within the Red River and Minnesota River drainages.

Individual Study Sites

Within each study landscape, up to 25 shallow lakes will be selected for measurement of fish assemblages, wetland characteristics, and surrounding landscape attributes. Study lakes will be distributed across both public and private ownerships. We expect that all lakes will be of semipermanent or permanent (type IV or V) duration of flooding (Shaw and Fredine 1956; Stewart and Kantrud 1971). Within these broad classifications, shallow lakes will be selected so as to span a range of values of surface area, depth, and adjacent upland cover types.

General Data Collection Approaches

<u>Development of land use and lake watershed variables using GIS and photo interpretation</u>

Our approach relies on methods developed by Minnesota DNR Waters (Watershed Delineation Project [DNR-WDP]) which created a unique watershed methodology that incorporates three techniques: traditional on-paper; modern on-screen; and GIS-automated delineation into one comprehensive methodology. Merging these three techniques involves a complex, iterative process of heads-up on-screen digitizing and utilizes as many as 30 different datasets, sources of information and field reviews. Resulting products are best described as manually derived, human interpreted, "off-site" height of land watershed delineation, developed and maintained using GIS technology.

GIS data layers will be used to derive metrics that characterize features of the landscape associated with each study site. Both upstream and downstream hydrologic connectivity of each study site will be identified, delineated and digitized for analysis. Lake watershed boundaries will be delineated for each site. When possible, existing land cover layers will be overlaid and summarized for the individual lake watersheds. GIS data layers will be used to derive metrics that characterize features of the lake watershed associated with each study site. Data summaries will be developed as needed. These will primarily include connectivity attributes, and watershed characteristics (e.g. surface area of different cover types, inter-lake surface connection distances, watershed:lake area ratios).

Landscape/watershed connectivity analyses may include but are not limited to the following: 1) presence of upstream/downstream connections to surface waters capable of supporting fish populations, 2) modeled upstream/downstream connections of surface water from digital elevation models (DEM) to surface waters capable of supporting fish populations, 3) network distances to represent "as the fish swims" to surface waters capable of supporting fish populations (horizontal and vertical dimensions), and 4) rank variable for type and degree of connectivity to other surface waters (also a potential proxy for geomorphic setting).

Fish assemblages

Fish species composition and relative abundance (biomass per unit effort) will be determined using a combination of gears deployed overnight. All fish sampling will be done during July and August each year. Three mini-fyke nets (6.5 mm bar mesh with 4 hoops, 1 throat, 7.62 m lead, and a 0.69 X 0.99 m rectangular frame opening into the trap) will be set overnight in the littoral zone of each lake. One experimental gill net (61.0 m multifilament net with 19, 25, 32, 38, and 51-mm bar meshes) will be set along the deepest depth contour available in lakes less than 2 m deep or along a 2 m contour in lakes with sufficient depth. The protocol outlined above has been shown to be effective in sampling fish assemblages in shallow lakes in Minnesota (Herwig et al. In review) as well as small lakes from other regions (Tonn and Magnuson 1982; Rahel 1984; Jackson and Harvey 1989; Robinson and Tonn 1989). This should enable us to capture both small- and large-bodied fish, and species from all of the major trophic guilds (e.g., plankivores, benthivores, piscivores) potentially present in the study wetlands. All fish sampled will be sorted by species, rated (counts per unit weight), and weighed in bulk. Fish data will likely be summarized as the summed total biomass of each species collected in all four nets. Voucher specimens will be collected and returned to the laboratory for identification when field identification cannot be made.

Aquatic invertebrates

Zooplankton will be sampled once per year in July concurrent with fish sampling by collecting two replicate vertical column samples (Swanson 1978) at 5 locations in each wetland. Estimates will be made of density and taxon richness. Relative abundance of macroinvertebrates will be sampled concurrent with other sampling in July using sweep net samples (Murkin et al. 1983) at 0.75m depth at 5 randomly selected locations in each lake. Abundance and taxon richness of macroinvertebrates will be measured.

Nutrients, specific conductance, light attenuation, and phytoplankton

Surface (dip) water samples will be taken from the center of each lake once during July concurrent with other sampling. Samples will be frozen and transported to the University of St. Thomas (Dr. Kyle Zimmer's lab) for analysis of chlorophyll *a*, total nitrogen, total phosphorus and total dissolved phosphorus. Turbidity will be measured in the field with a portable nephelometer. Phytoplankton biomass will be estimated from chlorophyll *a* (Strickland and Parsons 1972). Collection of samples for chlorophyll *a* simultaneously with measurement of turbidity will allow assessment of the contribution of phytoplankton to turbidity, and ultimately to light attenuation.

Submerged macrophytes

Abundance of submerged macrophytes and *Chara* spp. will be assessed using modified techniques of Jessen and Lound (1962), and Deppe and Lathrop (1992). In each lake, submerged macrophytes will be sampled at 15 stations located equidistant along four transects running the width of each basin in July or August of each year. Two throws of a weighted plant rake will be made at each station, and dragged along 3 m of lake bottom. Plants collected on the first throw will be weighed (all taxa combined) and frequency of occurrence (1 = sampled on one throw, or 2 = sampled on both throws) will be recorded for each plant species sampled. Plant data will be summarized as mass and frequency of occurrence (all taxa combined) averaged across the total number of throws used for each metric.

Earthworms

We will study earthworm effects on shallow lakes in only one region due to lack of facilities and personnel for examining this phenomenon elsewhere. Earthworms will be collected from uplands within 50 m of all study lakes in our Itasca core area. Near each lake, 10 35 cm x 35 cm areas will be cleared of surface duff and flooded with a saturated solution of mustard (after methods of Laurence and Bowers 2002). Extracted worms will be collected, preserved in 75% ethanol, and identified according to an ecological classification system of Hale et al. (2005). Data will be used to develop a relative abundance estimate for earthworms in catchment areas immediately adjacent to study lakes.

We will correlate earthworm abundance and ecological classifications with the nutrient concentrations, chlorophyll *a*, and other water quality characteristics in adjacent study basins. Earthworm collections will be restricted to lakes within our Itasca core area due to relatively uniform forest composition in this ecological region (enabling earthworm effects to be assessed independent of other factors) and because related measurements require laboratory facilities available at the UM field station in Itasca State Park. It is also important to note that REU students (using non-project funds provided to J. Cotner) will be collecting ancillary data on forest characteristics and soils in this region.

Intensive sampling

In consultation with MN Ducks Unlimited staff, we will identify 8 case study lakes to evaluate effectiveness of restoration strategies typically used by state, federal, and private organizations working on shallow lake management. Study sites will include lakes undergoing management manipulations during 2010-11. Specifically, we plan to assess the effectiveness either alone, or in combinations, of installation of fish barriers, water level draw downs, rotenone, and perhaps other measures to be prescribed by lake managers.

We will collect one year of data before and for one year after the management activity during the two years of LCCMR funding. We will measure the same predictor and response variables as described above in the *General Data Collection Approaches* section. The only difference is that response variables will be measured monthly from May through August for two years in the Intensive lakes, while the Extensive lakes are to be sampled only once in July of each year.

We will measure the effectiveness of the various management activities by assessing changes in ecosystem features following the specific manipulation to the lake. Variables to be assessed include water clarity, nutrient levels in the water column, and abundance and species composition of phytoplankton, submerged macrophytes, zooplankton, macroinvertebrates, and fish. The relative improvement in each of these variables will be assessed using data from our larger Extensive study for lakes in the same ecoregion. For example, it is difficult to quantify the degree of "successfulness" if lake-drawdown causes phytoplankton abundance to drop from 88 ug/L to 23 ug/L. However, the Extensive (128) lake study will help to quantify this change as the lake shifting from a probable turbid-water state to a probably clear-water state following the drawdown. Interpreting lake response in of the context of natural regional variability should also facilitate assessment of success across ecoregions where lake features naturally vary.

Data Analysis

We anticipate applying a suite of analysis strategies to evaluate the various hypotheses outlined above. This is necessary because no single approach we are aware of allows for identification and measurement of multiple complex linkages discussed above. Our approach will include gradient analysis (ter Braak 1995; ter Braak and Smilauer 1998; McCune and Grace 2002), classification and regression tree techniques (Breiman et al. 1984, De'ath and Fabricus 2000), variance partitioning (Borchard et al. 1992; ter Braak and Wiertz 1994), mixed effect linear models (Littell et al. 2006), piecewise regression (Toms and Lesperance 2003), information-theoretic model selection techniques (Burnham and Anderson 1998; Anderson et al. 2000), and traditional parametric approaches (SLR, ANOVA) (Zar 1999). Collectively, our analyses are intended to provide evidence whether ecological features of study lakes differ in predictable ways (thus whether lakes can be grouped) and, if so, whether fish communities, landscape and lake watershed features, cover types, ambient nutrients, lake basin morphology, and climate and other regional patterns account for observed differences among groups. Analyses will likely include situations where data are pooled from all landscapes to ensure a considerable range of values in both predictor and response variables, and situations where analyses will be developed for each study landscape separately, especially if separate modeling improves predictive ability, or if region-specific prediction and models are required. Below we have highlighted four major statistical approaches that will be used: gradient analysis, classification and regression trees, variance partitioning via constrained ordination, and model selection using information-theoretic approaches.

Ordination techniques (principal components analysis or correspondence analysis) will be used to identify whether unique wetland fish assemblages exist among our study lakes (ter Braak 1995; ter Braak and Smilauer 1998). Once assemblage types are identified, we will use classification and regression tree (CART) analysis (a binary recursive partitioning technique) to develop two separate decision tree models to predict fish presence/absence, and type of fish assemblage present within a lakes based on environmental and landscape attribute variables (Breiman et al. 1984). Our response variables will be categorical; therefore, classification trees will be constructed. In classification tree analysis (CTA), the estimated probability for each response level is the fitted value, and the most significant split is determined by the largest likelihood-ratio chi-square statistic (Breiman et al. 1984). The splits are chosen to maximize the difference in the responses between the two branches of the split. Also, CART may perform well using input data, but model prediction may be very poor for new data sets (Lookingbill and Urban 2005). Several techniques will be used during tree building and pruning to avoid over-fitting the data, and ensure parsimonious models, including 1) setting the minimum split value (minimum size split allowed, defined as a proportion of total sample), 2) setting the minimum number of cases included in a terminal node, and 3) overbuilding the trees, and then pruning back until k-folded (k=25) cross-validation errors plateau, or until there was no remaining residual error, and 4) model validation via comparison of misclassification rates for learning and validation data sets, where 30% of sites are left out as the validation set.

We will use direct gradient analysis (ter Braak 1986, 1995; ter Braak and Smilauer 1998) to relate major drivers (climate, ambient nutrients, landscape features, land use, lake morphometric features, and more proximately, fish populations) to a suite of ecological characteristics of study lakes. More specifically via constrained ordination, we will use driver variables to predict lake responses such as water transparency, phytoplankton biomass, water-column nutrient concentrations, extent of submerged macrophytes, invertebrate abundance and community features, and other characteristics of each lake study site. Preliminary ordinations will be conducted using detrended correspondence analysis. This will be necessary to assess length of environmental gradients, thus to determine whether linear (redundancy analysis, RDA) or unimodal (canonical correspondence analysis, CCA) response models are likely most appropriate for analysis of these data (Van Wijngaarden et al. 1995). Previously, we have successfully used both linear and unimodal forms of gradient analysis on data sets similar to that described here (Zimmer et al. 2000, 2003; Hanson et al. 2005). Where necessary, response variables (water quality and invertebrate data, and others) will be log-transformed prior to analysis to equalize variances (Van Wijngaarden et al. 1995; ter Braak 1995). We anticipate using variance partitioning to assess the comparative importance of major drivers and the spatial scales at which they are functionally important (Borchard et al. 1992; ter Braak and Wiertz 1994). This will allow us to assess the relative contribution ("pure effect") of each predictor variable, and to assess the statistical significance of each using Monte Carlo simulation procedures. Where necessary, we will use Bonferroni corrections (Rice 1990) to maintain experiment-wise Type 1 error rates of 0.05. All gradient analyses and variation partitioning will be performed using CANOCO 4.0 (ter Braak and Smilauer 1998).

Finally, we will also assess the relative strength of relationships among external drivers (e.g., climate, ambient nutrients, land use), within-lake drivers (morphometry, fish communities) and key ecosystem characteristics, such as water clarity or abundance of submerged macrophytes using an information-theoretic (IT) approach (Burnham and Anderson 1998; Anderson et al. 2000). Model selection involves consideration of problems associated with both overfitting (low-precision models due to too many parameters) and underfitting (models biased due to insufficient numbers of parameters) the data. The IT approach assesses the relative strength of support for competing models, and selects the most parsimonious model that adequately fits the data, representing the optimal tradeoff between over- and under-fitting the data (Hillborn and Mangel 1997). The IT approach is based on Akaike's information criterion and it avoids pitfalls associated with more traditional approaches to model selection in multiple regression and ordination (i.e., forward and backward selection), as well as the problems inherent in use of null hypothesis testing (Johnson 1999; Anderson et al. 2000).

Using the techniques described above we also expect to test and evaluate data and models from our previous study by ecoregion. Various data combinations will be used to assess model performance and whether our approaches will be useful for different landscapes and, perhaps, for different time periods. Such analyses will be useful for determining whether or not management and restoration strategies need to be tailored to specific regional settings or be modified over time.

Economic Analysis – Assessing Cost-Effectiveness of Management Options for Maintaining and Restoring Shallow Lakes

An economic analysis will be conducted using the empirical data from all study lakes in identifying the water quality improvements (such as cost per unit of algae reduced [µg/L chlorophyll *a*]) resulting from various application of various management options being utilized or considered within Minnesota. We plan to quantify the costs of applying various combinations of upland vegetation restoration (conversion of agriculture to grass) and in-lake habitat enhancements (fish removal, installation of barriers, etc.) to achieve a given measure of lake water quality improvement. We expect that costs of management options will vary widely among ecological regions due to regionally variability in lake characteristics, lakesheds, upland easement costs, property values, and other attributes of lakes and adjacent uplands.

Comparison of restoration costs will be informative and will help elucidate trade-offs on temporal and spatial scales. Some options may generate quick results but may need to be repeated frequently, so that variations in long-run costs (over multiple decades) will be important to consider. Easement costs for land to be restored to vegetative buffers are known to vary across regions of the state. Cost data for the management options being studied are known to be currently available or obtainable.

Synthesis and research products

We will use data from 8 Intensive and 128 Extensive lakes and from characterization of associated watersheds to address specific hypotheses above. Along with results from our economic analysis, we will specifically address Results 1-3 as summarized in the attached Work Plan to develop and suggest management guidelines for shallow lakes based on data and outcomes from specific ecological regions of the state. Study results will be synthesized and distributed in the form of several peer-reviewed manuscripts and a project summary, the latter to be developed specifically for shallow lake managers in Minnesota.

References

Anderson, D.R., Burnham, K.P., and Thompson, W.L. 2000. Null hypothesis testing: problems, prevalence, and an alternative. Journal of Wildlife Management 64: 912-923.

Bayley, S.E., and Prather, C.M. 2003. Do wetland lakes exhibit alternative stable states? Submersed aquatic vegetation and chlorophyll in western boreal shallow lakes. Limnology and Oceanography 48: 2335-2345.

Bendell, B.E., and McNicol, D.K. 1987. Fish predation, lake acidity and the composition of aquatic insect assemblages. Hydrobiologia 150: 193-202.

Borchard, D., Legendre, P., and Drapeau, P. 1992. Partialling out the spatial component of ecological variation. Ecology 73: 1045-1055.

Braig, E.C., and Johnson, D.L. 2003. Impact of black bullhead (*Ameiurus melas*) on turbidity in a diked wetland. Hydrobiologia 490: 11-21.

Breiman, L., Friedman, J.H., Olshen, R.A., and Stone, C.J. 1984. Classification and Regression Trees. Chapman & Hall (Wadsworth, Inc.), New York, NY.

Burnham, K.P., and Anderson, D.R. 1998. Model selection and inference: a practical information-theoretic approach. Springer-Verlag, New York, NY.

Carpenter, S.R., Benson, B.J., Biggs, R., Chipman, J.W., Foley, J.A., Golding, S.A., Hammer, R.B., Hanson, P.C., Johnson, P.T.J., Kamarainen, A.M., Kratz, T.K., Lathrop, R.C., McMahon, K.D., Povencher, B., Rusak, J.A., Solomon, C.T., Stanley, E.H., Turner, M.G., Vander Zanden, M.J., Wu, C.-H., and Yuan, H. 2007. Understanding regional change: a comparison of two lake districts. BioScience 57: 323-335.

De'ath, G., and Fabricius, K.E. 2000. Classification and regression tree: a powerful yet simple technique for ecological data analysis. Ecology 81(11): 3178-3192.

Deppe, E.R., and Lathrop, R.C. 1992. A comparison of two rake sampling techniques from sampling aquatic macrophytes, Wisconsin Bureau of Research Findings 32, Madison.

Detenbeck, N.E., Johnston, C.A., and Niemi, G.J. 1993. Wetland effects on lake water quality in the Minneapolis/St. Paul metropolitan area. Landscape Ecology 8: 39-61.

Dominquez, Jorge, Patrick J Bohlen, and Robert W Parmelee. 2007. Earthworms Increase Nitrogen Leaching to Greater Soil Depths in Row Crop Agroecosystems. Ecosystems 7: 672-685.

Euliss, N.H., Jr., LaBaugh, J.W., Fredrickson, L.H., Mushet, D.M., Laubhan, M.K., Swanson, G.A., Winter, T.C., Rosenberry, D.O., and Nelson, R.D. 2004. The wetland continuum: a conceptual framework for interpreting biological studies in the prairie pothole region. Wetlands 24: 448-458.

Friederichs, S., K.D. Zimmer, B.R. Herwig, and M.A. Hanson. In Review. Top-down and bottom-up influences on shallow lake food webs. Submitted to Oecologia.

Frelich, Lee E, Cindy M Hale, Stefan Scheu, Andrew R Holdsworth, Liam Heneghan, Patrick J Bohlen, and Peter B Reich. 2006. Earthworm Invasion Into Previously Earthworm-Free Temperate and Boreal Forests. *Biological Invasions* 8: doi:10.1007/s10530-006-9019-3.

Gorman, M.W., Zimmer, K.D., Herwig, B.R., Hanson, M.A., Wright, R.G., Vaughn, S.R., and Younk, J.A. 2008. Ambient nutrient levels, fish communities, and watershed characteristics as drivers of phytoplankton abundance in shallow lakes. (IN PREP).

Hale, C. M., L. E. Frelich and P.B. Reich. 2005. Exotic European Earthworm Invasion Dynamics in Northern Hardwood Forests of Minnesota, USA. Ecological Applications 15: 848-860.

Hanson, M.A., and Butler, M.G. 1994. Responses of plankton, turbidity, and macrophytes to biomanipulation in a shallow prairie lake. Canadian Journal of Fisheries and Aquatic Sciences 51: 1180-1188.

Hanson, M.A., Zimmer, K.D., Butler, M.G., Tangen, B.A., Herwig, B.R., and Euliss, N.H., Jr. 2005. Biotic interactions as determinants of ecosystem structure in prairie wetlands: an example using fish. Wetlands 25: 764-775.

Heiskary, S.A., Wilson, C.B., and Larsen, D.P. 1987. Analysis of regional patterns in lake water quality: using ecoregions for lake management in Minnesota. Lake and Reservoir Management 3: 337-344.

Herwig, B.R., Hanson, M.A., Reed, J.R., Parsons, B.G., Potthoff, A.J., Ward, M.C., Zimmer, K.D., Butler, M.G., Willis, D.W., and Snook, V.A. 2004. Walleye stocking as a tool to suppress fathead minnows and improve habitat quality in semipermanent and permanent wetlands in the prairie pothole region of Minnesota. Minnesota Department of Natural Resources, Division of Fisheries and Wildlife, Special Publication 159, St. Paul, MN.

Herwig, B.R., Zimmer, K.D., Hanson, M.A., Konsti, M.L., Younk, J.A., Wright, R.W., Vaughn, S.R., and Haustein, M.D. In Review. Factors influencing fish distributions and community structure in shallow lakes within prairie and prairie-parkland regions of Minnesota, USA. Submitted to Wetlands.

Hillborn, R., and Mangel, M. 1997. The ecological detective: confronting models with data. Princeton University Press, Princeton, NJ.

Hobaek, A., Manca, M., and Andersen, T. 2002. Factors influencing species richness in lacustrine zooplankton. Acta Oecologia 23: 155-163.

Jackson, D.A., and Harvey, H.H. 1989. Biogeographic associations in fish assemblages: local vs. regional processes. Ecology 70: 1472-1484.

Jackson, L.J. 2003. Macrophyte-dominated and turbid states of shallow lakes: evidence from Alberta lakes. Ecosystems 6: 213-223.

Jessen, R., and Lound, R. 1962. An evaluation of a survey technique for submerged aquatic plants, Minnesota Department of Conservation Game Investigational Report 6, St. Paul.

Johnson, D.H. 1999. The insignificance of significance testing. Journal of Wildlife Management 63: 763-772.

Kratz, T.K., Webster, K.E., Bowser, C.J., Magnuson, J.J., and Benson, B.J. 1997. The influence of landscape position on lakes in northern Wisconsin. Freshwater Biology 37: 209-217.

Lawrence, A. P. and M. A. Bowers. 2002. A test of the ‘hot’ mustard extraction method of sampling earthworms. Soil Biology and Biochemisty, 34: 549-552.

Littell, R.C., Milliken, G.A., Stroup, W.W., and Wolfinger, R.D. 1996. SAS Systems for Mixed Models. SAS Institute Inc., Cary, North Carolina, USA.

Lookingbill, T.R., and Urban, D.L. 2005. Gradient analysis, the next generation: towards more plant-relevant explanatory variables. Canadian Journal of Forest Research 35: 1744-1753.

McCune, B., and Grace, J.B. 2002. Analysis of Ecological Communities. MJM Software Design, Gleneden Beach, OR.

Murkin, H.R., Abbott, P.G., and Kadlec, J.A. 1983. A comparison of activity traps and sweep nets for sampling nektonic invertebrates in wetlands. Freshwater Invertebrate Biology 2: 99-106.

Omernik, J.M. 1987. Ecoregions of the conterminous United States. Map (scale 1:7,500,000). Annals of the Association of American Geographers 77: 118-125.

Parkos III, J.J., Santucci, V.J., Jr., and Wahl, D.H. 2003. Effects of adult common carp (*Cyprinus carpio*) on multiple trophic levels in shallow mesocosms. Canadian Journal of Fisheries and Aquatic Sciences 60: 182-192.

Paukert, C.P., and Willis, D.W. 2003. Aquatic invertebrate assemblages in shallow prairie lakes: fish and environmental influences. Journal of Freshwater Ecology 18: 523-536.

Potthoff, A.J., Herwig, B.R., Hanson, M.A., Zimmer, K.D., Butler, M.G., Reed, J.R., Parsons, B.G., and Ward, M.C. 2008. Cascading food-web effects of piscivore introductions in shallow lakes. Journal of Applied Ecology 45:1170-1179.

Prepas, E.E., Planas, D., Gibson, J.J., Vitt, D.H., Prowse, T.D., Dinsmore, W.P., Halsey, L.A., McEachern, P.M., Paquet, S., Scrimgeour, G.J., Tonn, W.M., Paszkowski, C.A., and Wolfstein, K. 2001. Landscape variables influencing nutrients and phytoplankton communities in Boreal Plain lakes of northern Alberta: a comparison of wetland- and upland-dominated catchments. Canadian Journal of Fisheries and Aquatic Sciences 58: 1286-1299.

Rahel, F.J. 1984. Factors structuring fish assemblages along a bog lake successional gradient. Ecology 65: 1276-1289.

Rice, W.R. 1990. A consensus combined P-value test and the family-wide significance of component tests. Biometrics 46: 303-308.

Robinson, C.L.K., and Tonn, W.M. 1989. Influence of environmental factors and piscivory in structuring fish assemblages of small Alberta lakes. Canadian Journal of Fisheries and Aquatic Sciences 46: 81-89.

Scheffer, M. 1998. Ecology of Shallow Lakes. Champman and Hall, London, UK.

Scheffer, M., Hosper, S.H., Meijer, M.-L., Moss, B., and Jeppesen, E. 1993. Alternative equilibria in shallow lakes. Trends in Ecology and Evolution 8: 275-279.

Scheffer, M., van Geest, G.J., Zimmer, K., Jeppesen, E., Søndergaard, M., Butler, M.G., Hanson, M.A., Declerck, S., and De Meester, L. 2006. Small habitat size and isolation can promote species richness: second-order effects on biodiversity in shallow lakes and ponds. Oikos 112: 227-231.

Shaw, S.P., and Fredine, C.G. 1956. Wetlands of the United States, U.S. Fish Wildlife Service Circular 39, Washington, D.C.

Spencer, C.N., and King, D.L. 1984. Role of fish in regulation of plant and animal communities in eutrophic ponds. Canadian Journal of Fisheries and Aquatic Sciences 41: 1851-1855.

Stewart, R.E., and Kantrud, H.A. 1971. Classification of natural ponds and lakes in the glaciated prairie region, Bureau of Sport Fisheries and Wildlife Resources Publication No. 92, Washington, D. C.

Strickland, J., and Parsons, T.R. 1972. A practical handbook of seawater analysis. Bull. Fish. Res. Bd. Can. 167.

Suarez, E R, D M Pelletier, T J Fahey, P M Groffman, P J Bohlen, and M C Fisk. 2004. Effects of Exotic Earthworms on Soil Phosphorus Cycling in Two Broadleaf Temperate Forests. Ecosystems 7: 28-44.

Swanson, G.H. 1978. A plankton sampling device for shallow wetlands. Journal of Wildlife Management 42: 670-672.

ter Braak, C.J. 1986. Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology 67: 1167-1179.

ter Braak, C.J. 1995. Ordination. *In* Data Analysis in Community and Landscape Ecology. *Edited by* R.H. Jongman, C.J. ter Braak and O.F. van Tongeren. Cambridge University Press, Cambridge, U.K.

ter Braak, C.J., and Smilauer, P. 1998. Reference Manual and User's Guide to Canoco for Windows: Software for Canonical Community Ordination (version 4). Microcomputer Power, Ithaca, NY, USA.

ter Braak, C.J., and Wiertz, J. 1994. On the statistical analysis of vegetation change: a wetland affected by water extraction and soil acidification. Journal of Vegetation Science 5: 361-372.

Toms, J.D., and Lesperance, M.L. 2003. Piecewise regression: a tool for identifying ecological thresholds. Ecology 84: 2034-2041.

Tonn, W.M., and Magnuson, J.J. 1982. Patterns in the species composition and richness of fish assemblages in northern Wisconsin lakes. Ecology 63: 1149-1166.

Van Wijngaarden, R.P., Van den Brink, P.J., Oude Voshaar, J.H., and Leeuwangh, P. 1995. Ordination techniques for analyzing response of biological communities to toxic stress in experimental ecosystems. Ecotoxicology 4: 61-77.

Vaughn, S.R., 2009. DNR Watershed Delineation: *Project History, Methodology, Terminology & Data Attribution*. Minnesota Department of Natural Resources - Waters.

Verant, M.L., Konsti, M.L., Zimmer, K.D., and Deans, C.A. 2007. Factors influencing nitrogen and phosphorous excretion rates of a fish community in a shallow lake. Freshwater Biology 52: 1968-1981.

Walker, R.E., and Applegate, R.L. 1976. Growth, food, and possible ecological effects of young-of-the-year walleyes in a South Dakota prairie pothole. The Progressive Fish-Culturist 38: 217-220.

Zar, J.H. 1999. Biostatistical Analyses. Fourth Edition. Prentice Hall, Upper Saddle River, New Jersey, USA.

Zimmer, K.D., Hanson, M.A., and Butler, M.G. 2000. Factors influencing invertebrate communities in prairie wetlands: a multivariate approach. Canadian Journal of Fisheries and Aquatic Sciences 57: 76-85.

Zimmer, K.D., Hanson, M.A., and Butler, M.G. 2001. Effects of fathead minnow colonization and removal on a prairie wetland ecosystem. Ecosystems 4: 346-357.

Zimmer, K.D., Hanson, M.A., and Butler, M.G. 2002. Effects of fathead minnows and restoration on prairie wetland ecosystems. Freshwater Biology 47: 2071-2086.

Zimmer, K.D., Hanson, M.A., and Butler, M.G. 2003. Relationships among nutrients, phytoplankton, macrophytes, and fish in prairie wetlands. Canadian Journal of Fisheries and Aquatic Sciences 60: 721-730.

Zimmer, K.D., M.A. Hanson, B.R. Herwig, and M.L. Konsti. 2009. Thresholds and stability of alternative regimes in shallow prairie-parkland lakes of central North America. Ecosystems 12:843-852.

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Research Experience and Perspective:
My research has long been directed toward development of ecologically-based management strategies for wetlands and shallow lakes. I have focused broadly on wetland ecology, relationships among wetland-dependent wildlife species, and interactions between wetland and shallow lake communities and landscape features. Long-term research themes have centered on food web interactions and effects of fish as structuring influences on native communities of invertebrates and water quality features of prairie wetlands and shallow lakes. Most recently, with collaborators and students, I have sought to identify and measure influences of upland vegetation features on communities and hydrological processes in small wetlands, and to use scale- and watershed-dependent landscape characteristics to model fish and invertebrate communities, and regime dynamics (shallow- v. clear-water states) in shallow lakes.

Other Recent Projects:

2004-2007	Functional linkages among landscapes and shallow lakes: evaluating roles of land use and fish on shallow lake characteristics. (with B. Herwig and K. Zimmer co PIs)
2000-2004	Efficacy of forested buffers for conservation of small wetlands (with B. Palik and others)
2000-2003	Evaluating use of walleye fry to suppress fathead minnow populations in shallow lakes (with B. Herwig and others).
1999-2005	Measuring responses of seasonal wetland communities to age structure and removal of adjacent forest (with students and others)

Publications Related to This Proposal:
Zimmer, K.D., **M.A. Hanson**, B.R. Herwig, and M.L. Konsti. 2009. Thresholds and stability of alternative regimes in shallow prairie-parkland lakes of central North America. Ecosystems 12:843-852.
Potthoff, A.J., B.R. Herwig, **M.A. Hanson**, K.D. Zimmer, M.G. Butler, J.R. Reed, B.G. Parsons, and M.C. Ward. 2008. Cascading effects of piscivore introductions in shallow lakes. Ecological Applications 45: 1170-1179.
Hanson, M.A., K.D. Zimmer, M.G. Butler, B.A. Tangen, and N.H. Euliss, Jr. 2005. Biotic Interactions as determinants of ecosystem structure in prairie wetlands. Wetlands 25:764-775.
Zimmer, K.D., **M.A. Hanson**, and M.G. Butler. 2003. Relationships among nutrients, phytoplankton, macrophytes, and fish in prairie wetlands. Canadian Journal of Fisheries and Aquatic Sciences 60:721-730.
Angeler, D.G., P. Chow-Frazer, **M.A. Hanson**, and S. Sanchez-Carillo. 2003. Biomanipulation: a useful tool for freshwater wetland mitigation? Freshwater Biology 48:2203-2213.
Zimmer, K.D., **M.A. Hanson**, and M.G. Butler. 2001. Effects of fathead minnow colonization and removal on a prairie wetland ecosystem. **Ecosystems 4:346-357**.
Bouffard, S.H., and **M.A. Hanson**. 1997. Fish in waterfowl marshes: waterfowl managers' perspective. Wildlife Society Bulletin 25:146-157.
Hanson, M.A, and M.R. Riggs. 1995. Potential effects of fish predation on wetland invertebrates: a comparison of wetlands with and without fathead minnows.
Hanson, M.A., and M.G. Butler. 1994. Responses of plankton, turbidity, and macrophytes to biomanipulation in a shallow prairie lake. Canadian Journal of Fisheries and Aquatic Sciences 51:1180-1188.

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Research Experience
My current research focuses on the ecology of shallow lakes at community-, ecosystem-, and landscape-scales. I am especially interested in the ecology and influences of fish populations in shallow lakes. Current and recent research projects include:

2004-2007. Evaluating functional linkages among landscapes and wetland attributes: assessing the roles of geomorphic setting, land use, and fish on wetland community characteristics. (M. Hanson and K. Zimmer co PIs)

2000-2003. Evaluation of walleye to suppress fathead minnow populations in Type V wetlands (M. Hanson, J. Reed, B. Parsons co PIs).

Publications Relevant to This Proposal:
Zimmer, K.D., M.A. Hanson, **B.R. Herwig**, and M.L. Konsti. 2009. Thresholds and stability of alternative regimes in shallow prairie-parkland lakes of central North America. Ecosystems 12:843-852.

Potthoff, A.J., **B.R. Herwig**, M.A. Hanson, K.D. Zimmer, M.G. Butler, J.R. Reed, B.G. Parsons, M.C. Ward, and D.W. Willis. 2008. Cascading food web effects of piscivore introductions in shallow lakes. Journal of Applied Ecology 45:1170-1179.

Ward, M.C., D.W. Willis, **B.R. Herwig**, S.R. Chipps, B.G. Parsons, J.R. Reed, and M.A. Hanson. 2008. Consumption estimates of walleye stocked as fry to suppress fathead minnow populations in west-central Minnesota wetlands. Ecology of Freshwater Fish 17: 59-70.

Herwig, B.R., and K.D. Zimmer. 2007. Population dynamics and prey consumption by fathead minnows in prairie wetlands: importance of detritus and larval fish. Ecology of Freshwater Fish 16:282-294.

Zimmer, K.D., **B.R. Herwig**, and L.M. Laurich. 2006. Nutrient excretion by fish in wetland ecosystems and its potential to support algal production. Limnology and Oceanography 51:197-207.

Hanson, M.A., K.D. Zimmer, M.G. Butler, B.A. Tangen, **B.R. Herwig**, and N.H. Euliss. 2005. Biotic interactions as determinants of ecosystem structure in prairie wetlands: an example using fish. Wetlands 25:764-775.

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Research Experience
Dr. Zimmer's research focuses on community and ecosystem ecology of shallow lakes and wetlands. He is particularly interested in food-web interactions involving fish, and the subsequent effect of these interactions at the ecosystem scale. Current and recent research projects include:

2009 - 2012. Collaborative Research (RUI): Burial of organic carbon in temperate, shallow lakes. Funded by the National Science Foundation (K. Theissen, J. Cotner, and M. Edlund co PIs).

2005 - 2008. Carbon Sequestration in Minnesota's Wetlands: An Important Sink with Management Implications. Funded by the Initiative for Renewable Energy and the Environment (K. Theissen, J. Cotner, and S. Sugita co PIs).

2004 - 2007. Evaluating functional linkages among landscapes and wetland attributes: assessing the roles of geomorphic setting, land use, and fish on wetland community characteristics. (M. Hanson and B. Herwig co PIs).

Publications Relevant to This Proposal:
Zimmer, K.D., M.A. Hanson, B.R. Herwig, and M.L. Konsti. 2009. Thresholds and stability of alternative regimes in shallow prairie-parkland lakes of central North America. Ecosystems 12:843-852.
Potthoff, A.J., B.R. Herwig, M.A. Hanson, **K.D. Zimmer**, M.G. Butler, J.R. Reed, B.G. Parson, M.C. Ward, and D.W. Willis. 2008. Cascading food web effects of piscivore introductions in shallow lakes. Journal of Applied Ecology 45:1170-1179.
Verant, M.L., M.L. Konsti, **K.D. Zimmer**, and C.A. Deans. 2007. Factors influencing nitrogen and phosphorus excretion rates by fish in a shallow lake. Freshwater Biology 52:1968-1981.
Herwig, B.R., and **K.D. Zimmer**. 2007. Population dynamics and prey consumption by fathead minnows in prairie wetlands: importance of detritus and larval fish. Ecology of Freshwater Fish 16:282-294.
Scheffer, M., G.J. van Geest, **K.D. Zimmer**, E. Jeppesen, M.G. Butler, M.A. Hanson, M. Søndergaard, S. Declerck, and L. De Meester. 2006. Small habitat size and isolation can promote species richness: second-order effects on biodiversity in shallow lakes and ponds. Oikos 112:227-231.
Zimmer, K.D., B.H. Herwig, and L.M. Laurich. 2006. Nutrient excretion by fish in wetland ecosystems and its potential to support algal production. Limnology and Oceanography 51:197-207.
Hanson, M.A., **K.D. Zimmer**, M.G. Butler, B.A. Tangen, B.H. Herwig, and N.H. Euliss. 2005. Biotic interactions as determinants of ecosystem structure in prairie wetlands: an example using fish. Wetlands 25:764-775.
Zimmer, K.D., M.A. Hanson, and M.G. Butler. 2003. Interspecies relationships, community structure, and factors influencing the abundance of submerged macrophytes in prairie wetlands. Wetlands:717-728.
Zimmer, K.D., M.A. Hanson, and M.G. Butler. 2002. Effects of fathead minnows and restoration on prairie wetland ecosystems. Freshwater Biology 47:2071-2086.

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Current position: Professor, Department of Ecology, Evolution and Behavior, University of Minnesota

Education:

B.A., Wittenberg University, Springfield, Ohio, 1981, Biology.
M.Sc., Kent State University, Kent, Ohio, 1984. Biology.
Ph.D., University of Michigan, Ann Arbor, 1990. Biology.
Post-doctoral research fellow, Great Lakes Environmental Research Laboratory and University of Michigan, Biological Limnology and Oceanography, 1990-1992.

Research Experience: The goal of my research program is to understand how bacteria and humans affect biogeochemical processes in aquatic systems. Microbes are incredibly important to ecosystem processes because of the great magnitude of their biomass and their diverse modes of heterotrophy and autotrophy. Because of this diversity of function, bacteria have significant impacts on the geochemistry of lakes, rivers and oceans. Humans have important effects on lakes and rivers through landscape and species alterations. Current research projects are focused on the Laurentian Great Lakes carbon and phosphorus cycling and the role of shallow lakes and wetlands in the global carbon cycle. Current funded projects:

2007-09 NSF REU ($224,000) for "Field Studies in Global Change at the Headwaters of the Mississippi" , PI: J. Cotner, co-PI: S. Cotner.
2009-2012 NSF Ecosystems RUI for "Burial of organic carbon in temperate, shallow lakes. (K. Theissen, J. Cotner, and M. Edlund co PIs).

Publications relevant to this proposal:

Cotner, J.B., J. Kenning and J.T. Scott. 2009. The microbial role in littoral zone biogeochemical processes: Why Wetzel was right. Verh. Internat. Verein. Limnol. 30 (6): 981-984.
Cotner, J.B., and B.A. Biddanda. 2002. Small players, large role: Microbial influence on auto-heterotrophic coupling and biogeochemical processes in aquatic ecosystems. Ecosystems 5, 105-121.
Biddanda, B.A., and J.B. Cotner. 2002. Love handles in aquatic ecosystems: Role of dissolved organic carbon drawdown, resuspended sediments and terrigenous inputs in the carbon balance of a Great Lake (Michigan). Ecosystems 5: 431-445**.**
Biddanda, B., M. Ogdahl and J.B. Cotner. 2001. Dominance of bacterial metabolism in oligotrophic relative to eutrophic waters. Limnology and Oceanography 46: 730-739.
Cotner, J.B., T.H. Johengen, and B.A. Biddanda. 2000. Intense winter heterotrophic production stimulated by benthic resuspension. Limnology and Oceanography 45: 1672-1676.

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Current Position: GIS Hydrologist, DNR Watershed Delineation Project - Project Manager

Education:

B.S. Water Resources - Hydrology, University of Minnesota, St Paul, MN, 1989

Experience and Perspective

Over the long term, my work has focused on the identification, delineation and digitization of hydrologic features of the surface water system for client consumption and incorporation into GIS applications. As a GIS Hydrologist I have strived to produce watershed delineations that accurately represent the hydrology of the landscape. My intent is to produce watersheds that function as containers of hydrologic entities for modeling and GIS analysis. More recently, I have emphasized the importance of proper watershed data utilization associated with water quality and decision making processes through client and data-user education.

Other Recent Projects:

1998 – Present. DNR Watershed Delineation Project. I Developed all aspects of this intricate statewide project from the ground up, including: project design, GIS production, methodology design and documentation, problem solving, database design, hydrologic-GIS analysis and data development.

2004 – 2007. Evaluating functional linkages among landscapes and wetland attributes: assessing the roles of geomorphic setting, land use, and fish on wetland community characteristics. (with B. Herwig, M. Hanson and K. Zimmer co PIs)

1993 – 1998. Developed an inventory methodology to identify drained wetland boundaries in Chisago County, Minnesota employing the integration of aerial photography interpretation, National Wetlands Inventory, scope and effect of surface water channelization and hydric soil.

Publications Related to This Proposal:

Vaughn, S.R., 2009. DNR Watershed Delineation: *Project History, Methodology, Terminology & Data Attribution*. Minnesota Department of Natural Resources - Waters. Print

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PRESENT POSITION: Professor of Economics & Environmental Studies
Bemidji State University: Sept. 1982 - present

EDUCATION: Ph.D. Economics, 1986, Univ. of Wisconsin-Madison
M.A. Economics, 1980, Univ. of Wisconsin-Madison
B.A. 1978, St. John's Univ.-Collegeville, MN

RECENT PUBLICATIONS:

Boody, Gowda, Westra, van Schaik, Welle, Vondracek and Johnson, "Multifunctional Grass Farming: Science and Policy Considerations," forthcoming in the conference proceedings Farming With Grass, Soil and Water Conservation Society, 2009.

Welle, Cloutman, Koch and Parson, "Biological and Shoreline Trend Monitoring at Tea Cracker Lake, Becker County, MN," technical report to the Minnesota Pollution Control Agency, December 2008.

Welle and Hodgson, "Property Owners' Willingness To Pay For Restoring Impaired Lakes: A Survey In Two Watersheds of the Upper Mississippi River Basin," technical report to the Minnesota Pollution Control Agency, October 2008.

Welle, Cloutman, Koch and Parson, "Biological and Shoreline Trend Monitoring at Beauty Lake, Hubbard County, MN," technical report to the Minnesota Pollution Control Agency, December 2006.

Boody, Vondracek, Andow, Krinke, Westra, Zimmerman, and Welle, "Multifunctional Agriculture in the United States", BioScience, Vol. 55, No.1, January 2005.

Krysel, Marsh Boyer, Parson and Welle, "Lakeshore Property Values and Water Quality: Evidence from Property Sales in the Mississippi Headwaters Region," technical report to the Legislative Commission on Minnesota Resources, June 2003.

Welle, "Economic Perspectives on Water: Clean Water Makes Good Sense (Cents and Scents)," Focus on the Water, Vol. 13, No. 3, May 2002.

Welle, "Multiple Benefits from Agriculture: A Survey of Public Values in Minnesota", technical report to the Legislative Commission on MN Resources, July 2001.