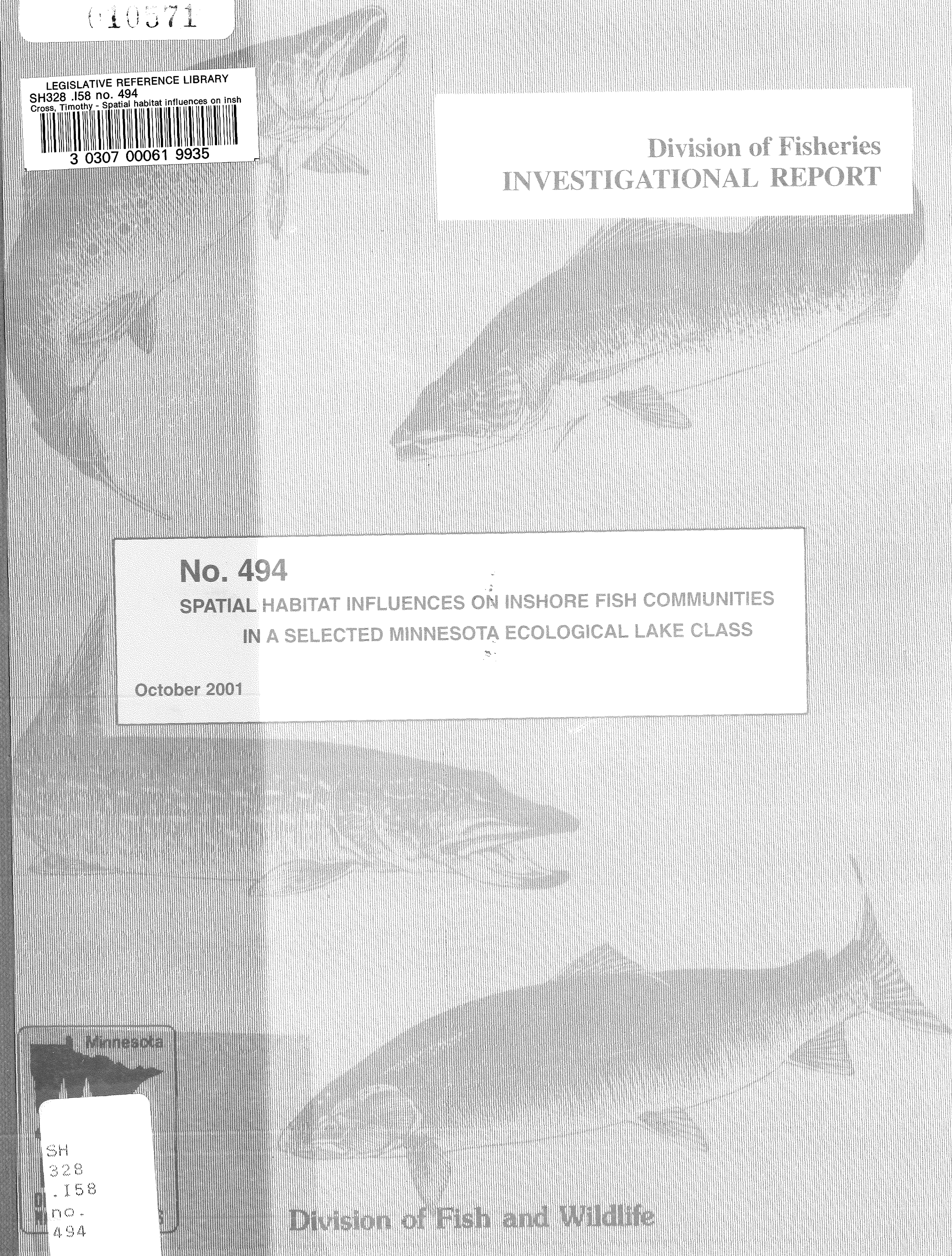

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SPATIAL HABITAT INFLUENCES ON INSHORE FISH COMMUNITIES IN A SELECTED MINNESOTA ECOLOGICAL LAKE CLASS[1]

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Abstract - We described habitat characteristics of 113 Minnesota ecological Lake Class 24 lakes at different spatial scales and developed empirical models linking habitat characteristics to species and abundances of fish. At the largest scale of analysis, variation among Lake Class 24 trap net catches were linked to a geographic gradient from north to south that corresponded to regional differences in edaphic characteristics and geomorphology along with land use. At the watershed-lake scale of analysis, we reduced a list of 18 physical and chemical variables to 7 less redundant key variables. Using these 7 variables in regression tree analysis, we accounted for 25 to 67 percent of the variation in trap net catch per unit effort (CPE) among lakes for 8 individual fish species. Also, for 53 lakes that had lake survey plant data collected, we found the frequency of fine-leaf type plant cover occurrence was a key variable used in regression tree models of bluegill, pumpkinseed, black crappie, yellow bullhead, black bullhead, walleye, and common carp trap net CPE. A strong influence of submergent plant cover on more localized fish abundance was also found in the analysis of a second data set consisting of data on plant, substrate, and depth mapped at individual trap net and electrofishing sampling sites in six representative lakes. Models of bluegill abundance at sampling sites developed in this analysis were integrated in a geographical information system to illustrate the distribution of bluegill habitat suitability within lakes. These models reveal how bluegill abundance relates to human shoreline activity, fetch and aspect towards prevailing winds, or other external factors with locational attributes.

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Introduction

Management of natural lake habitats is vital for maintaining quality sportfishing in Minnesota, and quantitative information on the influence of these habitats on fish populations is needed for effective fisheries management. Current fisheries management practices in Minnesota lakes were founded on fundamental relationships between lentic habitats and fish communities. Moyle (1946; 1956) described increases in fish yield and changing species assemblages along a geographical gradient from northeast Minnesota to southwest Minnesota that corresponds to increased water fertility. Moyle (1956) wrote that: *"A natural balance tends to be achieved between the size and structure of the fish population and the chemistry of the water and the factors which influence that chemistry. Fish-management procedures should be considered in this light for often corrective stocking and rough-fish removal are aimed at changing the structure of fish populations that are already in natural balance with the physical and chemical environment."* The Minnesota ecological lake classification system (Schupp 1992) provides a foundation for furthering our understanding of fish-habitat relationships by providing subsets of lakes similarly affected by large-scale limnological variables. Jackson et al. (2001) suggested that lakes different only in their macrophytes, nutrient load, and connections be studied together to predict the effect of changing these variables. Holistic approaches that combine large scale analysis of abiotic influences with smaller scale studies of fish yield and production are needed so that wise management decisions can be made (Hinch 1991; Pierce et al. 1994).

Many relationships between habitats and fish populations have been identified, but interactions among habitat variables are complex. Colby et al. (1987) and Summerfelt (1993) reviewed several case histories illustrating eutrophication, lake morphometry, water level fluctuations, macrophyte abundance, and turbidity affects on food, spawning, and nursery areas that subsequently favored some fish species over others. Within lakes, spatial variables related to lake morphometry affect the productivity, faunal distribution, habitat complexity, and spatial separation of habitats. Physicochemical factors within lakes such as dissolved oxygen concentrations, temperature, turbidity, and chemical contaminants also affect productivity, as well as physiological tolerances and concomitant distribution of fish (Mathews 1998). Bottom and macrophyte substrates appear to influence fish populations by providing spawning habitat and protective cover for small fish, and invertebrate food sources (Engel 1985; Poe et al. 1986). The land-water interface, plant communities, and bottom substrates contribute to an ecological "edge effect" linked to increased diversity and densities of animals. Fish in lakes are distributed mostly inshore (Keast and Harker 1977; Craig and Babaluk 1993), where increased habitat complexity provides more habitat types to meet the needs of a variety of species and life stages (Keast 1978).

Fish habitats are defined by several spatial and temporal scales of analysis (Mason and Brandt 1999), and spatial data sets describing geological, hydrological, and land-cover characteristics are rapidly being developed to integrate with information on fish populations (Lewis et al.1996). Large-scale watershed factors relating to glacial isolation and connections with other aquatic environments are known to affect fish communities and species composition. Differences in fish assemblages among many lakes in Minnesota and Ontario are the result of post-glacial dispersal of fishes (Underhill 1989; Jackson and Harvey 1989; Hinch et al. 1991). Within drainages, fish communities are affected by connections among water bodies that allow fish to exchange (Tonn and Magnuson 1982; Robinson and Tonn 1989; Osborne and Wiley 1992). Often, a significant portion of the habitat utilized by fish during a particular season or life stage occurs in interconnected wetlands or streams. For example, wetlands often act as spawning and nursery areas for many fish species dependent upon this type of habitat (Navarro and Johnson 1992). The quantity and quality of water draining into lakes from their watersheds also affects the community structure and abundance of fish found in lakes. Watershed size and land use directly influence the amounts of sediments and nutrients entering lakes (National Research Council 1992). Watershed size also affects water residence times which in turn affects primary productivity and the volume of water exchanged with other water bodies. Lakes with high flushing rates tend to provide less stable environments that are associated with decreased fish production (Carline 1986; Marshall and Ryan 1987; Regier and Henderson 1973). In Minnesota, Cross and McInerny (1995) found that lakes with smaller watersheds favored higher abundances of sunfish *Lepomis* spp., northern pike *Esox lucius*, and largemouth bass *Micropterus salmoides* while lakes with larger watersheds favoured higher abundances of black bullhead *Ameiurus melas*, black crappie *Pomoxis nigromaculatus*, and common carp *Cyprinus carpio*. Likewise, Mitzner (1995) reported that Iowa impoundments with smaller watersheds had higher quality bluegill populations.

At smaller scales of analysis, recent advances in digital technology such as global positioning systems (GPS) and geographic information systems (GIS) have greatly enhanced our ability to identify relationships between fish populations and spatial habitat attributes. To document habitat in these inshore areas, new GPS technology has facilitated precise and accurate location fixes (Keating 1993). Quantitative attributes assigned to locational data are readily adapted to spatial analysis in digital form using GIS. The use of GIS enables several layers of descriptive and quantitative inventories with geographical attributes to be analysed simultaneously (Berry 1993).

Minnesota DNR (1993) guidelines recommend documenting effects of fish habitat at both community and species levels. Protection and enhancement of the fisheries in lakes according to these guidelines will require information describing the effects of human activities on fish habitat. Previous work revealed fish populations in Minnesota ecological Lake Class 24 lakes (Schupp 1992) were susceptible to human influences associated with extensive recreational use and watershed development (Cross and McInerny 1995). However, GIS data coverages describing hydrology and land cover attributes at a scale appropriate for individual lake watershed analysis were subsequently developed which offer significant improvements over those used by Cross and McInerny (1995). Also, the potential for using GPS to facilitate accurate and detailed GIS coverages of lake habitat features and fish sampling sites adds another dimension to defining fish habitat relationships in these lakes. Frequently, such site-specific information is needed for the review and permitting of human shoreland and aquatic plant community alterations. Consequently, we attempted to develop and use these new approaches to quantitatively examine relationships between lake habitats and fish populations geographically linked over different spatial scales to document effects of human interactions on fish populations. The objective of this study was to quantitatively describe habitat characteristics of ecological Lake Class 24 lakes over several spatial and temporal scales, and develop empirical models linking these habitat characteristics to species and fish abundances. After further development, such empirical models will benefit aquatic resource management by facilitating the identification, protection and restoration of essential habitats required to sustain and conserve fish populations.

Methods

Two data sets representing different scales of analysis were used in this study. These data focussed primarily on relationships of aquatic habitats to the abundance of sportfish species (primarily bluegill and largemouth bass) commonly sampled by inshore sampling gears (trap nets and electrofishing). The first data set, comprised of data representing most ecological Lake Class 24 lakes (113), was analysed to describe how differences in lake location, watershed factors, lake habitat parameters quantifying whole lake water quality, inshore substrates, and aquatic plant abundance related to differences in trap net and electrofishing catches in the standardized MNDNR lake surveys and assessments. The second data set was collected at a finer spatial scale than the first, and consisted of six Lake Class 24 lakes selected to represent a wide range of habitats. These data were analysed to examine how detailed mapped data on inshore substrates, aquatic vegetation, and bottom slope relate to localized (site to site) differences in fish assemblages as sampled by trap nets and electrofishing gear during four different time periods.

Study Area

Most ecological Lake Class 24 lakes were formed as buried ice in glacial end moraines, and are located in areas of kame - kettle topography (Figure 1). Slightly over one-half of the lakes, mostly located to the west and south of the geographic range of these lakes, were in an area most recently covered by the Des Moines Lobe of the Wisconsin glaciation. Glacial till of the Des Moines Lobe contained a high volume of Paleozoic limestone and Cretaceous shale fragments, which with loess swept from the surface by wind, comprise the parent material for most of the soils in this area (Ojakangas and Matsch 1982). Topsoils throughout this area were formed under wooded vegetation that has been removed in many areas for agricultural production (NRCS 2000). The remaining Lake Class 24 lakes, located more to the east and north, were in an area most recently covered by the Grantsburg Sublobe of the Wisconsin glaciation. Soils associated with this area have lower pH and phosphorus (MNDNR 2000a).

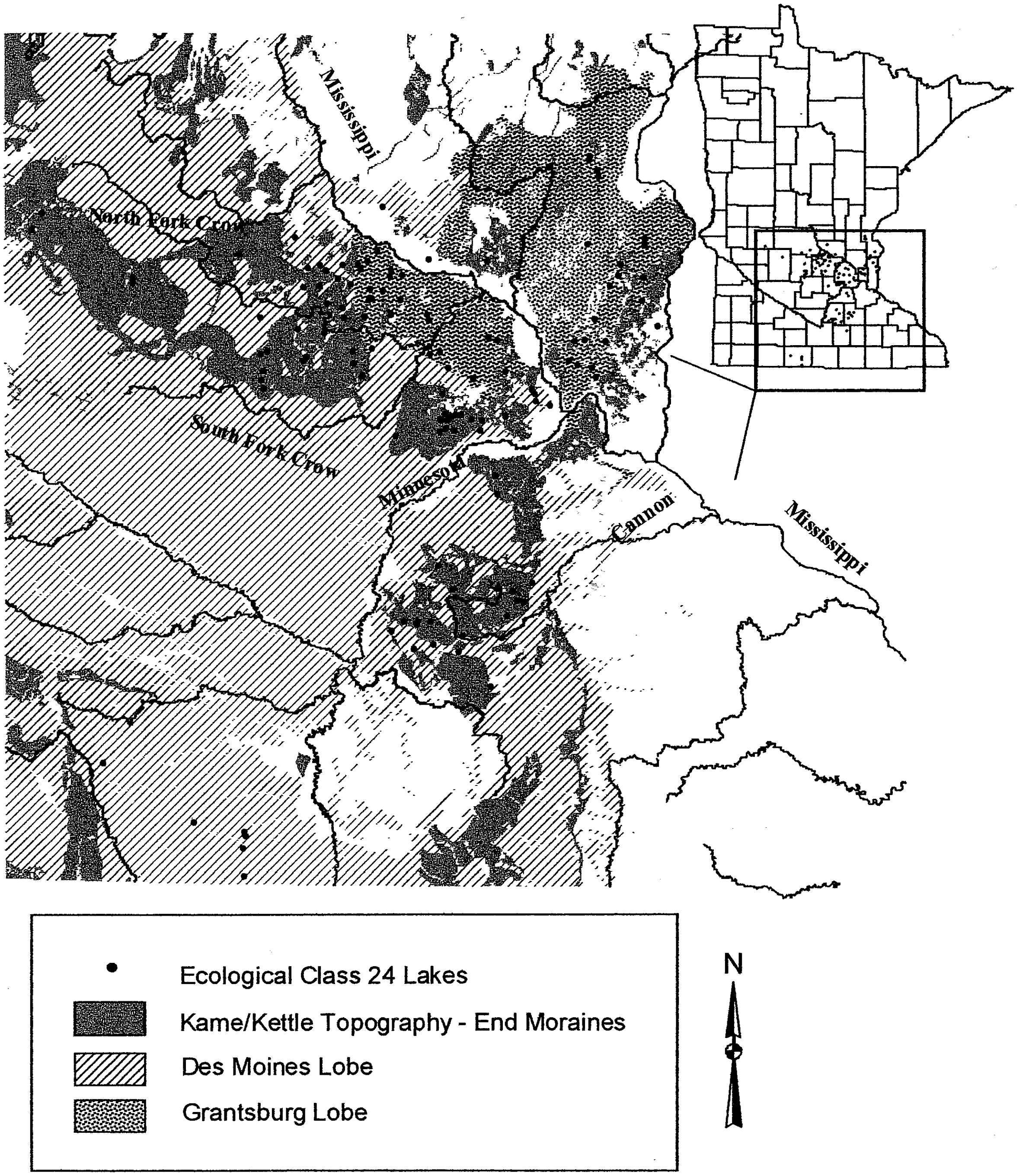
Data Set I: Ecological Lake Class 24 Analysis

Several watershed and whole lake habitat variables for Lake Class 24 lakes were examined and screened to develop empirical models describing relationships between habitat and sportfish abundance. First, we compiled a data set of various watershed and whole lake habitat parameters. Next, we applied principal components analysis (Stenson and Wilkinson 2000), correlation analysis, and graphical analysis to examine interrelationships among the parameters, including spatial auto-correlations, and to reduce the list of habitat variables to a less ambiguous subset of the most influential. Finally, we determined effects of connections between Lake Class 24 lakes to other water bodies on fish catches, and derived empirical models describing watershed and whole lake habitat effects on sportfish abundance using the reduced list of independent habitat variables.

Habitat Data

We quantified a comprehensive list of lake ecosystem variables for ecological lake Lake Class 24 lakes. Lake watershed boundaries were delineated and matched with data describing geologic, edaphic, and land cover characteristics using GIS. Height-of-land watershed boundaries (MNDNR 1979) for each lake were delineated. We used ArcView® GIS and MNDNR ArcView extensions to overlay MNDNR minor watershed delineations (watersheds > 13 km^2 of any stream, river, or ditch) on United States Geological Survey (USGS)1:24,000 scale topographic map digital raster graphics (DRG), digital elevation models (DEM), and digital orthophoto quadrangles (DOQ) to identify watershed boundaries that were subsequently digitized as polygons using heads-up digitizing procedures. Lake watershed polygons were used to extract corresponding data from GIS coverages of hydrology, land cover, and geomorphology (MNDNR 2000b and MNDNR 2000c). Land cover data were based on an 8 category

Figure 1. Location of ecological class 24 lakes in relation to glacial history and geomorphology.



classification assigned by 30 m grid cells which encompasses the entire state of Minnesota. Wetlands identified in the National Wetlands Inventory (NWI) GIS coverage were extracted as United State Fish and Wildlife Service (USFWS) Circular 39 types following MNDNR conversion from the Cowardin et al. (1979) classification (MNDNR file data). Wetlands were categorized as either lake connected or not connected based on visual inspection of the NWI data overlayed with stream hydrography GIS data and topographic map DRG's. Areas of each wetland classification were calculated in ArcView® for each lake watershed and standardized by converting to percentages of the watershed area. We also categorized connections between Lake Class 24 lakes and other water bodies as strong or weak. Lakes connected to other water bodies by streams classified as permanent on USGS 1:24,000 topographic maps or with open water connections to other water bodies visible on USGS DOQ's were defined as strongly connected. Lakes without connections or with only intermittent stream connections on USGS 1:24,000 maps were defined as weakly connected.

We derived lake morphometric data from lake contour maps using GIS. Existing scanned images of MNDNR lake depth contour maps (Tiff files) were converted to GIS polygon coverages of depth contours for morphometric calculations. An ArcView® extension developed by the MNDNR was used for rectifying scanned images to correct geographic coordinates cross referenced with control points on a geocorrect base layer, which in our case was either a USGS DOQ or 1:24,000 topographic map DRG. Generally at least seven control points identified from prominent shoreline features, inlets, outlets, boat ramps, or road features were used to register the maps to Universal Transverse Mercator (UTM) coordinates. With the scanned lake contour map superimposed on a DOQ, we again used ArcView® heads-up digitizing techniques to digitize the lake boundary and contour lines. For most lakes, contour lines were in 1.5 m (5 ft) increments to 6.1 m (20 ft) of depth, and 3 m (10 ft) increments thereafter. We calculated areas for each contour using an ArcView® calculator extension. Littoral area was calculated as the percentage of the total lake area with < 4.6 m (15 ft.) water depth, and limnetic area was calculated as the area > 3m (10 ft). Lake volumes were estimated by summing the volume (v) of each isobath estimated from the equation:

$$V_{z0} - V_{z1} = \tfrac{1}{3}(A_{z0} + A_{z1} + \sqrt{A_{z0} \times A_{z1}})(z_0 - z_1),$$

where A is the contour area (m^2), z_0 is the upper contour depth (m), and z_1 is the lower contour depth (m) (Cole, 1979). Mean depths were calculated by dividing the lake volume (m^3) by the lake surface area (m^2). Shoreline development factor was from MNDNR lake survey file data.

Additional data describing physical, chemical, and biological characteristics for many ecological Lake Class 24 lake were obtained from standardized MNDNR lake surveys. Values for lake water chemistry parameters included Secchi transparency (m), total alkalinity (mg/l $CaCO_3$), pH, total phosphorus (mg/l), total dissolved solids (mg/l), chlorophyll *a* (μg/l), and specific conductance (μS/cm) were extracted from lakes surveyed between 1980 and 1997. The Fisheries data warehouse also provided data on shoal substrate composition and aquatic plant cover as estimated by lake survey crews using MNDNR standardized procedures (MNDNR 1993). Areal cover of *Chara*, coontail *Ceratophylum* spp., milfoil *Myriophylum* spp., wild celery *Valisneria* spp., cattail *Typha* spp., bullrush *Scirpus* spp., and water lily *Nymphaea* spp. in each lake were estimated as the percent of transects in which they occurred. Likewise, we quantified the occurrence of different shoal substrate types as the percent of transects in which they occurred.

Fish Survey Data

MNDNR Fisheries data warehouse was used for describing trap net catches in standardized lake surveys. Scientific and common names of fish species analysed in this study are listed in Appendix I. Catch per unit effort (CPE) for each individual fish species was averaged in each lake for the period 1980 to 1997. Lake Class 24 lakes were typically surveyed on two to five occasions during this period. Lake surveys are primarily conducted by the MNDNR from June through August. To detect the influence of seasonal variation in trap net catches, we correlated the average catches of individual species with their average survey date. Significant temporal variation was evident for catches of bluegill (-), pumpkinseed (-), and walleye (+). Consequently, for subsequent analysis of trap net catches for these species, the data were separated into early (June) and late (July-August) periods.

In addition to surveys of trap netted fish, we also compiled data on electrofishing catches of largemouth bass. Data were queried from the MNDNR Fisheries data warehouse and supplemented with data on Lake Class 24 lakes sampled in a previous study by McInerny and Cross (1996). We only used electrofishing surveys conducted at night during the months of May and June in order to minimize effects of temporal and seasonal variation (McInerny and Cross 2000).

Data Analyses

We applied several statistical techniques to synthesize habitat-fish relationships and develop predictive models of the relative abundance of littoral fish species. Patterns among habitat data and occurrences of similarly correlated variables were examined with Pearson correlation matrices after transformation of individual variables (Snedecor and Cochran, 1980). Due to the limitations imposed by listwise deletion of variables, we used several correlation matrices in order to include as many lakes as possible in each analysis. Significance of correlation coefficients was uncorrected for multiple comparisons. Geographical associations were also determined as Pearson correlation coefficients between individual lake ecosystem parameters and UTM easting and northing coordinates. Principal components analysis (PCA) with varimax rotation was used to reduce the dimensionality of the 19 watershed, lake morphometry, and water quality variables that cover the entire set of 113 lakes (Table 1). We used a correlation matrix as input because of large differences among variables in the units of measurement (Rexstad et al. 1988). For subsequent analyses, where the use of fewer independent variables would be advantageous, a subset of variables highly correlated with individual rotated principal components was selected.

We also used principal components analysis to identify gradients in fish assemblage structures among lakes. As with the analysis of ecosystem habitat variables, PCA with varimax rotation (Stenson and Wilkinson 2000) was used with a correlation matrix as input. Spatial variability in average trap net CPE among lakes for key fish species was examined both graphically and by correlation with UTM northing and easting coordinates. The influence of connections to other water bodies on trap net CPE was examined by use of a series of two-sample t-tests comparing trap net CPE of individual species and species richness in weakly verse strongly connected lakes.

We used regression tree analysis (Wilkinson 2000) to predict trap net CPE of several common fish species, and trap net species richness in individual lakes using lake ecosystem habitat factors. Seven key lake ecosystem variables identified with PCA were used as independent variables for analysing the complete set of 113 lakes. Additionally, on a subset of 53 lakes for which more extensive lake survey data were available, we added 4 additional independent variables; frequency occurrence of emergent vegetation (bullrush and water lily), frequency occurrence of fine-leaf vegetation (*Chara*, coontail, and milfoil), total phosphorus, and frequency occurrence of gravel substrates in shoal areas. These four variables were selected based on their influence in correlation analysis. The regression tree analysis (RTA) procedure of SYSTAT 10 was used with least-squares loss function which minimizes within-group sum of squares about

Table 1. Statistical description of physical, chemical, and biological lake and watershed parameters for Lake Class 24 lakes. Asterisks denote variables used by Schupp (1992) to classify Minnesota lakes.

Variable	n	Minimum	Maximum	Median	Coefficient of Variation %
Watershed					
Watershed area (ha)	113	459	100,788	4,058	158
- urban (%)	113	0.7	74.4	5.5	125
- cultivated (%)	113	<0.1	89.8	36.9	64
- grass/brush (%)	113	0	26.6	11.9	50
- forest (%)	113	0.7	39.5	12.7	6
- open water (%)	113	2.2	48.8	16.5	54
- marsh (%)	113	0	25.3	4.1	87
Connected water area (ha)	113	136	25,637	840	173
- lake/ type 5 wetlands (%)	113	6.1	100.0	70.9	35
- marsh/ type 4 wetlands (%)	113	0	3.2	0.06	185
Lake Morphometry					
Lake area (ha)*	113	36	912	115	85
Volume (m^3)	113	1,269,171	32,258,933	6,320,770	83
Mean depth (m)	113	2.4	10.2	4.5	32
Maximum depth (m)*	113	5.2	32.9	13.7	42
Littoral area (%)*	113	20	79	50	25
Area > 3 meters deep (%)	113	20	68	40	27
Shoreline development*	113	1.04	2.44	1.42	23
Water Chemistry					
Secchi transparency (m)*	113	0.31	5.00	1.36	54
Total alkalinity (mg/L $CaCO_3$)*	113	52	236	138	26
pH	96	7.1	22	8.5	17
Total phosphorus (mg/L)	90	0.005	0.450	0.050	126
Total dissolved solids (mg/L)	90	44	453	254	30
Chlorophyll *a* (μg/L)	72	3	141	13	106
Specific conductance (μS/cm)	60	135	600	358	29
Shoal Substrate Occurrence (Percent of Transects)					
Boulder	54	0	77	4	155
Clay	54	0	100	0	209
Detritus	54	0	100	5	145
Gravel	55	0	93	50	55
Marl	55	0	24	0	340
Muck	55	0	90	15	100
Rubble	55	0	87	23	87
Sand	55	23	100	90	23
Silt	55	0	100	27	99
Plant Occurrence (Percent of Transects)					
Chara	56	0	100	10	124
Coontail	56	0	100	80	52
Milfoil	56	0	100	15	118
Eurasian water milfoil	56	0	100	0	194
Vallisneria	56	0	100	0	177
Cattail	56	0	90	17.5	96
Bullrush	56	0	47	5	131
Lily	56	0	160	16	129

the group mean for each split in the classification tree. The minimum proportional reduction in error allowed at each split was set to 0.05, the minimum split value was set to 0.05, and the minimum number of lakes classified at the end of each node was set to 5. These settings appeared to provide a reasonable level of classification given the number of variables and lakes in the data set. The overall proportion of reduction in error term (PRE), which is equivalent to the multiple R^2 statistic, was used to judge the suitability of RTA models.

Application of Lake Class 24 bluegill habitat model to study lakes

Lake Class 24 RTA models predicting mean lake trap net catches of bluegill were applied to the six selected study lakes using data on bluegill CPE and plant and substrate occurrence compiled independent of the database (Table 2). Bluegill trap net CPE predicted from RTA models with and without lake survey variables were plotted against observed August bluegill CPE for each study lake and compared graphically. This was done to gage on how well watershed and lake scale variables describe the relative abundance of bluegill in the study lakes, as well as provide insight into the effects of site-scale variables described in subsequent analyses.

Data Set II: Study Lake Analysis

For six selected Lake Class 24 lakes, we used mapped data on inshore substrates, aquatic vegetation cover, and bottom slope to describe the occurrence and abundance of sportfish at a site specific scale over different time periods. Surveys of inshore substrates and aquatic vegetation as well as fish sampling locations were all mapped in a GIS which enabled us to geographically link site specific habitat descriptions to relative fish abundance as determined from catch data. This information was then used to develop empirical models of site specific habitat-fish relationships with the potential for geographically linking back to the mapped data layers as spatial models of fish habitat suitability.

Table 2. Description of the study lakes (Erie, French, Stahls, Cokato, Granite, and Mary) with selected variables used in regression tree analysis of trap net catches in Lake Class 24 lakes.

Variable	Erie	French	Stahls	Cokato	Granite	Mary
Physical - Chemical Variables						
Lake area (ha)	80	141	58	224	148	77
Mean depth (m)	4.5	5.0	4.1	6.5	5.2	5.6
Secchi depth (m)	1.9	1.0	1.5	1.6	1.5	1.3
Total alkalinity (mg/L)	145	156	133	235	120	123
Watershed area (ha)	467	3741	2178	30200	2198	552
Forested land cover (%)	12	13	14	4	8	8
Cultivated land cover (%)	36	43	45	77	54	35
Lake Survey Variables						
Emergent plant occurrence (%)	20	25	15	1	10	1
Fine leaf submergent occurrence (%)	80	15	95	5	85	100
Shoal gravel occurrence (%)	60	32	80	50	80	80

Habitat Data

We measured and mapped aquatic habitat features in six lakes (Lake Erie,Meeker Co.; Stahls Lake, McLeod Co.; and Mary, Granite , French and Cokato lakes, Wright Co.) chosen to represent a broad range of ecological Lake Class 24 habitat types. Lakes Erie and French were sampled in 1997, lakes Cokato and Stahls in 1998, and lakes Granite and Mary in 1999. In each lake, point-transect sampling methodology adapted from the MNDNR Lake Survey Manual (1993) was used for assessing inshore shoal (0 to 1.8 m depth) bottom substrates and plant habitat parameters. Transects were spaced completely around each lake at intervals of approximately 200 m depending upon habitat uniformity (interval distance decreased with increased habitat variability). Point samples started at the shoreline and proceeded towards the center of the lake at approximately 0.6 m to 1 m depth increments until the limits of plant growth were exceeded (usually < 5 m). At each sampling point, depth, shoal bottom substrate composition, and submergent aquatic plant cover were measured and tagged with a differential corrected GPS location (±1 - 3 m) using a Corvallis Microtechnology Incorporated March II®, 2 Megabyte GPS data recorder. Shoal bottom substrates were assessed in May and classified as detritus, muck, marl, clay, silt, sand, gravel, cobble, and boulder (MNDNR 1993). Percent composition of each substrate type was estimated in 10% increments (0, 1-10,11-20,21-30,31-40,41-50,51-60,61-70,71-80,81-90,and 91-100). Submergent aquatic plant cover was assessed during spring (early May), early summer (late June), late summer (August), and fall (late September). Plant cover was classified as broad-leaf, narrow-leaf, milfoil, coontail, *Chara*, wild celery, matted or attached algae, and *Elodea*. Areal cover of each submergent plant class was also estimated in 10% increments. Emergent aquatic plant cover areas were assessed in early summer and classified as cattail, bullrush, lily, or woody. Boundaries of emergent plant beds were traversed with a boat or on foot and recorded in a GPS. Emergent plant cover areas were recorded as polygon or line features that were later edited to polygons in a GIS with a USGS DOQ basemap.

Lakewide coverages of submergent vegetation and shoal bottom substrates were estimated with raster GIS processing. First, depth contours at 0.6 m to 1.0 m intervals were digitized and added to depth contours digitized from MNDNR lake maps in a raster format (1 m resolution). Transect point substrate and plant cover attributes were downloaded from the GPS unit with UTM coordinates and copied to a GIS layer of each lake contour (ie. 0-0.6 m, 0.6-1.2 m, 1.2-1.8 m, 1.8-2.4, 2.4-3.1 m, 3.1-3.7 m, and 3.7-4.5 m) using the EPPL7 gridpoint procedure (LMIC 1997). Interpolated values for each attribute were assigned to areas between transect points within each depth contour layer using the EPPL7 interpolate function (LMIC 1997). The EPPL7 interpolate function converts values between point data by computing a weighted average of the nearest surrounding data values which results in a continuous surface between isolated sampling points. A lakewide GIS coverage for each substrate and vegetation type was then created by merging data layers for all the depth contours. The final step was to smooth areas of exaggerated contrast between the contour intervals of this merged data layer using the EPPL7 moving windows function specified with a 10 m circular average (LMIC 1997). In addition, a data layer of distance from the 4.6 m (15ft) contour was calculated using EPPL7 radius procedure (LMIC 1997). This variable relates to both depth and slope as well as representing travel distance from limnetic habitats.

Fish Data

We sampled fish populations in all six study lakes during the same four time periods as the plant surveys using trap nets and a boat mounted electrofishing unit. Locations of trap net and electrofishing sites were determined with a GPS (±1 - 3 m), and held constant for all sampling periods. Trap net sites were recorded as point features and electrofishing sites were recorded as line features. Double-frame 3/8 inch trap nets were set at 12 locations in each lake following standardized MNDNR lake survey procedures (MNDNR 1993). During mid-day, five minute electrofishing runs were done at seven or eight locations in each lake using pulsed DC current. During the electrofishing runs, the electrofishing boat was guided between the shoreline and 1.8 m (6 ft) contour in a sinuous pattern aimed at sampling all depths representatively. One netter was used to collect all fish. For night samples, the same electrofishing procedure was repeated after sunset. All fish captured at each site and gear were identified to species and measured (total length in cm).

Quantitative descriptions of site habitats were extracted from GIS data layers of habitat inventories. Trap net sites were defined as the set location buffered by 50 m, and electrofishing sites were defined as the area between the shoreline and 1.8 m contour adjacent to the electrofishing run line. The 50 m buffer distance for trap net sites was judged to be appropriate for the resolution of the habitat data in the GIS and for keeping sites discrete. Average site values for each GIS habitat layer (distance to 4.6 m contour, plant cover types, and substrate types) were calculated for each trap net and electrofishing site using EPPL7 outtable averaging (LMIC 1997).

Data Analyses

We developed empirical models linking site habitats to the relative abundance for littoral fish species using similar procedures to those applied to the Lake Class 24 analysis. First, summary statistics were calculated to examine spatial and temporal variability of microhabitat data in the study lakes. Because of the discontinuous nature of some of the rarer habitat features, similar plant cover and substrate types were consolidated to obtain variables with continuous distributions; organic substrate was formed by combining detritus and muck substrates; rubble substrate was formed by combining cobble and boulder; and sand and gravel were also combined. Among plant cover types, all aquatic vascular aquatic plant types were combined as a single variable and fine-leaf plant cover was formed by combining *Chara*, coontail, and milfoil plant cover types (the fine-leaf category was a subset of the all vascular plants category). To approximate normal distributions, log transformations were applied to each of the site habitat variables except for distance to the 4.6 m contour that already approximated a normal distribution.

We examined interrelationships among habitat variables with PCA and correlation analyses. Pearson correlation matrices were calculated for trap net site data to reveal patterns in the data and identify similarly correlated variables. Significance was determined for correlation coefficients with $P < 0.05$ uncorrected for multiple comparisons. As with the analysis of Lake Class 24 data, PCA with varimax rotation was used on a list of 13 electrofishing site habitat variables (organic, silt, sand-gravel, and rubble substrates; May algae, May broad-leaf, May fine-leaf, and May total plant cover; June algae, June broad-leaf, June fine-leaf, and June total plant cover; and 4.6 m contour distance) using a correlation matrix as input. Site habitat variables highly correlated with the rotated principal components were used to interpret habitat gradients identified by each calculated principal component.

Predictive models of fish catches in trap nets and electrofishing runs were derived from site habitat data. Stepwise logistic regression analysis was initially used to elucidate possible predictive relationships with presence and absence of fish species or sizes based on 9 site habitat variables (distance from 4.6 m. contour, organic substrate, silt substrate, sand/ gravel substrate, rubble substrate, attached algae plant cover, broad-leaf plant cover, fine-leaf plant cover, and vascular plant cover). This analysis was only applied to fish species and size groups that occurred too infrequently (<75% of the samples) for the application of stepwise multiple linear regression techniques requiring a continuous distribution in the dependent variable. Probability for variables to enter and be removed from the model was set to 0.10. The models were judged based on McFadden's Rho^2 (a statistic intended to mimic an R^2 value except that values between 0.20 and 0.4 are considered satisfactory), and prediction success indicators which show the model gain over a purely random model that assigns the same probability of species occurrence to every observation (Steinberg and Colla 2000). The success indicators are broken down as the gain over the random model for species presence (sensitivity) and species absence (specificity) cases (Steinberg and Colla 2000). We applied multiple linear regression analysis to explore predictive models of CPE of fish species occurring in >75% of the trap net and electrofishing samples (bluegill and black crappie in trap nets and bluegill and yellow perch in electrofishing samples) using both forward and backward stepping strategies. As with logistic regression, the probability for variables to enter and be removed from the model was set to 0.10.

Regression tree analysis (Wilkinson 2000) was used to develop predictive models of fish catches and species richness based on site habitat variables. The same nine variables used in stepwise regression procedures were also used in the RTA. The minimum proportional reduction in error allowed at each split was set to 0.05, the minimum split value was set to 0.05, and the minimum number of sites classified at the end of each node was set to 5. The overall PRE was used to judge the predictability of the resulting RTA models.

We developed spatial models of habitat suitability based on RTA results using GIS habitat inventories of the study lakes. The entire inshore electrofishing zone (shoreline out to 2 m of water depth) and inshore trap netting habitat (shoreline and 50 m into the lake) for each study lake were segregated into discrete sampling units corresponding in size to sites used in the site analysis. Averages for each habitat type (plant cover, substrate composition, and distance from 4.6 m depth contour) were calculated using the same procedure used in the site analysis. These values were then categorized according to criteria identified in RTA models for predicting abundances of fish at each site, and then displayed spatially on maps for each lake.

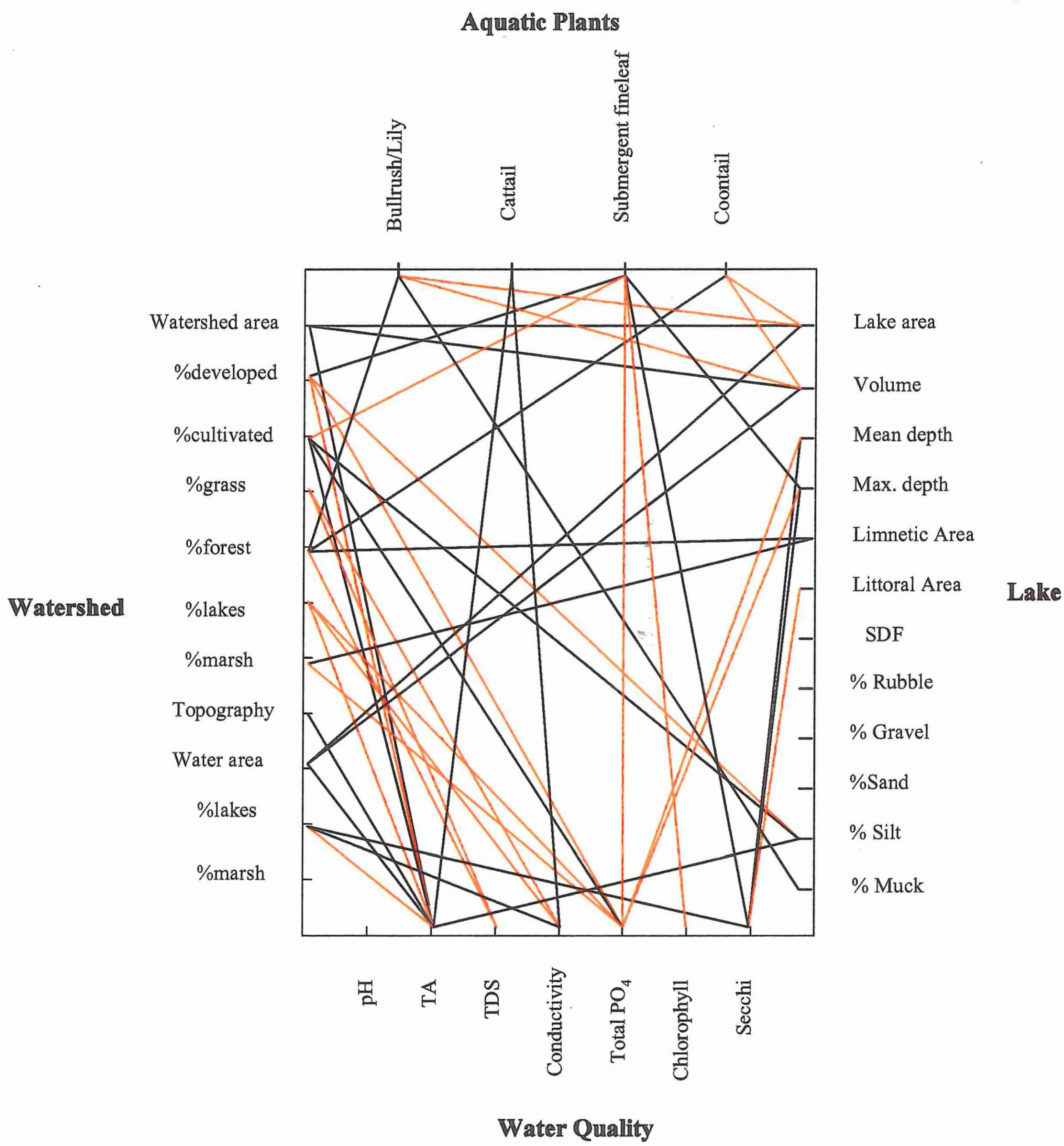
Results

Data Set I: Ecological Lake Class 24 Analysis

Habitat

Several linkages occurred between watershed, lake morphometry, water chemistry, bottom substrate, and plant cover ecosystem components of Lake Class 24 lakes. Individual parameters of these ecosystem components were often variable with coefficients of variation exceeding 50% (Table 1). Watershed size, connected water area, and the percentage of connected water classified as marsh were the most variable watershed parameters. Lake size was the most variable lake morphometry parameter, total phosphorus was the most variable water chemistry parameter, frequency occurrence of marl and clay substrates were the most variable bottom substrate parameters, and frequency occurrence of eurasian watermilfoil and *Valisneria* were the most variable plant parameters. Patterns of correlations between ecosystem components provide insight into possible linkages among these components. For example, increases in cultivated land cover in the watershed is associated with higher lake phosphorus concentrations, which is linked to less submergent vegetation, which is also associated with lower maximum lake depths (Figure 2). Parameters within ecosystem components were usually not considered as independent and hence these correlations are not shown in Figure 2; however, similarities in some of the correlation patterns are the result of this lack of independence. For example, patterns of parameters correlated with lake area and lake volume are similar because lake area is a multiplying factor in the calculation of lake volume. On the other hand, the pattern of correlations seen for developed and cultivated watershed land cover percentages are directly

Figure 2. Significant ($P < 0.05$) correlations among lake ecosystem components for Lake Class 24 lakes. Red lines denote negative correlations and black lines denote positive correlations.



opposite each other because the percent developed land cover subtracts directly from the percent cultivated land cover in most lake watersheds.

Many individual lake ecosystem parameters were also strongly linked to geographic location. Generally, the more easterly Lake Class 24 lakes have more developed and less cultivated watershed land cover, and are lower in alkalinity, specific conductance, and silt (Table 3; Figure 3). Towards the north, lakes are smaller, have greater water clarity, and have more forested watersheds, muck shoals, and emergent plant cover (Table 3; Figure 3). These results correspond with soils to the west and south being more calcareous and higher in phosphorus. Because of these edaphic characteristics and a positive correlation (r=0.31) between cultivated land cover and watershed size, Lake Class 24 lakes to the south and west were probably more fertile and alkaline with correspondingly less water transparency and submergent plant growth even prior to alterations via agricultural cultivation. Conversely, lakes with higher developed land cover are located more to the east and associated with smaller watershed size. Due to smaller watersheds and the nature of the soils, Lake Class 24 lakes with more developed land cover usually contain less phosphorus, alkalinity, and silt than other Lake Class 24 lakes, contrary to the expected influences of human perturbations associated with developed land cover. Also, the proportion of developed land cover is often high in small watershed lakes because they tend to be high quality lakes (clear water) that attract development compounded by the fact that, for small watersheds, developed shorelines inherently lead to higher proportions of developed land cover than in large watersheds. (For example, a lake ringed with lake homes could be close to 100% developed if it had a very small watershed confined to the immediate shoreline, but < 5% if it had a very large drainage watershed.).

Principal components analysis reduced the list of watershed and lake physical and chemical parameters from 18 to 7. Five principal component factors explained 66.2 % of the variation in the data (Table 4). Habitat PC 1 explained 18.3% of the variation in the data and appeared mostly related to watershed size. Habitat PC 2 explained 15.3% of the variation and related most strongly to water depths (mean and maximum) as well as Secchi depth. Habitat PC 3 differentiated between cultivated and forested land cover and explained an additional 12.2% of variation in the data. Habitat PC 4 explained 12.7% of the variation and appeared to be a function of lake area while habitat PC 5 explained only 7.7% of the variation and was most strongly associated with watershed topography and lake alkalinity. Using the list of variables highly correlated with individual rotated principal components, we selected watershed area, mean depth, Secchi depth, forested land cover, cultivated land cover, lake area, and alkalinity for subsequent analysis. Only 1 or 2 variables were chosen to represent each principal component to maintain independence among the variables. Also, we attempted to select the more common and the easiest to quantify variables from the list of correlated variables.

Table 3. Physical, chemical, and biological lake and watershed parameters in Lake Class 24 lakes significantly correlated with geographic location. The (+) symbol denotes a positive coefficient, (-) denotes a negative coefficient, and (ns) denotes no significance.

Variable	Easting	Northing
Developed land cover	+	ns
Cultivated land cover	-	ns
Forested land cover	+	+
Kame/kettle topography	-	ns
Lake area	ns	-
Secchi depth	ns	+
Total alkalinity	-	ns
Conductivity	-	ns
Total dissolved solids	ns	-
Muck shoal substrates	ns	+
Silt substrates	-	ns
Emergent plant frequency	ns	+

Figure 3. Geographic distribution of Class 24 lakes by alkalinity of water (mg/l as $CaCO_3$) and watershed land cover types; proportion of total watershed classified as developed (residential and commercial use), cultivated, and forested according to MNDNR 2000a.

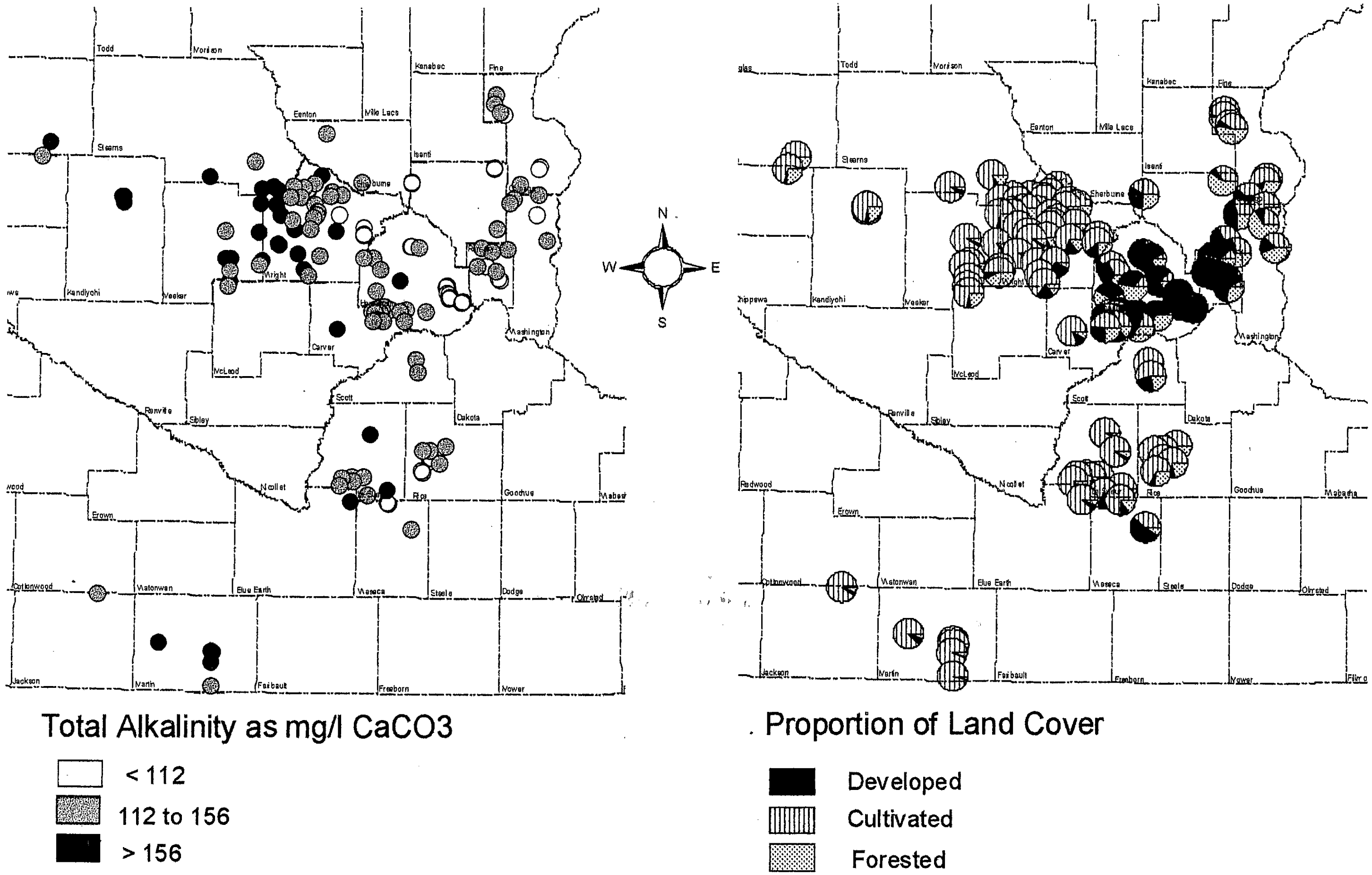


Table 4. Principal component loadings with varimax rotation on Lake Class 24 (n=113) physical-chemical lake and watershed variables.

Variable	Principal component 1	Principal component 2	Principal component 3	Principal component 4	Principal component 5
Lake area (ha)	0.031	0.121	-0.050	0.954	0.011
Volume (m^3)	0.035	-0.255	-0.111	0.926	-0.025
Mean depth (m)	-0.010	-0.936	-0.156	0.019	-0.100
Maximum depth (m)	0.064	-0.779	0.146	0.188	0.054
Littoral area (%)	-0.043	0.828	0.177	0.194	0.065
Area > 3 meters deep (%)	0.038	0.528	0.552	0.119	0.243
Shoreline development	0.210	0.087	0.112	0.229	0.110
Watershed area (ha)	0.816	0.046	-0.067	0.442	0.013
Connected wetlands (ha)	0.745	0.071	-0.002	0.535	0.013
		Watershed - percent land cover			
- urban	-0.335	-0.187	0.411	-0.100	-0.341
- cultivated	0.409	0.113	-0.691	0.076	0.301
- grass/brush	0.380	0.116	0.193	0.158	0.151
- forest	0.095	0.000	0.749	-0.204	-0.008
- open water	-0.866	-0.017	0.015	0.182	-0.075
- marsh	0.141	0.036	0.729	0.041	0.006
- connected Type 4 wetlands	0.450	-0.305	0.226	-0.095	-0.314
- connected Type 5 wetlands	-0.841	-0.063	-0.209	0.055	-0.221
- kame/kettle topography	0.023	0.039	0.103	-0.066	0.840
		MN DNR lake survey water chemistry			
Secchi transparency (m)	-0.289	-0.607	0.222	0.130	0.063
Total alkalinity (mg/l $CaCO_3$)	0.439	-0.013	-0.305	0.075	0.592
Percent of variation explained	18.3	15.3	12.2	12.7	7.7

Fish catch

Thirteen species of fish (including hybrid sunfish) were captured by lake survey trap nets in over 75% of Lake Class 24 lakes. Trap net catches were dominated numerically by centrarchids, namely bluegill and black crappie, as well as yellow bullhead and black bullhead (Table 5). The average number of species captured by trap nets (species richness) in each lake ranged from 6 to 15.3. Results of principal components analysis used to reduce the dimensionality of the trap net data set resulted in 4 factors that explained 57.3% of the variation in the data set; however, only fish PC 1, which accounted for 24.2% of the variation, provided more than 14% of the variation (Table 6). Fish PC 1 differentiated between a fish catch assemblage of sunfish (bluegill, pumpkinseed, green, and hybrid) and an assemblage consisting of common carp, walleye, and black bullhead.

Habitat - fish catch relationships

Variation in trap net catches was associated with geographic location as well as connectivity with other water bodies. Bluegill CPE increased to the north and east; whereas, walleye CPE increased to the south and west (Table 7, Figure 4). Fish assemblage structure identified by fish PC 1 also shared a northeast to southwest trend. Towards the north, lakes generally had lower trap net catches of common carp, black bullhead and yellow perch, and higher catches of yellow bullhead and sunfish (bluegill, pumpkinseed, green sunfish, and hybrid sunfish). Black crappie catches increased slightly to the east (Table 7, Figure 4). Lakes with permanent water body connections rather than small intermittent connections have significantly lower catches of bluegill and higher catches of common carp, black bullhead, and black crappie, as well as a higher species richness (Table 8).

Table 5. Interquartile ranges of mean lake trap net catch per unit effort for selected individual fish species, all species combined (Total), and number of species captured in Lake Class 24 lakes.

Parameter	northern pike	common carp	white sucker	black bullhead	yellow bullhead	hybrid sunfish	green sunfish	pumpkinseed	bluegill	largemouth bass	black crappie	yellow perch	walleye	Total	Number of Species
Minimum	0	0	0	0	0	0	0	0	1.2	0	0.1	0	0	20	6
1st quartile	0	0.2	0	0.5	0.8	0.2	0	0.8	21.3	0.1	3.3	0.2	0	68	10
Median	0	0.5	0	2.5	2.3	1.3	0	2.5	38.6	0.2	8.6	0.4	0.3	93	12
3rd quartile	1	1.6	0	19.8	4.5	3.3	1	4.2	70	0.4	22	1.1	0.6	133	13
Maximum	2	18	7	211	32	19	3	28	378.31	3.1	138	14	3.4	420	15

Table 6. Principal component loadings with varimax rotation on Lake Class 24 (n=113) trap net catch per unit effort (number per 24 hour set) of common fish species.

Variable	Principal component 1	Principal component 2	Principal component 3	Principal component 4
Bowfin	0.071	-0.144	0.732	0.035
Northern pike	0.312	-0.264	0.282	0.643
Common carp	0.735	0.333	0.181	-0.145
Golden shiner	-0.273	0.594	-0.059	-0.093
White sucker	0.089	0.638	-0.100	0.049
Black bullhead	0.622	0.439	0.188	-0.127
Yellow bullhead	-0.303	-0.236	0.398	0.504
Brown bullhead	-0.308	0.071	0.592	0.179
Hybrid sunfish	-0.800	0.045	0.099	0.250
Green sunfish	-0.608	0.341	0.097	0.201
Pumpkinseed	-0.725	0.251	0.221	0.171
Bluegill	-0.775	-0.084	0.075	0.041
Largemouth bass	-0.184	0.109	0.158	0.565
White crappie	0.360	0.032	0.155	-0.622
Black crappie	0.091	0.553	0.289	-0.439
Yellow perch	0.201	0.720	-0.080	-0.045
Walleye	0.680	0.384	-0.167	0.111
Percent of variation explained	24.2	14.0	8.5	10.6

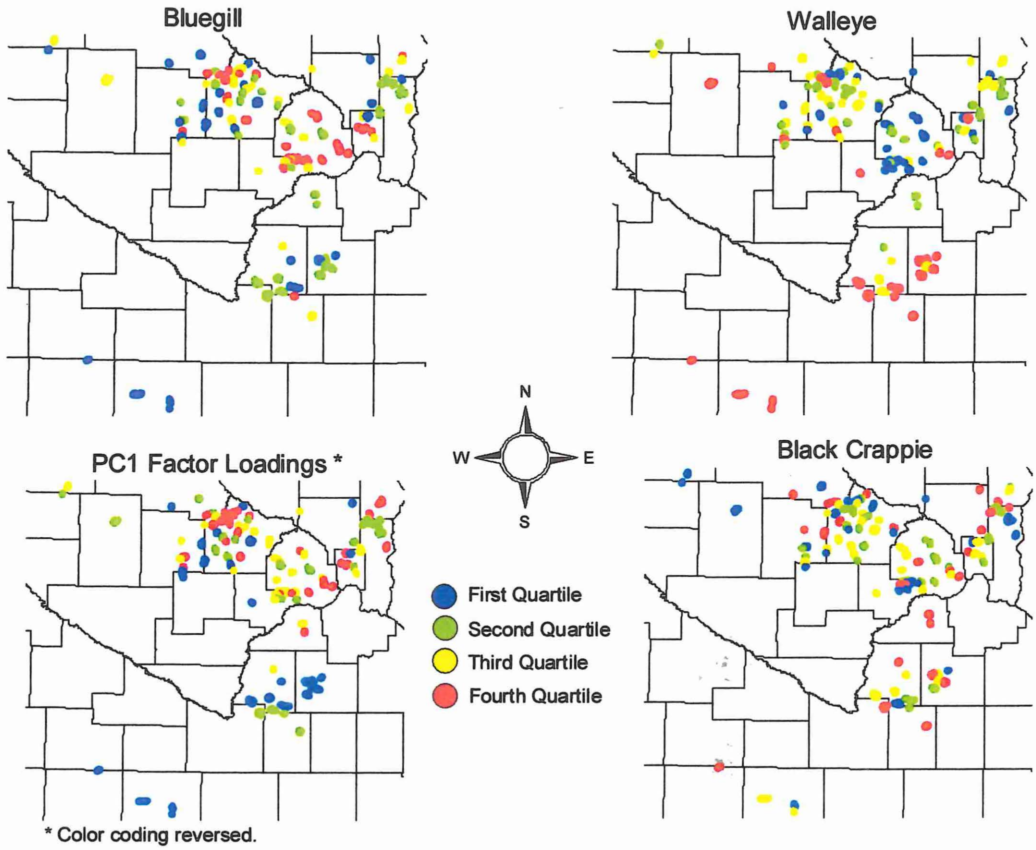
Table 7. Significant correlations between geographic location and Lake Class 24 trap net catch per unit effort (number per 24 hour set) of selected fish species, total CPE, and species richness. The (+) symbol denotes a positive coefficient, (-) denotes a negative coefficient, and (ns) denotes no significance.

Variable	Easting	Northing
Northern pike	ns	ns
Common carp	ns	-
White sucker	ns	ns
Black bullhead	ns	-
Yellow bullhead	ns	+
Hybrid sunfish	ns	+
Green sunfish	ns	+
Pumpkinseed	ns	+
Bluegill	+	+
Largemouth bass	ns	ns
Black crappie	+	ns
Yellow perch	ns	-
Walleye	-	-
Total CPE	ns	ns
Species number	ns	ns

Table 8. Mean trap net CPE of selected fish species in Lake Class 24 lakes with strong hydrologic connections to other water bodies, and in landlocked lakes with little or no hydrologic connections (* denotes $P < 0.05$; ** denotes $P < 0.01$; and *** denotes $P < 0.001$determined with two sample t-tests).

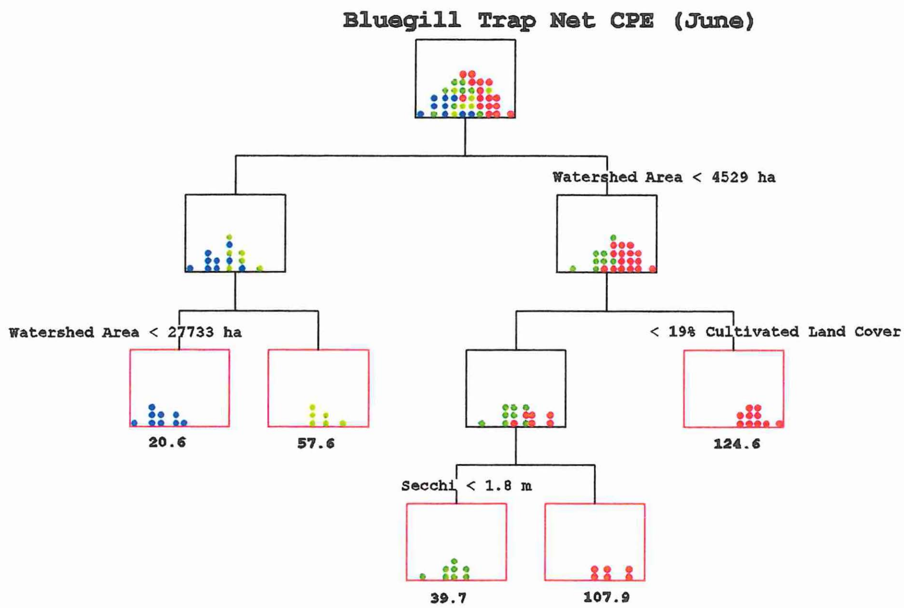
	Trap Net CPE	
Species	Connected lakes	Landlocked lakes
Northern pike	0.4	0.3
Common carp	1.3	0.4***
White sucker	0.3	0.2
Black bullhead	7.2	2.6**
Yellow bullhead	2.1	3.0
Hybrid sunfish	1.2	1.9
Green sunfish	0.3	0.3
Pumpkinseed	2.0	2.5
Bluegill	27.0	53.5***
Largemouth bass	0.3	0.4
Black crappie	10.4	6.4*
Yellow perch	0.9	0.6
Walleye	0.5	0.3
Species number	11.9	10.7**

Figure 4. Geographic distribution of Lake Class 24 lake survey trap net bluegill, walleye, and black crappie CPE quartiles and principal component 1 (PC 1) factor loading quartiles.



Key lake ecosystem habitat parameters identified by PCA along with four selected lake survey variables describing plant cover, water quality, and shoal substrates account for most of the variation in bluegill trap net catches among lakes. With RTA analysis, the 7 key independent variables explained approximately 60% of the variation in June bluegill CPE, and approximately 67% of the variation in July-August bluegill CPE (Figure 5; Appendix II). Mean June bluegill CPE ranking in the fourth Lake Class 24 quartile interval (Table 5) was predicted for lakes with < 19% cultivated land cover in their watersheds and for July-August bluegill CPE for lakes with < 7% cultivated land cover. Conversely, mean June bluegill CPE in the first quartile interval are predicted for lakes with moderate to large watershed areas (4,529 - 27,733 ha), and July - August first quartile catches are predicted for lakes with large watersheds having sparse to moderate amounts of cultivated land cover, as well as in shallow lakes where cultivated land cover was dominant. When bluegill catches predicted from these two RTA models were regressed against the observed values for all 24 lakes, the resulting slope was near 1.0 (0.962) and R^2 value was 0.62 (Figure 6). The addition of the four lake survey variables (emergent plant cover, fine-leaf plant cover, total phosphorus, and gravel substrate) to the RTA of bluegill catches did not improve prediction of bluegill catches (Appendix III); however, for this smaller lake survey data set

Figure 5. Dit plots of regression tree analyses on Lake Class 24 lake survey bluegill trap net catch per unit effort (CPE) data separated by sampling period (June and July/August). Each dot represents a lake and each color corresponds to a classification. The x-axis in each graph is a scaled trap net CPE. Numbers at the bottom of the terminal boxes are the classification group mean CPE.



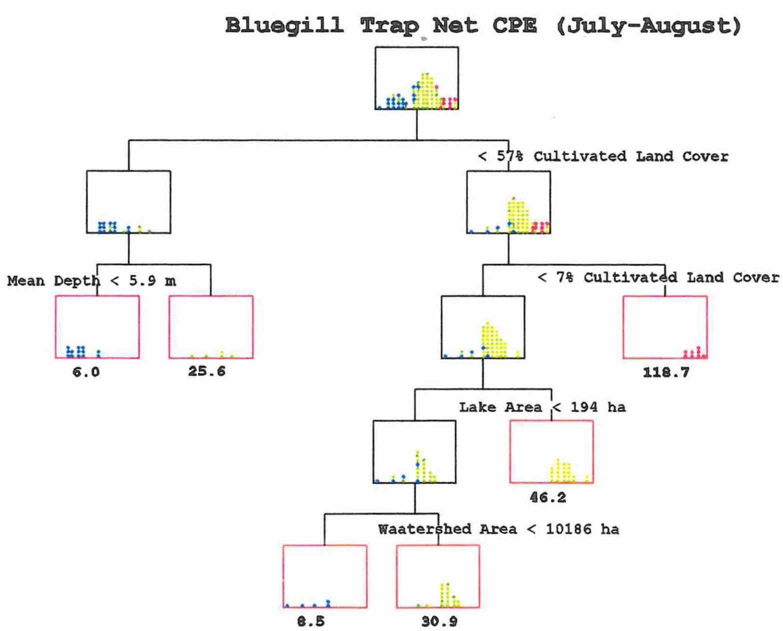
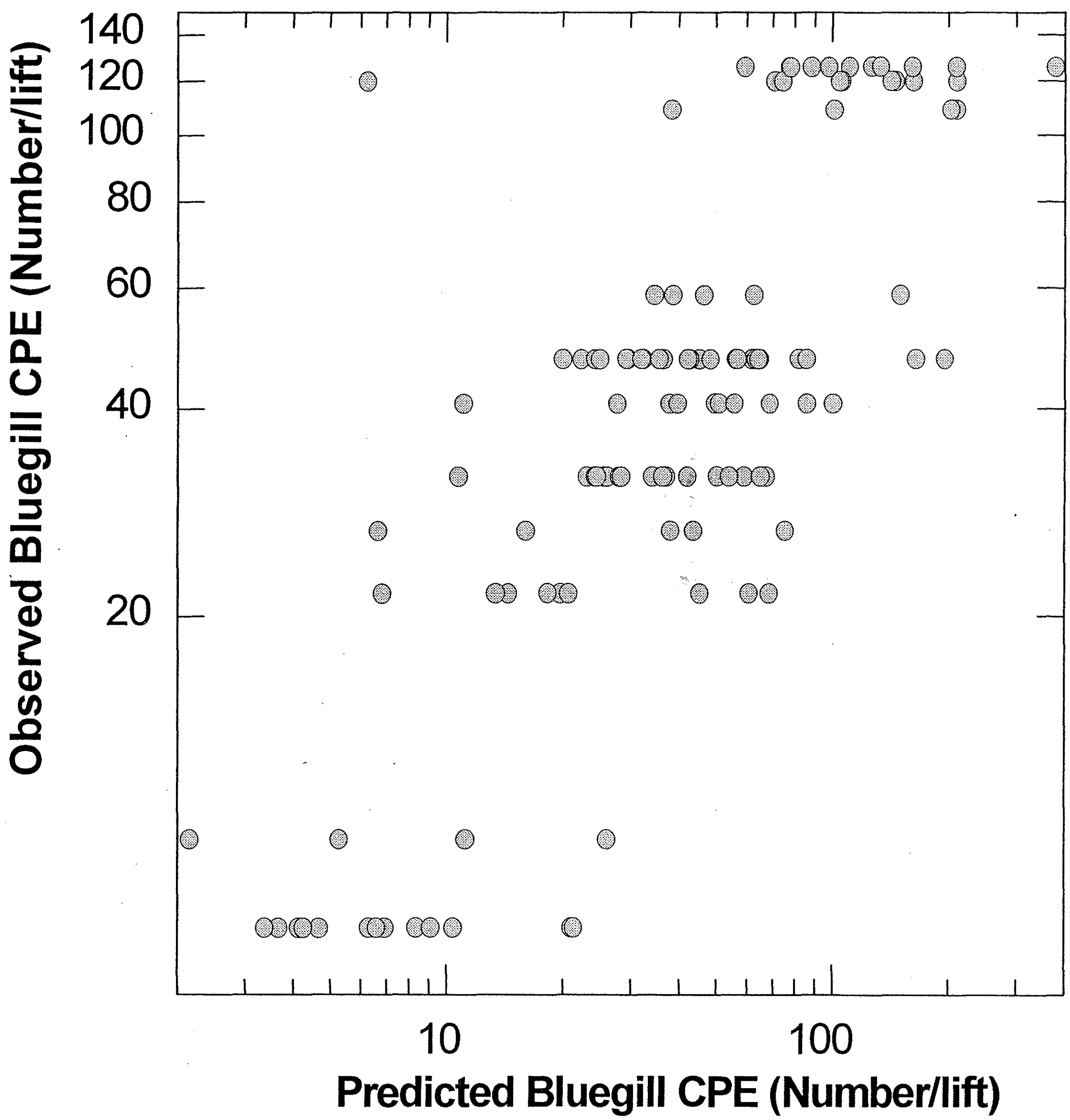


Figure 6. Trap net CPE predicted from June and July/August regression tree models versus observed trap net catches for Lake Class 24 lakes. The linear regression model for these data is log(observed CPE) = log (predicted CPE) * 0.962 - 0.054; R^2=0.62.



(53 lakes) it was not practical to separate the bluegill analysis by sampling period which could have improved the model fit. Interestingly, watershed size and cultivated land cover were replaced as first cut variables in the "lake survey" RTA model by fine-leaf vegetation occurrence indicating that watershed size and cultivated land cover may have acted as surrogates for the abundance of fine-leaf vegetation. A mean bluegill CPE of 7.0 was found for lakes that had fine-leaf vegetation occurring in < 17.5% of lake survey transects as opposed to mean bluegill CPE values of 109.9 and 40.2 for two groups of lakes with fine-leaf vegetation occurring in > 17.5% of the transects (Appendix III).

Trap net catches of pumpkinseed, black crappie, black bullhead, yellow bullhead, yellow perch, and common carp were also influenced by differences among lake habitats. Regression tree analysis using the 7 key lake ecosystem parameters accounted for 24% to 49% of the variation in CPE of these species (Appendix II). The most influential habitat variables affecting trap net CPE for many of these fish species were often the two that relate to watersheds, watershed area and cultivated land cover. Approximately 57% of the variation associated with the fish assemblage gradient identified by fish PC 1 was explained by cultivated land cover, mean depth, and Secchi depth. Species richness in trap net samples was related most strongly to watershed area modified by Secchi depth, cultivated land cover, and lake area.

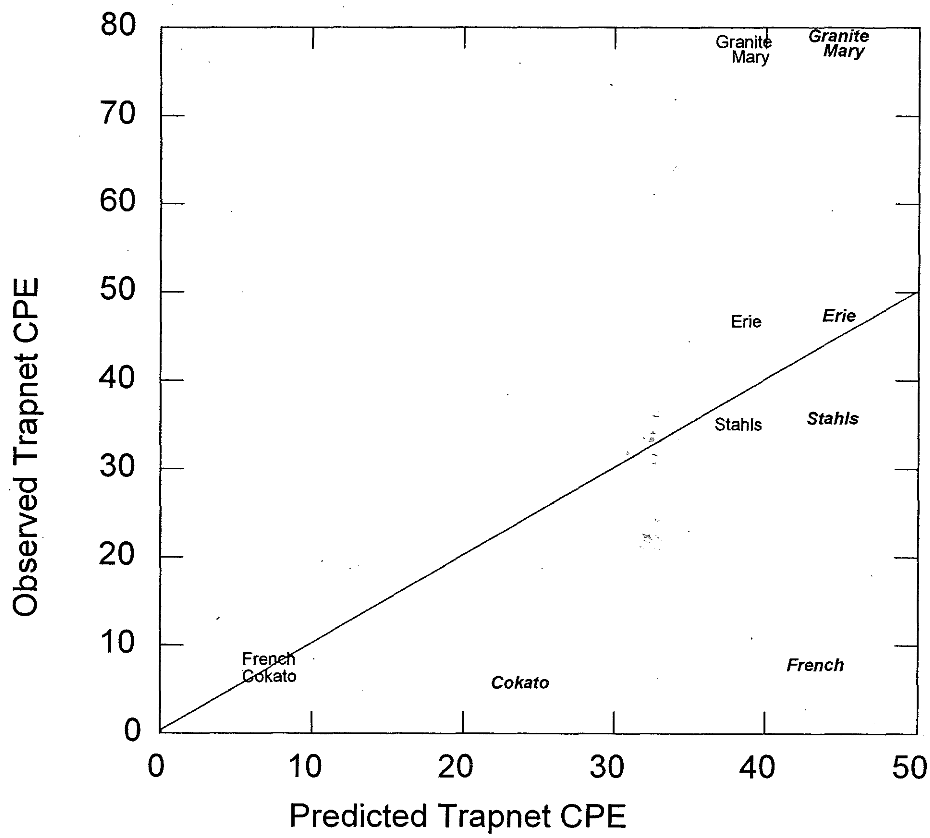
The addition of the four lake survey variables improved the RTA models for predicting trap net CPE of pumpkinseed, black crappie, yellow bullhead, black bullhead, walleye, and common carp (Appendix III). Frequency occurrence of fine-leaf submergent vegetation was a contributing factor in models for all species except black crappie and yellow perch. Fine-leaf vegetation was also a key factor in modelling the fish assemblage gradient represented by fish PC1. Emergent vegetation was a significant factor in modelling catches of pumpkinseed, yellow bullhead, and the PC1 fish assemblage gradient. Phosphorus concentration was a significant factor in modelling black bullhead catches, and gravel substrates improved the model to predict CPE of black crappie (Appendix III). Species richness was a function of the frequency occurrence of emergent vegetation in addition to watershed area and lake area.

Regression tree analysis was also used to classify lakes with suitable largemouth bass habitat using mean lake largemouth bass electrofishing CPE instead of trap net CPE. Electrofishing CPE of largemouth bass was highest in lakes that had sparse to moderate cultivated land cover (< 62.5%), contained relatively clear water (Secchi > 1 m), and were either low in alkalinity or had small watersheds (< 5212 ha) (Appendix IV). Given relationships between these parameters and submergent plant cover (Figure 2), lakes fitting the classification for high bass CPE would be expected to have extensive submergent plant cover, but there was insufficient data for that determination.

Application of Lake Class 24 bluegill habitat model to study lakes

Lake Class 24 RTA models of mean lake bluegill trap net CPE using fine-leaf plant cover accurately predicted bluegill CPE in the study lakes; whereas, the RTA model without the fine-leaf plant data did not. The Lake Class 24 bluegill regression tree model derived without the lake survey variables (emergent and fine-leaf plant cover, gravel substrate, and phosphorus concentrations) yielded overestimates of bluegill CPE in French and Cokato lakes, and underestimates of CPE in Granite and Mary lakes (Figure 7). All of the study lakes except for Cokato Lake were classified as having cultivated watershed cover between 7% and 57% and lake area < 194 ha (Appendix II and Table 2). Bluegill CPE in Cokato Lake would have been accurately predicted if the mean depth on Cokato Lake had been slightly less. The RTA model derived with lake survey variables used fine-leaf plant cover as a predictor and resulted in accurately predicted bluegill trap net CPE for Cokato and French lakes as well as Stahls and

Figure 7. Late summer (August) bluegill mean lake trap net catch per unit effort (CPE; number per 24 hour set) observed in lakes Erie, French, Stahls, Cokato, Granite, and Mary versus late summer bluegill trap net CPE predicted from classification tree models. Points labeled by lake names shown in normal typeface were predicted from model with lake survey variables added and points labeled by capitalized lake names were predicted from models without lake survey variables. The line depicts a 1:1 correspondence between predicted and observed CPE.



Erie lakes; however, bluegill catches in Mary and Granite lakes remained underestimated (Figure 7). However, unlike Granite Lake, the Lake Mary historical bluegill CPE values (24,48,46, and 34) are much lower than the CPE we measured during the study, and are close to that predicted by the model.

Data Set II: Study lake

Habitat

At trap net sites, the composition of shoal (shoreline to 1.8 m depth) bottom substrates varied both within and among the six study lakes (Figure 8). Sand and gravel substrates were common in all the study lakes, but dominated the broader shoal areas and on areas exposed to long fetches especially when downwind of prevailing northwest winds (Figure 9). Rubble (cobble and boulder) substrates also tended to occur downwind of longer northwest fetches, with the exception of Lake Erie where this type of substrate was more common and associated with shorelines of steep embankments. Silt substrates were mostly restricted to the outer shoal margins, and organic substrates (detritus and muck) often dominated areas protected from the influence of strong wave energy such as the backside of bays or upwind of the prevailing winds (Figure 9). Organic substrates were uncommon in Cokato Lake.

Aquatic vegetation cover differed more among lakes than within lakes both spatially and temporally. At trap net sites, during all sampling periods, Cokato and French lakes were devoid of any significant vegetative cover, while vascular aquatic plant cover was most extensive in lakes Mary and Granite where it was dominated by fine-leaf plant types (mostly coontail and milfoil along with some *Chara*; Figure 10). Lake Mary was the only lake with a significant amount of broad-leaf type cover, and Lake Erie was the only lake with wild celery cover. Wild celery cover was dominant throughout much of Lake Erie. Emergent (lily, bullrush, and cattail) cover was sparse in the study lakes. Submergent plant cover was relatively consistent from early summer through the fall sampling periods, but was much lower during the spring samples (Figure 11).

Plant cover and shoal bottom substrates were often spatially correlated. Among buffered trap net sites, overall submergent plant cover as well as fine-leaf plant types were significantly correlated with percent coverage of organic and silt substrates (Table 9). The amount of broad-leaf plant cover was positively correlated and attached algae negatively correlated with the extent of sand-gravel composition in the shoal bottom substrates at trap net sites. Also, both attached algae and fine-leaf plant cover increased with increased distance from the 4.6 m contour. Most trap net sites far from the 4.6 meter contour were located on the distal end of bays and generally protected from wave action.

Submergent plant and bottom substrate cover at electrofishing sites appears to be more uniform among the study lakes than within the study lakes. The first three rotated principal components collectively account for 71.3% of the variation in the site habitat data set (Table 10). The first component (PC 1) accounts for over one-half of that variation (36.0%) and is most strongly correlated to aquatic plant cover (particularly fine-leaf plant cover) occurring during both spring and summer. The second principal component (PC 2) accounts for 21.1% of the variation and is strongly correlated to organic shoal bottom substrates and distance from the 4.6 m contour (slope), and negatively correlated to sand-gravel. Principal component 3 (PC 3) was negatively correlated with rubble substrate composition and accounted for only 14.2 percent of the variation in habitat among electrofishing sites (Table 10). A plot between factor scores PC 1 and PC 2 indicate that habitats within lakes are more homogeneous than among lakes (Figure 12). Electrofishing sites on Cokato and French lakes had low PC 1 scores and electrofishing sites on Mary and Granite lakes had high PC 1 scores indicating less submergent plant cover in Cokato and French than in Mary and Granite. Also, electrofishing sites on Cokato and French lakes had mostly lower PC 2 scores than lakes Mary and Granite indicating less organic

Figure 8. Box diagram of percent substrate composition at trap net sites (trap net location buffered by 50 m) in lakes Cokato, Erie, French, Granite, Mary, and Stahls. Center horizontal line is the lake median, the box edges denote the first and third quartiles. The horizontal line (whiskers) extends the boxes to 1.5 times the interquartile range and the (*) and (o) indicate outside values.

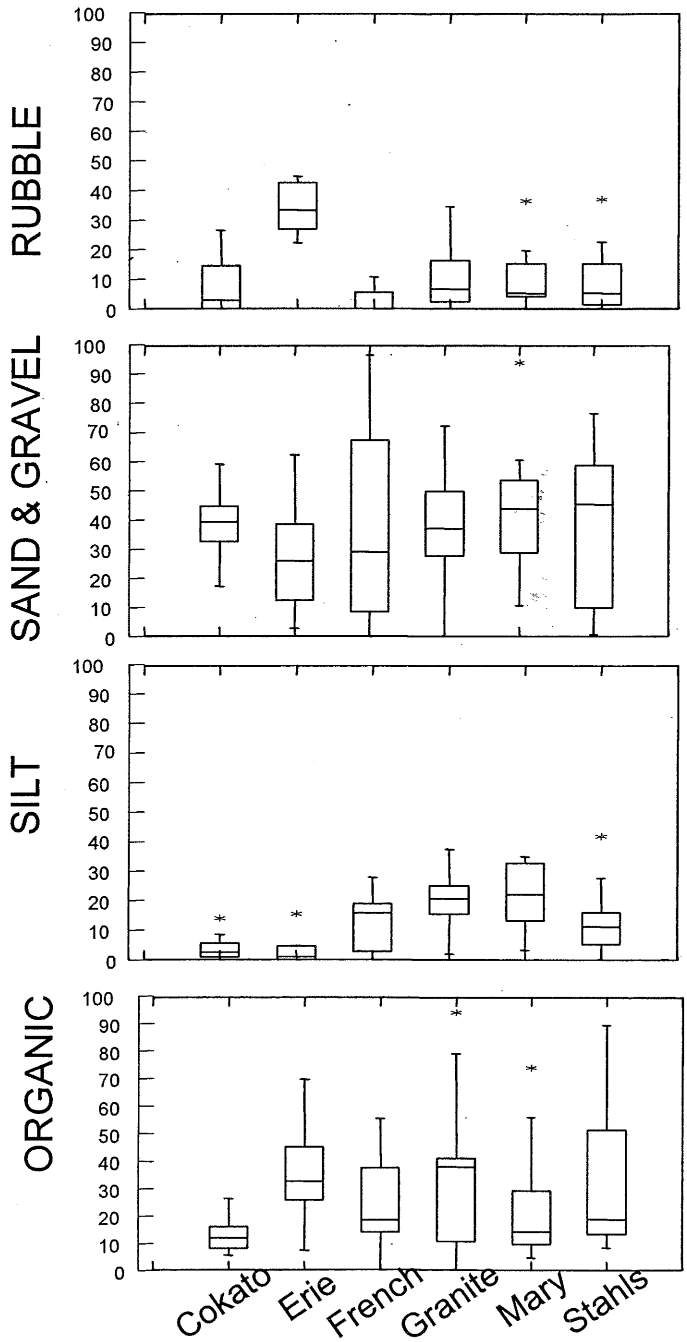


Figure 9. Dominant bottom substrate composition to 2 m depth contours in lakes Mary, Erie, French, Granite, Stahls, and Cokato. Grey and blank areas were not classified with a dominant substrate type.

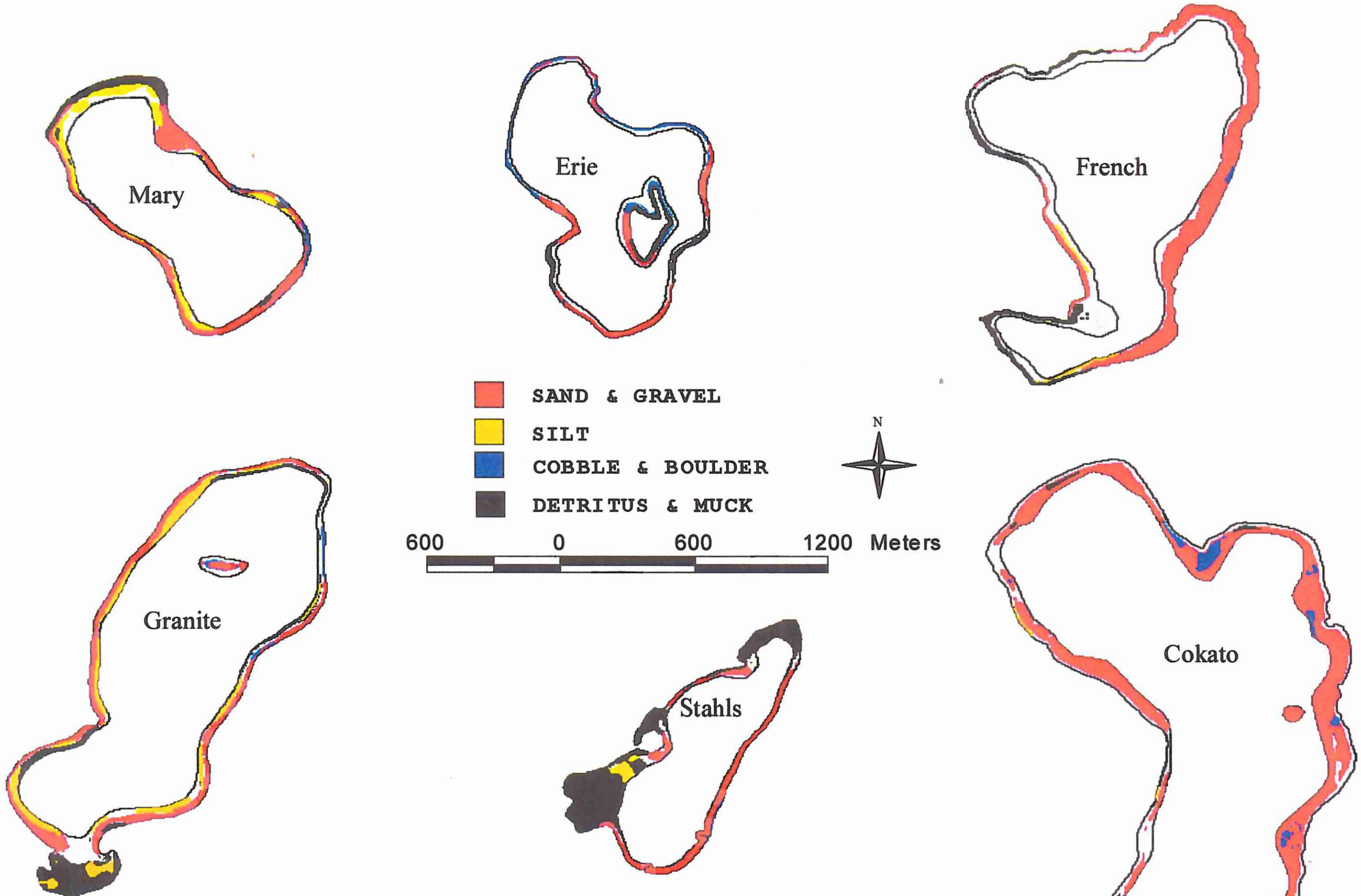


Figure 10. August aquatic plant cover by plant type in lakes Mary, Erie, French, Granite, Stahls, and Cokato. Coverage indicated only where it exceeded 40 percent.

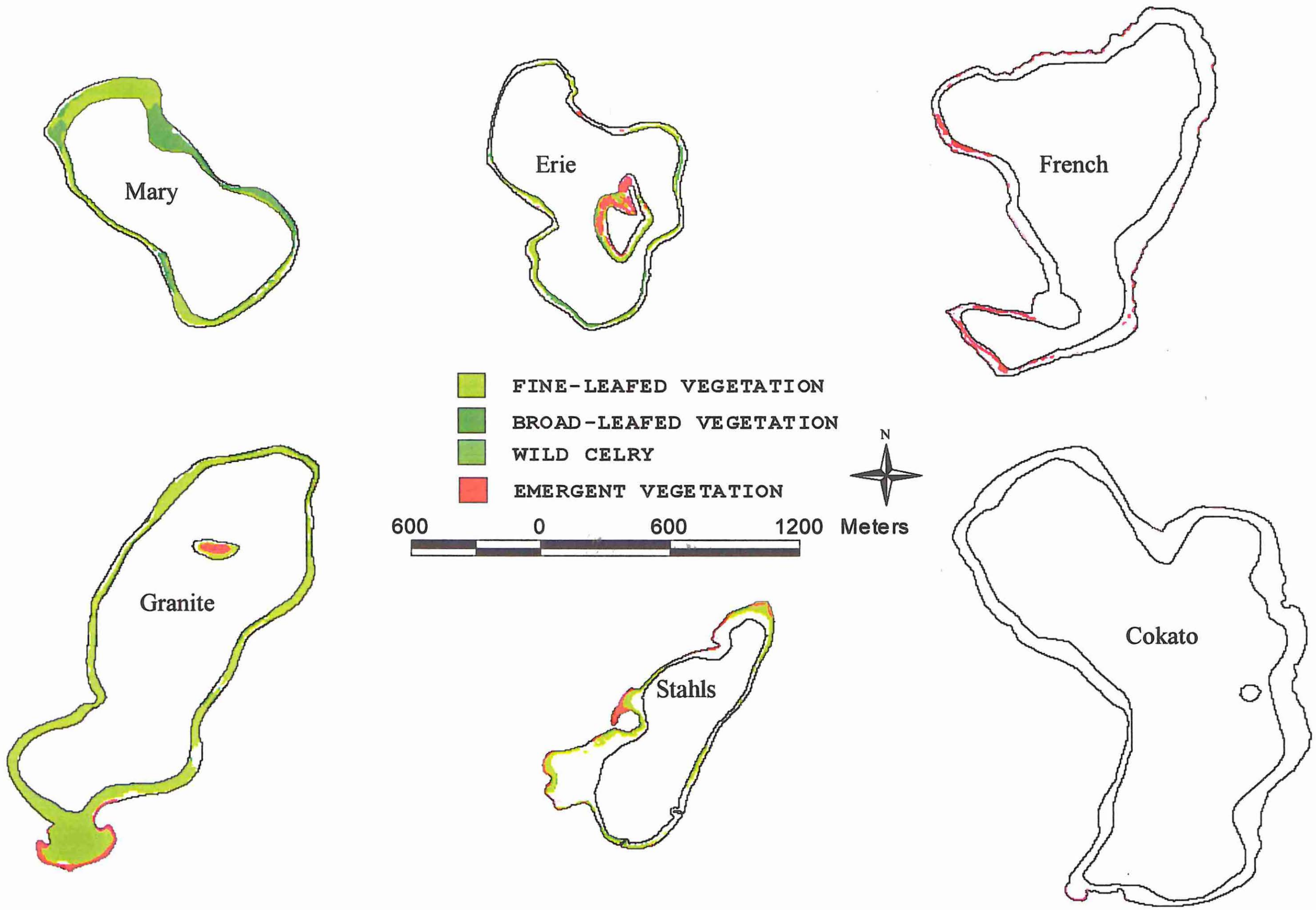


Figure 11. Box diagrams of seasonal variation in plant type cover at study lake trap net sites. Center vertical line is the lake median and the box edges denote the first and third quartiles. The horizontal line (whiskers) extends the boxes to 1.5 times the interquartile range and the (*) and (o) indicate outside values.

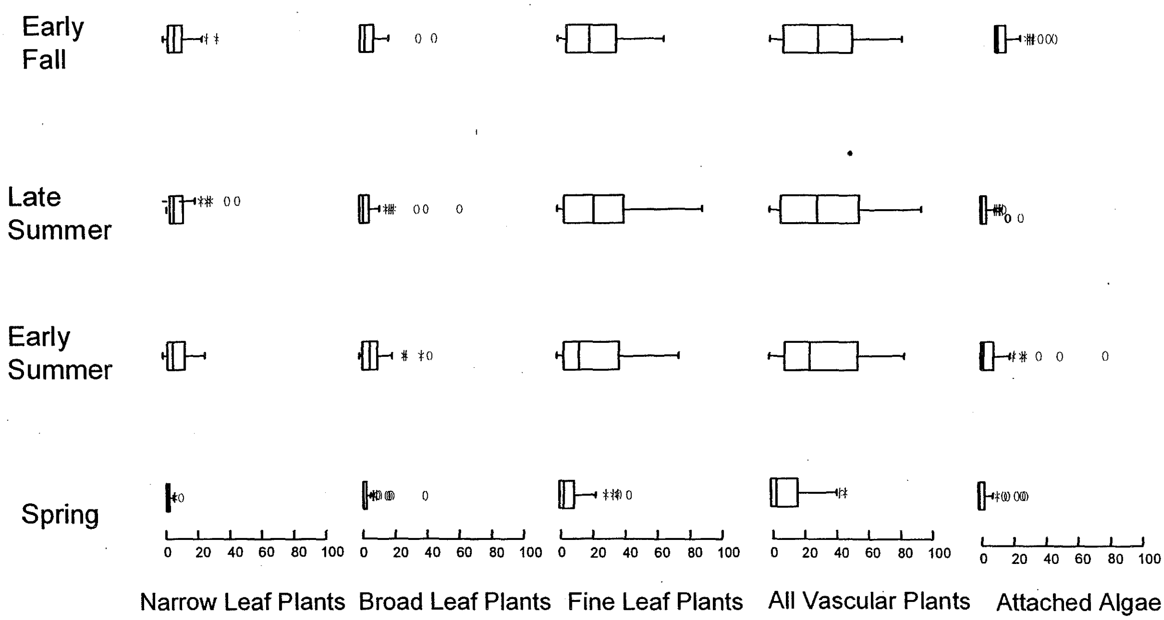


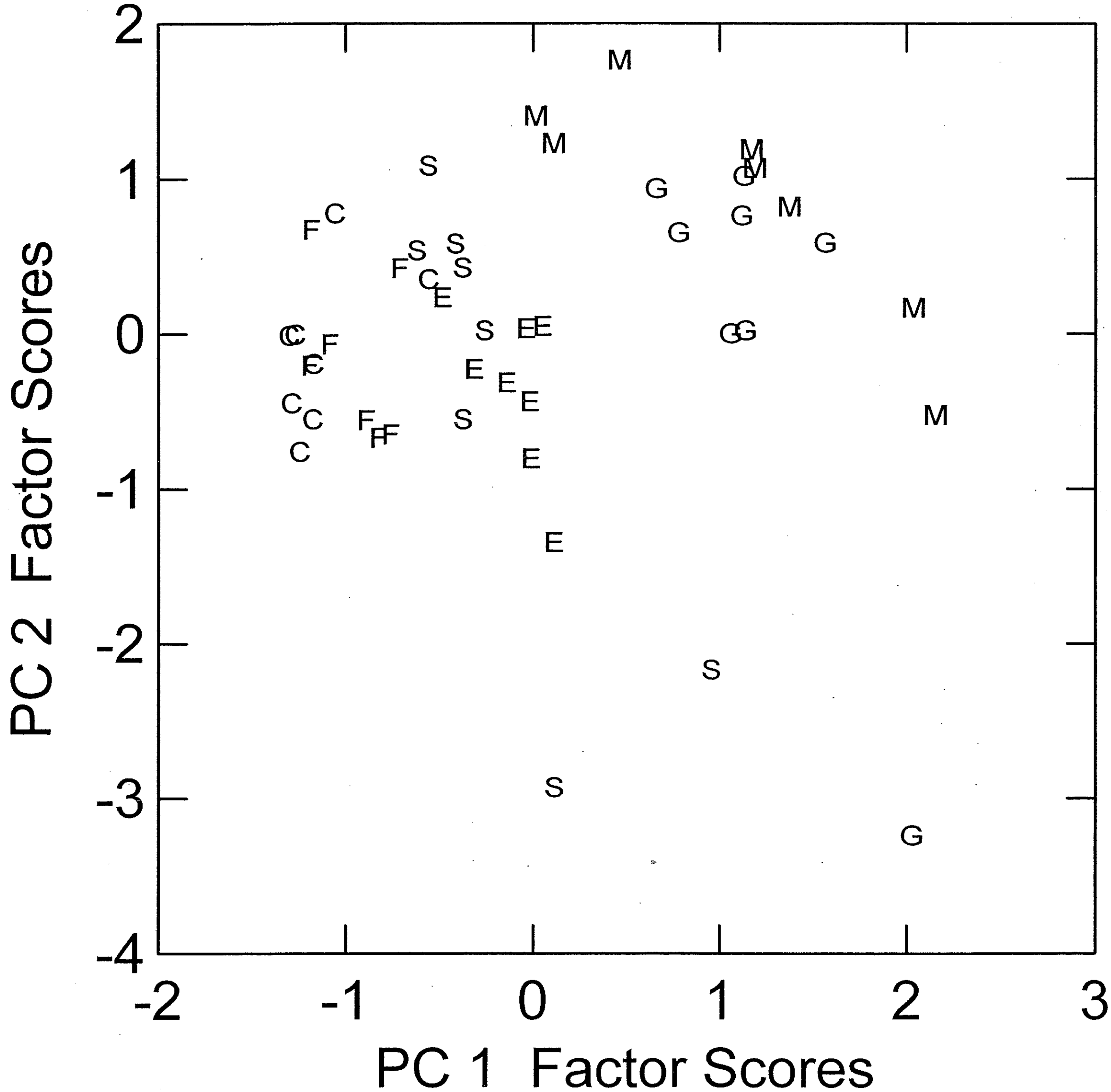
Table 9. Significant ($P < 0.05$) Pearson correlation coefficients between shoal distance and percent substrate composition and late summer aquatic plant cover at trap net sites (50 meter area around net sets) in study lakes (Erie, French, Stahls, Cokato, Granite, and Mary).

Physical parameters	Attached algae	All vascular plants	Broad-leaf	Fine-leaf
Organic substrates		0.3		0.37
Silt substrates		0.34		0.43
Sand-gravel substrates	-0.26		0.31	
Rubble substrates		0.28		
Distance to 4.6 meter depth	0.41			0.28

Table 10. Principal component loadings with varimax rotation on electrofishing site habitat data collected on 6 study lakes (n=47).

	Principal component 1	Principal component 2	Principal component 3
Distance from 4.6 m. contour	0.396	0.729	0.164
<u>Substrate composition (%)</u>			
Organic	0.192	0.837	0.001
Silt	0.592	-0.113	0.586
Sand and gravel	-0.021	-0.771	-0.299
Rubble	0.029	-0.174	-0.927
<u>Plant cover (%)</u>			
Spring attached algae	0.581	0.06	0.228
Late summer attached algae	-0.105	0.623	-0.389
Spring fine-leaf	0.841	0.381	0.004
Late summer fine-leaf	0.945	0.021	-0.063
Spring broad-leaf	0.667	-0.022	0.386
Late summer broad-leaf	0.419	-0.511	0.013
Spring all plants	0.924	0.194	0.15
Late summer all plants	0.841	-0.19	-0.378
Percent of variance explained	36	21.1	14.2

Figure 12. Electrofishing site habitat principal factor scores for the first 2 components (PC 1 and PC 2) for each electrofishing site identified by lake initial (E -Erie, F -French, S -Stahls, C -Cokato. G -Granite, M -Mary).



substrates in Cokato and French lakes. Electrofishing sites on lakes Erie and Stahls usually ranked intermediate to the other 4 lakes (Figure 12).

Habitat - trap net catch relationships

Bluegill and black crappie dominated the trap net catch in the six study lakes (Figure 13) and these were the only two species continuously distributed across enough sites to allow analyses of abundance (CPE) with RTA. Regression tree analysis showed that trap net CPE of bluegill and black crappie are strongly linked to plant cover. For all four sampling periods, RTA proportional reduction in error values ranged from 0.51 to 0.70 for bluegill and from 0.35 to 0.56 for black crappie (Table 11). The best fit for bluegill occurred for late summer samples when the highest bluegill CPE occurred at sites with > 42 % fine-leaf plant cover, and the lowest bluegill CPE occurred at sites with < 11% fine-leaf plant cover. Conversely, the highest black crappie CPE occurred at sites with < 4% fine-leaf plant cover or at sites with little attached algae and < 46% total vascular plant cover. There was a strong tendency for sites within a lake to be classified similarly for bluegill habitat (Figure 14) in much the same way shown with habitat PC1 and PC2. The fit of observed bluegill trap net CPE to that predicted by RTA classification provided an R^2 of 0.65.

Occurrences of several other fish species were also strongly linked to submergent plant cover. Pumpkinseed and hybrid sunfish were linked to increases in submergent plant cover in stepwise logistic regression models (Table 12). Conversely, black bullhead and yellow perch were linked to reductions in submergent plant cover. For all species except yellow perch, the strongest associations between their occurrence in trap net catches and habitat occur during summer sampling periods (Table 12). Predictive models of yellow perch presence in trap net catches were weak ($Rho^2 < 0.20$) throughout all sampling periods.

Habitat - electrofishing catch relationahips

Bluegill, yellow perch, and largemouth bass dominated the electrofishing catch (Figure 15). Total electrofishing CPE and species richness were highly correlated with electrofishing site habitat PC 1 (submergent plant cover) (Table 13). The proportion of sunfish species (green sunfish, pumpkinseed, bluegill, and hybrids) and largemouth bass in the electrofishing catches also had strong positive correlations with electrofishing site habitat PC 1. Conversely, the proportion of white suckers and spottail shiners (night samples during late summer and fall periods) had strong negative correlations with electrofishing site habitat PC 1. Associations between electrofishing catches and PC 1 tended to be stronger with night samples than with day samples. Catches of bluegill <8cm (JBLG) and 8 to 14 cm (SBLG) tended to be more related to electrofishing site habitat PC 1 than larger bluegill (QBLG) until the early fall period when the opposite occurred. Day and night CPE of largemouth bass <20cm (JLMB) and 20 to 29 cm (SLMB) were also more correlated to electrofishing site habitat PC 1 than CPE of largemouth bass ≥30 cm (QLMB). However, correlations between JLMB and electrofishing site habitat PC 1 dropped noticeably between the spring and fall sampling periods (Table 13).

Stepwise regression and RTA models of fish abundance in electrofishing catches also reflected a strong aquatic plant cover influence. Stepwise regression models of day and night electrofishing CPE increased with increases in submergent plant cover all fish species except the spottail shiner during most if not all seasons (Tables 14 and 15). Plant cover was also key in RTA models predicting individual site electrofishing catches of bluegill and largemouth bass. In particular, either fine-leaf plant cover or combined vascular plant cover usually accounted for the largest reduction of error among all the habitat variables and usually the first classification split of electrofishing sites (Table 16). Overall PRE values ranged from 0.57 to 0.89 and tended to be higher for bluegill than for largemouth bass. Also, PRE values were higher during the two

Figure 13. Trap net catch fish species composition (by number) for lakes Erie, French, Stahls, Cokato, Granite, and Mary.

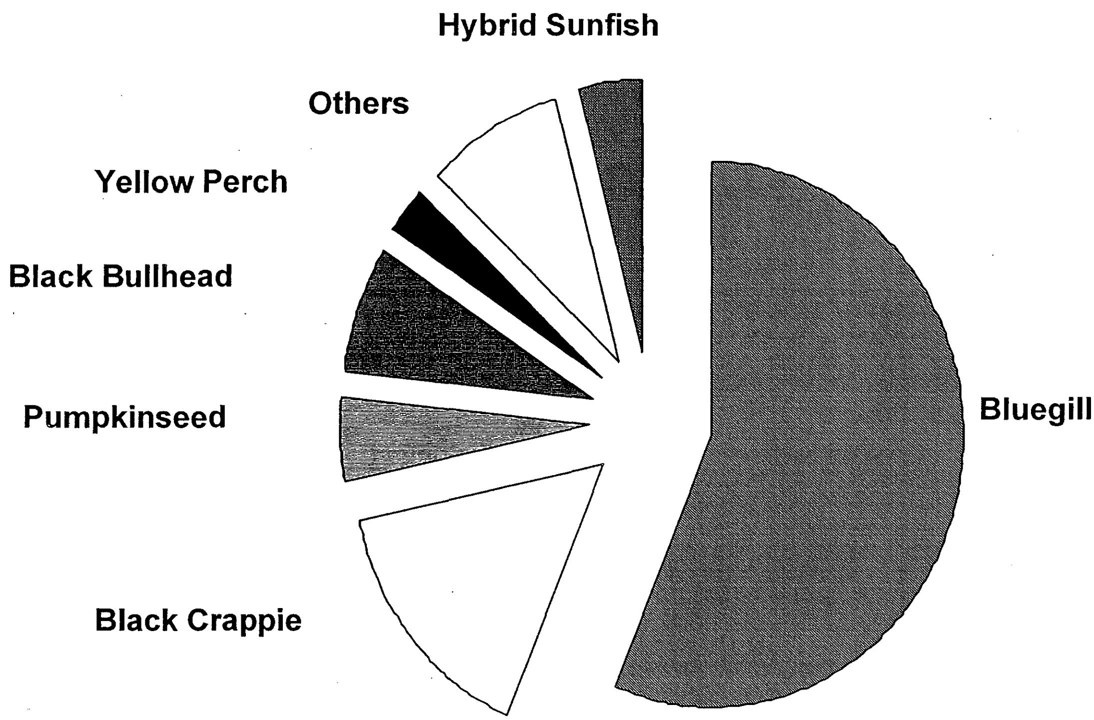


Table 11. Regression tree models of trap net CPE (number per lift) of bluegill and black crappie derived from nine trap net site habitat variables (distance from 4.6 m. contour, organic substrate, silt substrate, sand/gravel substrate, rubble substrate, attached algae plant cover, broad-leaf plant cover, fine-leaf plant cover, and vascular plant cover). Trap net sites were defined by a 50 m buffer around set location. The proportional reduction in error term (PRE) for each model is listed in parenthesis. Boldface type denotes mean trap net CPE within each classification (n=72).

Bluegill

Spring (PRE = 0.51)

- I. Vascular plant cover < 3%. **(1.6)**
- II. Vascular plant cover ≥ 3% and < 30%. **(27.1)**
- III. Vascular plant cover ≥ 30%. **(5.4)**

Early Summer (PRE = 0.54)

- I. Vascular plant cover < 13%.
  - A. Average distance from4.6 m. contour < 105m. **(12.5)**
  - B. Average distance from4.6 m. contour ≥ 105m. **(2.0)**
- II. Vascular plant cover ≥ 13%.
  - A. Broad-leaf plant cover < 4%. **(11.6)**
  - B. Broad-leaf plant cover ≥ 4%.
    - 1. Silt substrate composition < 4%. **(31.0)**
    - 2. Silt substrate composition ≥ 4%. **(95.4)**

Late Summer (PRE = 0.70)

- I. Fine-leaf plant cover < 11%. **(0.8)**
- II. Fine-leaf plant cover ≥ 11% and < 42%. **(9.7)**
- III. Fine-leaf plant cover ≥ 42%. **(26.9)**

Fall (PRE = 0.62)

- I. Vascular plant cover < 23%.
  - A. Silt substrate composition ≥ 5%. **(5.3)**
  - B. Silt substrate composition < 5%.
    - 1. Average distance from4.6 m. contour < 35m. **(4.9)**
    - 2. Average distance from4.6 m. contour ≥ 35m. **(0.3)**
- II. Vascular plant cover ≥ 23%.
  - A. Rubble substrate composition < 29%.
    - 1. Fine-leaf plant cover ≥ 47%. **(25.2)**
    - 2. Fine-leaf plant cover < 47%. **(9.0)**
  - B. Rubble substrate composition ≥29%.
    - 1. Average distance from4.6 m. contour < 51.3m. **(15.9)**
    - 2. Average distance from4.6 m. contour ≥ 51.3m. **(1.7)**

Black Crappie

Spring (PRE = 0.35)

- I. Broad-leaf plant cover > 1%. (**0.7**)
- II. Broad-leaf plant cover < 1%.
  - A. Average distance from4.6 m. contour < 18m. **(1.2)**
  - B. Average distance from4.6 m. contour > 18m.
    - 1. Rubble substrate composition < 24%. (**9.6**)
    - 2. Rubble substrate composition > 24%.
      - a. Fine-leaf plant cover < 3%. **(0.2)**
      - b. Fine-leaf plant cover > 3%. **(6.1)**

Early summer (PRE = 0.56)

- I. Fine-leaf plant cover < 10%. **(12.1)**
- II. Fine-leaf plant cover ≥ 10%. **(0.9)**

Late summer (PRE = 0.46)

- I. Fine-leaf plant cover < 4%. Broad-leaf plant cover < 4%.
- II. Fine-leaf plant cover ≥ 4%.
  - A. Attached algae cover ≥ 2%. **(0.6)**
  - B. Attached algae cover < 2%.
    - 1. Vascular plant cover < 46%. **(5.9)**
    - 2. Vascular plant cover ≥ 46%. **(1.3)**

Fall (PRE = 0.50)

- I. Sand-gravel substrate composition ≥ 46%.
  - A. Broad-leaf plant cover < 3%. **(5.3)**
  - B. Broad-leaf plant cover ≥ 3%. **(1.2)**
- II. Sand-gravel substrate composition < 46%.

Table 11. Cont.

A. Broad-leaf plant cover < 4%.
  1. Organic substrate composition < 17%. **(0.1)**
  2. Organic substrate composition ≥ 17%. **(0.9)**

B. Broad-leaf plant cover ≥ 4%.
  1. Fine-leaf plant cover < 36%. **(3.1)**
  2. Fine-leaf plant cover ≥ 36%. **(0.3)**

Figure 14. Late summer (August) bluegill trap net catch per unit effort (CPE; number per 24 hour set) observed at trap net sites in lakes Erie, French, Stahls, Cokato, Granite, and Mary versus late summer bluegill trap net CPE predicted from classification tree model in Table 11.

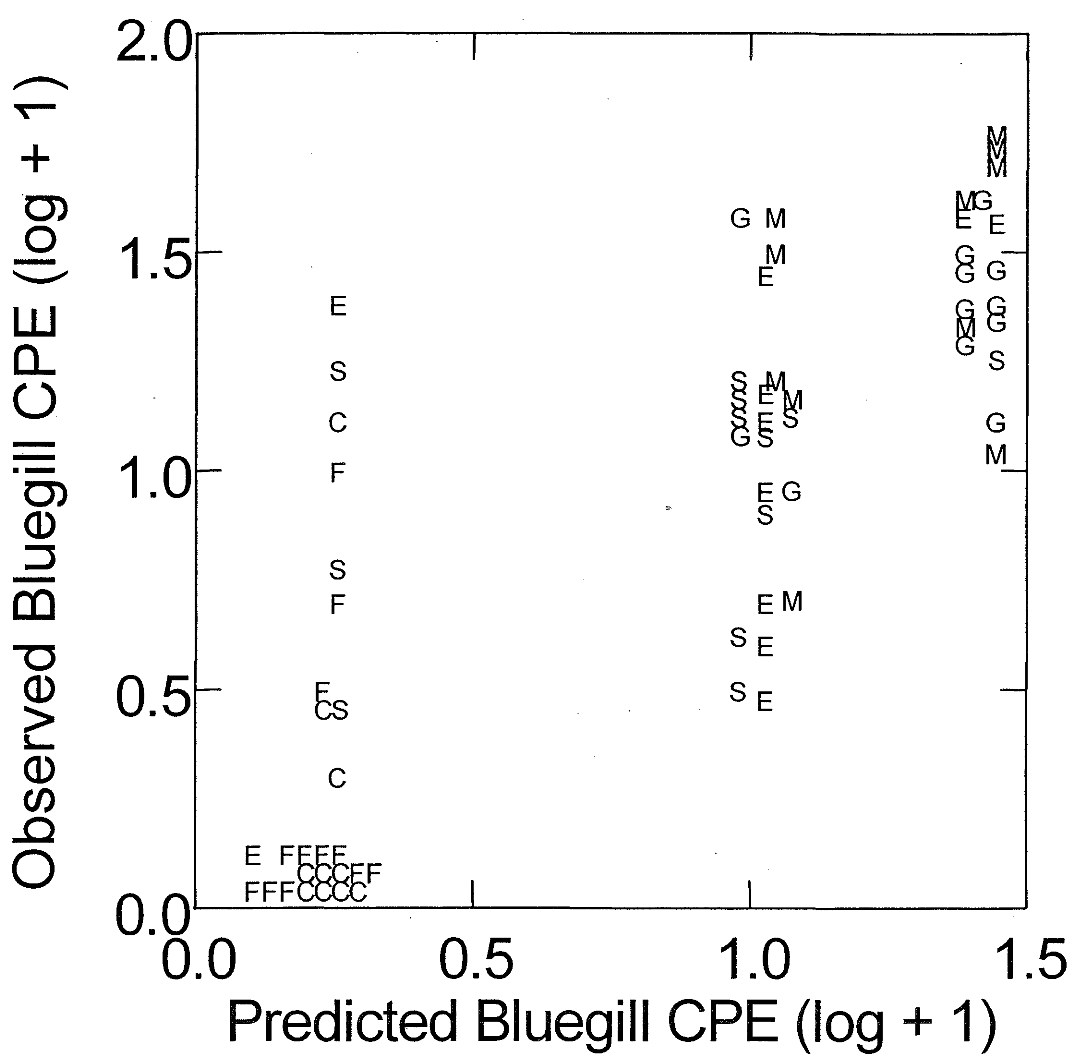
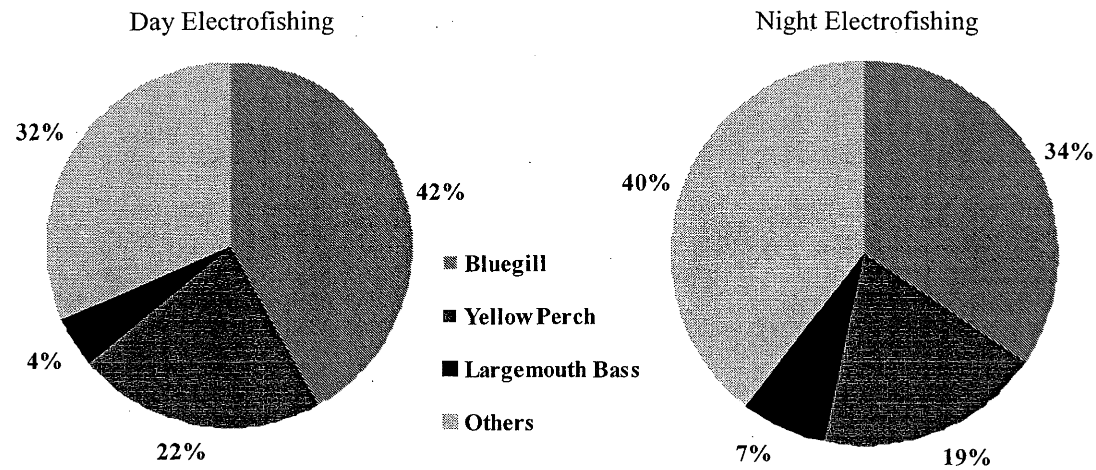


Table 12. Stepwise logistic regression model summaries for trap net CPE of bluegill > 15 cm (QBLG), pumpkinseed, hybrid sunfish, black bullhead, yellow bullhead, and yellow perch with distance to 4.6 m contour, percent shoal substrate composition (organic, silt, sand-gravel, and rubble) and percent plant cover (moss, broad-leaf, fine-leaf, and all vascular aquatic plants combined). Also, shown are statistics for the model fit (Rho^2) and predictive accuracy for the amount of probability gained over random assignments of model for species presence (sensitivity) and species absence (specificity) cases. The (+) symbol denotes a positive coefficient and a (–) denotes a negative coefficient. Sample size for each period is 72.

Species	Period	Rho^2	Sensitivity	Specificity	Organic	Silt	Sand	Rubble	Attached algae	Broad-leaf	Fine-leaf	All Vascular Plants	Distance to 4.6 m.
QBLG	spring	0.29	0.19	0.19								+	
	early summer	0.47	0.1	0.39	+	+	+						
	late summer	0.2	0.12	0.14							+		
	fall	0.13	0.05	0.11		+							
Pumpkinseed	spring	0.18	0.15	0.06								+	
	early summer	0.16	0.09	0.12								+	
	late summer	0.53	0.25	0.36								+	
	fall	0.1	0.06	0.07								+	
Hybrid sunfish	spring	0.35	0.29	0.11				+	+			+	
	early summer	0.47	0.25	0.28				+	+			+	
	late summer	0.48	0.35	0.17								+	
	fall	0.38	0.28	0.12								+	
Black bullhead	spring	0.13	0.08	0.09		+		–		–			
	early summer	0.24	0.21	0.09					+			–	
Yellow	spring	0.21	0.11	0.14		+		+					
	early summer	0	0.03	0.03								+	
	late summer	0.38	0.29	0.13					–		+		
	fall	0.1	0.05	0.03		+		+					
Yellow perch	spring	0.1	0.03	0.03									–
	late summer	0	0.03	0.02									–
	fall	0.16	0.12	0.08						–		–	

Figure 15. Day and night electrofishing fish species composition (by number) for lakes Erie, French, Stahls, Cokato, Granite, and Mary.



summer sampling periods than during the spring or fall sampling periods. There was a strong tendency for sites within lakes to be classified more similarly than among lakes as shown in Figure 16, reflecting the pattern seen with habitat characteristics (Figure 12). The fit of observed night and day bluegill electrofishing CPE to that predicted by RTA yielded R^2 values of 0.76 and 0.81, respectively. Stepwise regression models indicated that electrofishing catches of larger bluegill (QBLG) and largemouth bass (QLMB) were generally less associated with aquatic plant cover than the smaller size groups (Tables 14 and 15). Also, stepwise regression models of yellow perch CPE showed only weak habitat associations in the spring and early summer, and negative coefficients for fine-leaf and broad-leaf cover in late summer and fall suggesting these cover types are not strongly associated with yellow perch abundance. However, since yellow perch models show a positive coefficient for total plant cover in late summer and fall, it appears that other plant cover types such as wild celery could be associated with perch abundance.

The spatial distribution of bluegill habitat suitability in the study lakes provided additional insight into the habitat models and factors affecting bluegill habitat. Spatially linking the bluegill RTA habitat models to the habitat inventories of the study lakes using GIS indicated bluegill habitats within study lakes were more similar than between study lakes (Figure 17). In addition, it indicated that models developed using all three sampling gears resulted in similar spatial distributions of bluegill habitat suitability. Because these models are tied to specific geographical coordinates, it became possible to make a

Table 13. Correlation coefficients (r) between electrofishing site habitat principal component 1 and percent catch composition (by number) for selected fish species and size groups [bluegill ≥ 15 cm (QBLG), bluegill < 15 and ≥ 8 (SBLG), bluegill < 8 cm (JBLG), pumpkinseed, largemouth bass ≥ 30 cm (QLMB), largemouth bass <30 cm and ≥ 20 cm (SLMB), largemouth bass < 20 cm (JLMB)], total catch per unit effort, and electrofishing species richness. Boldface denotes correlation coefficients with R^2 accounting for more than 25% of the variation.

	Spring		Early Summer		Late Summer		Fall	
	Night	Day	Night	Day	Night	Day	Night	Day
Bowfin	-0.04	-0.078	-0.026	-0.111	0.05	-0.141	-0.057	0.06
Northern pike	0.129	0.292	0.013	0.262	0.385	0.323	-0.132	0.149
Common carp	-0.114	-0.278	-0.284	**-0.62**	-0.130	-0.331	-0.016	-0.068
Golden shiner	**0.576**	0.134	0.294	0.302	0.440	0.367	0.304	0.356
Spottail shiner	-0.172	-0.275	-0.28	-0.076	**-0.728**	0.009	**-0.838**	0.037
Bluntnose minnow	0.174	0.122	0.306	0.276	0.194	0.251	-0.048	0.003
White sucker	**-0.573**	-0.076	**-0.557**	**-0.579**	**-0.551**	-0.412	-0.494	**-0.519**
Black bullhead	0.140	0.077	-0.077	0.323	0.342	-0.146	0.153	0.141
Yellow bullhead	**0.607**	0.347	0.425	0.471	0.405	0.296	**0.657**	0.350
Brown bullhead	-0.087	-0.132	.	0.099	-0.016	-0.022	0.148	-0.087
Tadpole madtom	.	.	0.257	.	-0.013	0.145	-0.034	0.048
Banded killifish	.	0.011	.	.	-0.046	0.046	0.045	0.071
Brook silverside	0.310	.	0.228	.	0.277	-0.022	0.304	0.339
Hybrid sunfish	**0.630**	0.335	**0.590**	**0.580**	**0.683**	**0.591**	**0.655**	0.439
Green sunfish	**0.514**	0.349	**0.743**	0.444	**0.58**	0.410	**0.573**	0.382
Pumpkinseed	**0.611**	**0.616**	**0.676**	0.462	**0.621**	**0.584**	**0.663**	**0.677**
Bluegill	**0.811**	**0.602**	**0.874**	**0.825**	**0.851**	**0.77**	**0.673**	**0.748**
JBLG	**0.607**	0.083	**0.826**	**0.780**	**0.557**	**0.675**	-0.085	0.152
SBLG	**0.774**	**0.660**	**0.834**	**0.738**	***0.858***	**0.778**	**0.874**	**0.867**
QBLG	**0.712**	0.487	0.281	0.252	0.350	0.244	**0.704**	**0.616**
Largemouth bass	**0.658**	**0.582**	**0.555**	0.421	0.407	0.371	**0.523**	0.132
JLMB	**0.703**	**0.555**	**0.588**	0.431	0.375	0.358	0.300	-0.036
SLMB	0.491	**0.504**	**0.627**	**0.519**	**0.544**	**0.588**	**0.526**	0.493
QLMB	0.252	0.308	0.154	0.007	0.260	0.298	0.448	0.341
Black crappie	0.022	0.273	-0.484	-0.047	**-0.542**	0.100	-0.287	-0.003
Iowa darter	0.087	0.130	.	.	0.022	0.065	0.003	0.047
Johnny dater	0.059	-0.359	.	.	-0.217	.	-0.154	-0.188
Yellow perch	-0.011	0.153	-0.230	-0.041	-0.271	0.286	-0.153	-0.019
Walleye	-0.190	0.152	-0.176	-0.207	-0.144	-0.039	-0.391	-0.324
Total	**0.546**	**0.561**	**0.835**	**0.757**	**0.664**	**0.746**	**0.524**	**0.57**
Species richness	**0.547**	0.438	**0.503**	0.436	**0.524**	**0.603**	0.367	**0.564**

Table 14. Stepwise linear regression (R^2) and logistic regression (Rho^2) model summaries for night electrofishing CPE of bluegill ≥ 15 cm (QBLG), bluegill < 15 and ≥ 8 (SBLG), bluegill < 8 cm (JBLG), pumpkinseed, largemouth bass ≥ 30 cm (QLMB), largemouth bass <30 cm and ≥ 20 cm (SLMB), largemouth bass < 20 cm (JLMB), yellow bullhead, golden shiner, spottail shiner, and bluntnose minnow with percent shoal substrate composition (organic, silt, sand-gravel, and rubble), percent plant cover (attached algae, broad-leaf, fine-leaf, and all vascular aquatic plants combined), and distance to 4.6 m contour. The (+) symbol denotes a positive coefficient and a (−) symbol denotes a negative coefficient. Sample size for each period is 47.

Species	Period	R^2	Rho^2	Organic	Silt	Sand	Rubble	Attached algae	Broad-leaf	Fine-leaf	All plants	Distance to 4.6 m
Bluegill												
QBLG	spring		0.63		+	+					+	
	early summer		0.11		+							
	late summer		0.3		+		+					
	fall		0.52		+	+				+		
SBLG	spring	0.54				+			+			
	early summer	0.54					+				+	−
	late summer	0.71							+	+		
	fall	0.83							+	+		
JBLG	spring		0.25								+	
	early summer		0.42								+	
	late summer	0.25			+						+	
	fall	0.27					−	+				−
Pumpkinseed	spring		0.45			+					+	
	early summer		0.42		+						+	
	late summer		0.35								+	
	fall		0.33							+		
Largemouth bass												
QLMB	spring		0.07						+			
	early summer		0.05				+					
	late summer		0.23								+	−
	fall		0.31							+		
SLMB	spring		0.45					+		+		−
	early summer		0.56		+			+		+		
	late summer		0.46				−				+	−
	fall		0.26								+	
JLMB	spring		0.54			+					+	
	early summer		0.25								+	
	late summer		0.58	+							+	
	fall		0.51						−		+	
Yellow bullhead	spring		0.54		+							
	early summer		0.25							+		
	late summer		0.12							+		
	fall		0.45							+		

Golden shiner	spring	0.47					+			+	
	early summer	0.39	–						+		
	late summer	0.26						–	+		
	fall	0.05								+	
Spottail shiner	spring	0.03				–					
	early summer	0.12			+	–					
	late summer	0.52						–	–		
	fall	0.44							–		
Bluntnose minnow	spring	0.39					+				
	early summer	0.27								+	
	late summer	0.33				+			+		
	fall	0.22			–	+					

Table 15. Stepwise linear regression (R^2) and logistic regression model (Rho^2) summaries for day electrofishing CPE of bluegill $\geq$ 15 cm (QBLG), bluegill < 15 and $\geq$ 8 (SBLG), bluegill < 8 cm (JBLG) pumpkinseed, largemouth bass $\geq$ 30 cm (QLMB), largemouth bass <30 cm and $\geq$ 20 cm (SLMB), largemouth bass < 20 cm (JLMB), yellow bullhead, golden shiner, spottail shiner, and bluntnose minnow with percent shoal substrate composition (organic, silt, sand-gravel, and rubble), percent plant cover (attached algae, broad-leaf, fine-leaf, and all vascular aquatic plants combined), and distance to 4.6 m contour. The (+) symbol denotes a positive coefficient and a (-) denotes a negative coefficient. Sample size for each period is 47.

Species	Period	R^2	Rho^2	Organic	Silt	Sand	Rubble	Attached algae	Broad-leaf	Fine-leaf	All plants	Distance to 4.6 m
Bluegill												
QBLG	spring		0.13						+			
	early summer		0.05				+					
	late summer		0.1						+			
	fall		0.18								+	
SBLG	spring	0.55							+	+		
	early summer	0.52						+			+	
	late summer	0.7							+	+		
	fall	0.8							+	+		−
JBLG	spring		0.25								+	
	early summer		0.42								+	
	late summer	0.28									+	
Pumpkinseed	spring		0.47								+	
	early summer		0.38	+							+	
	late summer		0.42		+						+	
	fall		0.43	+							+	
QLMB	spring		0.13						+			
	late summer		0.05				+					
	fall		0.18								+	
SLMB	spring		0.35							+		
	early summer		0.41		+					+		
	late summer		0.32				−				+	
	fall		0.21							+		
JLMB	spring		0.29				+		+			
	early summer		0.2		+							
	late summer		0.76						−		+	
	fall		0.18	+				−			+	
Yellow bullhead	spring		0.26		+							
	early summer		0.28							+		
	late summer		0.21								+	
	fall		0.2							+		
Golden shiner	early summer		0.4							+	−	
	late summer		0.22						−	+		
	fall		0.13							+		

Spottail minnow	spring	0.18		–		–					
	late summer	0.1				+					
	early fall	0.2						–	–		
Bluntnose	late summer	0.35				+			+		
	early fall	0.38		–						+	

Table 16. Regression tree models of day and night electrofishing site CPE (number per 5 minute run) for bluegill, largemouth bass, and yellow perch derived from nine trap net site habitat variables (distance from 4.6 m. contour, organic substrate, silt substrate, sand/gravel substrate, rubble substrate, attached algae plant cover, broad-leaf plant cover, fine-leaf plant cover, and vascular plant cover). The proportional reduction in error term (PRE) for each model is listed in parenthesis. Boldface type denotes mean electrofishing CPE within each classification (n=47).

<u>**Day Electrofishing**</u>

Bluegill

<u>Spring (PRE = 0.77)</u>

- I. Vascular plant cover ≥ 1%. **(26.5)**
- II. Vascular plant cover < 1%.
    - A. Sand-gravel substrate composition ≥ 29%. **(0.1)**
    - B. Sand-gravel substrate composition < 29%. **(3.3)**

<u>Early summer (PRE = 0.86)</u>

- I. Fine-leaf plant cover < 0.1%.
    - A. Silt substrate composition < 6%. **(0.1)**
    - B. Silt substrate composition ≥ 6%. **(2.7)**
- II. Fine-leaf plant cover ≥ 0.1%
    - A. Silt substrate composition < 17%. **(14.0)**
    - B. Silt substrate composition ≥ 17%. **(41.8)**

<u>Late summer (PRE = 0.89)</u>

- I. Fine-leaf plant cover < 2%. **(0.6)**
- II. Fine-leaf plant cover ≥ 2%.
    - A. Fine-leaf plant cover ≥ 27%. **(47.6)**
    - B. Fine-leaf plant cover < 27%.
        - 1. Organic substrate composition < 21%. **(5.2)**
        - 2. Organic substrate composition ≥ 21%. **(25.4)**

<u>Fall (PRE = 0.74)</u>

- I. Vascular plant cover ≥ 13%. **(26.7)**
- II. Vascular plant cover < 13%.
    - A. Silt substrate composition ≥ 6%. **(4.8)**
    - B. Silt substrate composition < 6%. **(0.3)**

Largemouth Bass

<u>Spring (PRE = 0.57)</u>

- I. Vascular plant cover < 1%. **(0.9)**
- II. Vascular plant cover ≥ 1%
    - A. Silt substrate composition ≥ 13%. **(3.3)**
    - B. Silt substrate composition < 13%.
        - 1. Silt substrate composition ≥ 6%. **(13.6)**
        - 2. Silt substrate composition < 6%. **(4.9)**

<u>Early summer (PRE = 0.58)</u>

- I. Silt substrate composition ≥ 22%. **(2.6)**
- II. Silt substrate composition < 22%.
    - A. Silt substrate composition < 7%. **(0.4)**
    - B. Silt substrate composition ≥ 7%.
        - 1. Attached algae cover < 4%. **(1.9)**
        - 2. Attached algae cover ≥ 4%. **(2.6)**

<u>Late summer (PRE = 0.67)</u>

- I. Fine-leaf plant cover < 2%. **(0.4)**
- II. Fine-leaf plant cover ≥ 2%. **(6.5)**

<u>Fall (PRE = 0.33)</u>

- I. Vascular plant cover < 8%.
    - A. Organic substrate composition < 20%. **(0.5)**
    - B. Organic substrate composition ≥ 20%. **(3.1)**
- II. Vascular plant cover ≥ 8%.
    - A. Broad-leaf plant cover < 1%. **(9.4)**
    - B. Broad-leaf plant cover ≥ 1%. **(3.8)**

Yellow Perch

<u>Spring (PRE = 0.63)</u>

- I. Rubble substrate composition > 26.3%. **(23.8)**
- II. Rubble substrate composition ≤ 26.3%.
    - A. Vascular plant cover ≤ 3.3%. **(4.2)**
    - B. Vascular plant cover < 3.3%.

1. Silt substrate composition > 16.5%. **(5.5)**
2. Silt substrate composition ≤ 16.5%.
   a. Organic substrate composition ≤ **(8.6)**
   b. Organic substrate composition > **(25.0)**

<u>Early summer (PRE = 0.62)</u>

I. Vascular plant cover ≤ 18.5%. **(5.4)**
II. Vascular plant cover > 18.5%.
  A. Silt substrate composition > 16.7%. **(7.9)**
  B. Silt substrate composition ≤ 16.7%.
    1. Rubble substrate composition > 22.4%. **(27.3)**
    2. Rubble substrate composition ≤ 22.4%. **(14.0)**

<u>Late summer (PRE = 0.64)</u>

I. Fine-leaf plant cover ≤ 0.2%. **(1.1)**
II. Fine-leaf plant cover > 0.2%.
  A. Vascular plant cover ≤ 41.8%. **(36.0)**
  B. Vascular plant cover > 41.8%.
    1. Sand-gravel substrate composition ≤ 40.4%. **(8.8)**
    2. Sand-gravel substrate composition > 40.4%. **(21.7)**

<u>Fall (PRE = 0.66)</u>

I. Rubble substrate composition > 26.3%. **(23.9)**
II. Rubble substrate composition ≤ 26.3%.
  A. Fine-leaf plant cover > 12.1%. **(4.8)**
  B Fine-leaf plant cover > 12.1% and ≤ 5.4% **(27.8)**
  C. Fine-leaf plant cover ≤ 5.4%.
    1. Silt substrate composition > 6.3%. **(10.8)**
    2. Silt substrate composition ≤ 6.3%. **(2.1)**

<u>Night Electrofishing</u>

Bluegill

<u>Spring (PRE = 0.71)</u>

I. Fine-leaf plant cover < 0.1%. **(0.8)**
II. Fine-leaf plant cover ≥ 0.1%.
  A. Rubble substrate composition < 22%. **(27.6)**
  B. Rubble substrate composition ≥ 22%. **(4.6)**

<u>Early summer (PRE = 0.81)</u>

I. Fine-leaf plant cover < 0.1%. **(1.0)**
II. Fine-leaf plant cover ≥ 0.1%.
  A. Fine-leaf plant cover < 11%. **(18.0)**
  B. Fine-leaf plant cover ≥ 11%. **(82.4)**

<u>Late summer (PRE = 0.81)</u>

I. Fine-leaf plant cover < 0.2%. (3.4)
II. Fine-leaf plant cover ≥ 0.2%.
  A. Fine-leaf plant cover < 27%. **(30.6)**
  B. Fine-leaf plant cover ≥ 27%. **(104.4)**

<u>Fall (PRE = 0.65)</u>

I. Fine-leaf plant cover ≥ 18%. **(113.8)**
II. Fine-leaf plant cover < 18%.
  A. Vascular plant cover < 3%. **(9.6)**
  B. Vascular plant cover ≥ 3%.
    1. Silt substrate composition < 6%. **(22.4)**
    2. Silt substrate composition ≥ 6%.
      a. Broadleaf plant cover ≥ 0.3%. **(40.6)**
      b. Broadleaf plant cover < 0.3%. **(121.5)**

Largemouth Bass

<u>Spring (PRE = 0.63)</u>

I. Vascular plant cover < 13%. **(0.5)**
II. Vascular plant cover ≥ 13%.
  A. Vascular plant cover ≥ 28%. **(9.1)**
  B. Vascular plant cover < 28%.
    1. Organic substrate composition ≤ 11%. **(5.9)**
    2. Organic substrate composition > 11%. **(1.4)**

<u>Early summer (PRE = 0.72)</u>

I. Fine-leaf plant cover < 11%.
  A. Fine-leaf plant cover < 0.1%. **(0.2)**
  B. Fine-leaf plant cover ≥ 0.1%. **(1.4)**

II. Fine-leaf plant cover ≥ 11%.
 A. Average distance from 4.6 m. contour < 92 m. **(7.8)**
 B. Average distance from 4.6 m. contour ≥ 92 m. **(2.5)**

Late summer (PRE = 0.63)
I. Fine-leaf plant cover ≥ 0.2%. **(7.6)**
II. Fine-leaf plant cover < 0.2%.
 A. Silt substrate composition < 3%. **(0)**
 B. Silt substrate composition ≥ 3%. **(1.3)**

Fall (PRE = 0.73)
I. Fine-leaf plant cover < 2%.
 A. Silt substrate composition < 3%. **(0.2)**
 B. Silt substrate composition ≥ 3%.
  1. Silt substrate composition < 12%. **(3.4)**
  2. Silt substrate composition ≥ 12%. **(1.6)**
II. Fine-leaf plant cover ≥ 2%.
 A. Broad-leaf plant cover < 3%. **(10.6)**
 B. Broad-leaf plant cover ≥ 3%. **(5.5)**

Yellow Perch

Spring (PRE = 0.58)
I. Organic substrate composition > 44%. **(58.3)**
II. Organic substrate composition ≤ 44%.
 A. Vascular plant cover ≤ 28%. **(8.1)**
 B. Vascular plant cover >28%.
  1. Fine-leaf plant cover ≤ 0.5%. **(51.6)**
  2. Fine-leaf plant cover > 0.5%. **(18.3)**

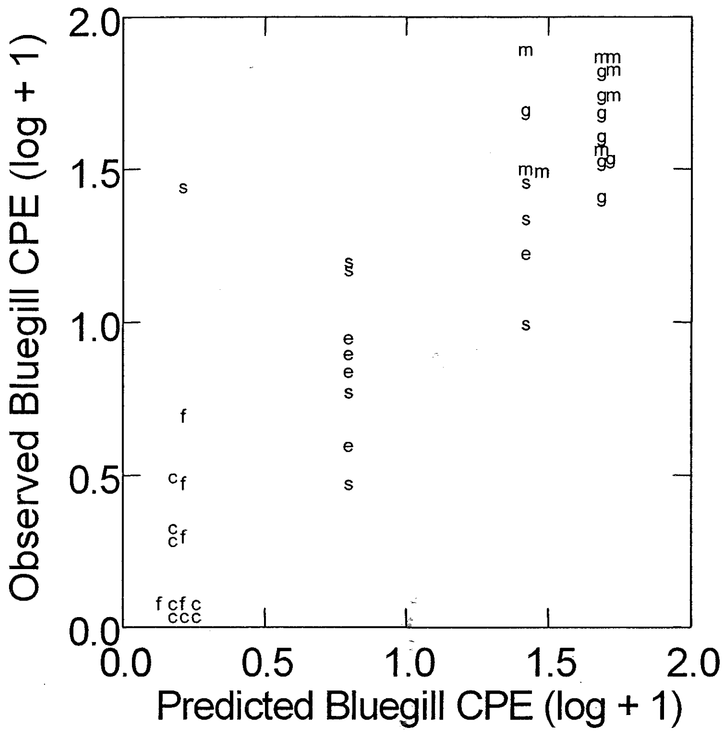
Early summer (PRE = 0.58)
I. Rubble substrate composition ≤ 11.4%.
 A. Organic substrate composition ≤ 18.9%. **(7.5)**
 B. Organic substrate composition >18.9%.
  1. Broad-leaf plant cover ≤ 10.6%. **(14.3)**
  2. Broad-leaf plant cover > 10.6%. **(31.0)**
II. Rubble substrate composition > 11.4%.
 A. Sand-gravel substrate composition ≤ 24.8%. **(53.6)**
 B. Sand-gravel substrate composition > 24.8%.
  1. Attached algae cover ≤ 9.5%. **(34.0)**
  2. Attached algae cover > 9.5%. **(15.2)**

Late summer (PRE = 0.13)
I. Sand-gravel substrate composition ≤ 46.8%. **(15.2)**
II. Sand-gravel substrate composition > 46.8%. **(39.4)**

Fall (PRE = 0.75)
I. Fine-leaf plant cover > 17.6%. **(4.6)**
II. Fine-leaf plant cover ≤ 17.6%.
 A. Organic substrate composition > 28.6%. **(66.5)**
 B. Organic substrate composition ≤ 28.6%.
  1. Broad-leaf plant cover > 3.0%. **(46.3)**
  2. Broad-leaf plant cover ≤ 3.0%.
   a. Silt substrate composition > 8.8%. **(33.0)**
   b. Silt substrate composition ≤ 8.8%. **(7.0)**

Figure 16. Late summer (August) bluegill electrofishing catch per unit effort (CPE; number per 24 hour set) observed at electrofishing sites in lakes Erie, French, Stahls, Cokato, Granite, and Mary versus late summer bluegill electrofishing CPE predicted from classification tree models listed in Table 18 for day electrofishing runs (A) and night electrofishing runs (B).

A



B

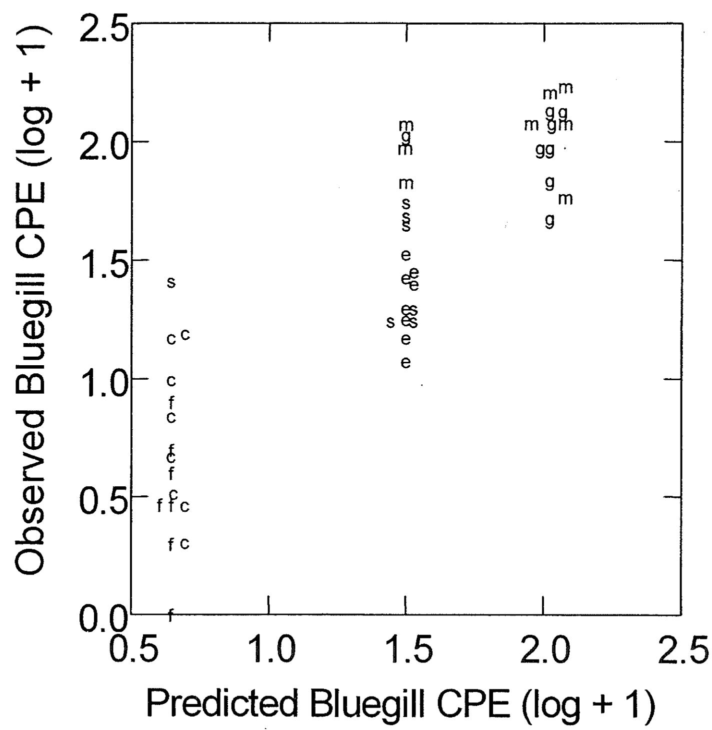
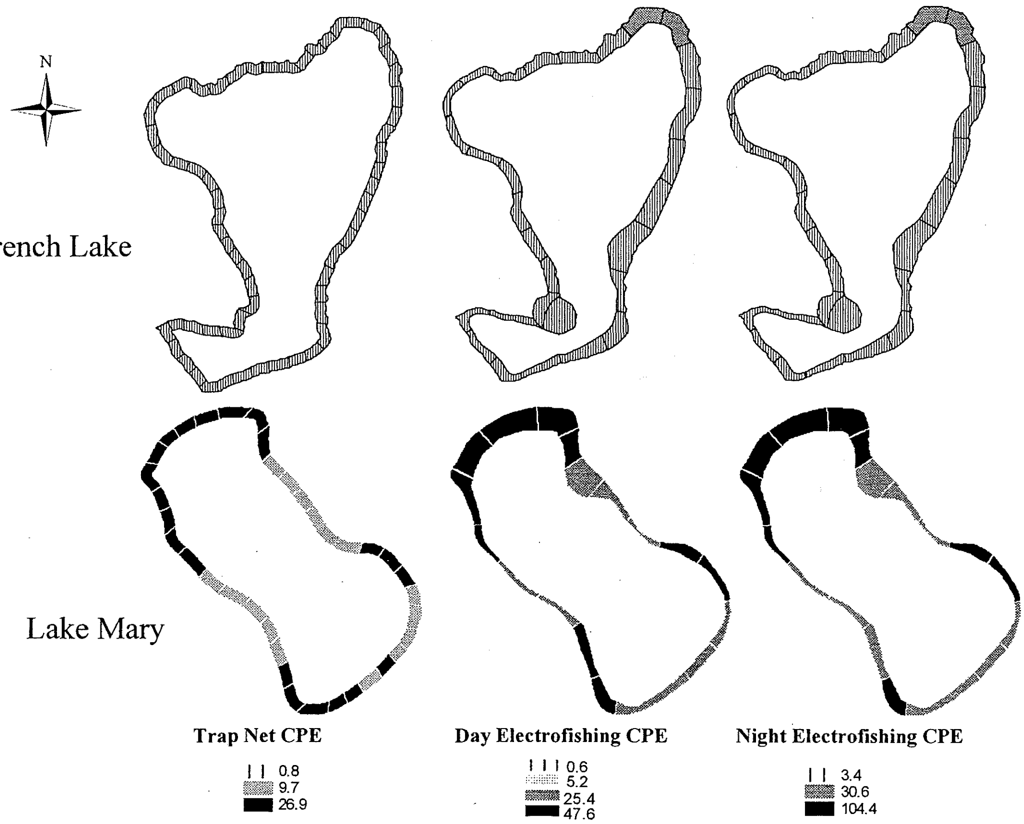


Figure 17. August day and night bluegill electrofishing CPE (number/5 min. run) and bluegill trap net CPE (number per 24 hour lift) for French Lake and Lake Mary predicted from regression tree analysis.



spatial query using a GIS to identify potential limiting factors or sources of perturbation affecting bluegill habitat suitability. For the study lakes, these queries showed effects of human shoreline activity, fetch and aspect towards prevailing winds, and other riparian features relating to bluegill habitat suitability.

Discussion

The abundance of sportfish and other fish species in Lake Class 24 lakes are limited by habitat factors linked through several spatial scales. We found that littoral fish species are heterogeneously distributed both among and within individual ecological Lake Class 24 lakes in patterns that are predictable based upon habitat descriptions. Our results are similar to those of Brazner and Beals (1997) and Randall et al. (1996) that show littoral fish populations most prominently affected by aquatic vegetation cover which was linked with other environmental variables through several spatial scales. These findings would be expected given that the dominant littoral fish species occurring in many of these lakes (bluegill, pumpkinseed, and largemouth bass) are frequently cited with habitat preferences for plant cover, and that Lake Class 24 lakes are defined by limnological parameters (Schupp 1992) that are favorable for extensive plant cover (i.e. relatively shallow and fertile with moderate transparency). Plant cover is a critical habitat factor for largemouth bass and other centrarchids in providing food and cover from predators (Crowder and Cooper 1979; Dibble et al 1996; Johnson and Jennings 1998).

The geographical distribution of Lake Class 24 lakes in Minnesota controls fish populations in these lakes both directly and indirectly. Likewise, Hinch et al. (1991) observed differences in fish community structures among 25 central Ontario lakes due to species colonization and zoogeographic processes. Direct effects are seen with physical barriers such as Saint Anthony Falls on the Mississippi River, which excludes several species of fish (Underhill 1989) from access to more northern Lake Class 24 lakes with drainages above the falls. Indirect controlling factors arise from the statewide gradient in lake fertility that increases towards the south and west in Minnesota (Moyle 1956), and is reflected by increases in turbidity and dominance by phytoplankton. Lake Class 24 lakes towards the south and west tend to have larger watersheds with more agricultural cultivation. Larger watershed sizes and cultivated land cover results in higher contributions of sediments and nutrients to lakes than other land cover types (National Research Council 1992; Crosbie and Chow-Frazer 1999). Higher sediment and nutrient loading in turn inhibits growth of submergent vascular plants at deeper depths due to reduced transparency and competition with phytoplankton communities (Crowder and Painter 1991; Crosbie and Chow-Frazer 1999). A previous investigation of a smaller subset of similar Minnesota lakes also showed that lakes with larger more agricultural watersheds had higher catches of black bullhead, common carp and black crappie, and lower catches of bluegill and other sunfish than lakes with smaller, more forested watersheds (Cross and McInerny 1995). Larger watersheds also typically allow more connections with other water bodies than small watersheds. Often these connections can be with shallow turbid water bodies dominated by black bullhead and common carp which can migrate extensively; hence, we observed a significant relationship between connected lakes and black bullhead and common carp catches in Lake Class 24 lakes. The influence of connections was also seen with increases in fish species richness which could be attributed to an influx of species commonly associated with stream habitats such as that observed by Willis and Magnuson (2000) in Wisconsin lakes, where more fish species were sampled at confluences with stream connections than at locations distant from stream connections. In Michigan lakes, Schneider (1981) also observed that large lakes connected to large rivers had the highest species diversity and small seepage lakes had the lowest.

Within the bounds set on Lake Class 24 fish populations by regional and watershed parameters, species richness increased with lake size, mean depth, and Secchi depth because habitat complexity increased. Increases in species richness with increases in lake area were also documented by Allen et al. (1999) and by Eadie and Keast (1984) citing Barbour and Brown (1974) who stated that fish diversity responds to increased habitat diversity found in larger lakes. Increases in water clarity (Secchi depth) probably relate to increases in the diversity and amount of aquatic plant cover, which again corresponds to greater fish species richness. The strong influence of plant cover in deeper Lake Class 24 lakes (mean depth > 4.5 m) corresponded to increases in *Lepomis* species (bluegill, pumpkinseed, and hybrid sunfish) known to have a strong affinity for plant cover.

Annual variation in habitat conditions and fish populations among Lake Class 24 lakes confounds a precise identification of habitat - fish interactions. For example, chlorophyll *a* and total phosphorus concentrations, as well as plant communities in lakes are quite dynamic and can fluctuate greatly, yet in many cases lakes are represented by only a single value representing one point in time. Schupp (1992) found all surveyed Secchi disk values averaged for each lake improved his ability to classify lakes in contrast to a single

Secchi value. Also, significant amounts of annual variation exist with trap net catches, so long term averages probably characterize a lake's fish population better than data from any single year. A data set that includes more observations over time for each individual lake should improve parameter estimates. However, immediate responses of fish populations to habitat change measured from long term averages, such as the 17 year period (1980 to 1997) used in this study, would not be detected. Many Lake Class 24 lakes are relatively shallow and are subject to changes in alternative stable states, one state dominated by aquatic macrophyte growth and another characterized by higher levels of turbidity and domination by phytoplankton (Carpenter and Cottingham 1997). Additionally, Nichols (1997) found that seasonal and sampling variability is highly variable in lakes with Secchi depths < 2 m, reflecting the dynamic nature of plant communities in these more turbid lakes. However, to our knowledge, annual variation in aquatic plant communities or aquatic plant cover has not been quantified for any lake in south-central MN, including these study lakes. Hall and Werner (1977) showed that fluctuations of fish year-classes and species are related to habitat stability. However, there is a time lag for generations of fish to develop and pass. This "lag" period is problematic for the analysis of habitat - fish population interactions in the more dynamic lakes.

At the site scale of analysis, aquatic plant cover was again an effective habitat variable for discerning differences in fish catches. Weaver et al. (1993) also observed significant associations between fish and littoral vegetation in Wisconsin lakes, and Hinch and Collins (1993) correlated bluegill and pumpkinseed abundance with near shore aquatic plant cover. Our results indicated that differences in plant cover among sampling sites could explain significant amounts of variation in electrofishing and trap net catches. Because electrofishing catches of smaller bluegills and largemouth bass responded more to increases in plant cover than the larger sizes, it was apparent that aquatic plants functioned to protect small fish from predation. This would be consistent with observations by Weaver et al. (1996) that small fish are confined by predation to areas of dense plant cover. Fine-leaf plant cover generally appeared to influence fish populations more than other plant forms, and appeared to form the densest cover. Also, increases in electrofishing fish species richness with plant cover probably relates to the increased habitat complexity as well as protective cover from predators for smaller fish species (Eadie and Keast 1984).

Our analysis did not account for spatial arrangements in habitat that could have influenced fish populations. Correlations of local abundances do not account for spatial arrangement of habitat types and therefore ignore spatial autocorrelation (Essingtion and Kitchell 1999). For example, the location of preferred habitat relative to size of habitable area may be important. Often, the density and distribution of animals is not limited by the quantity of any one habitat component, but rather its degree of interspersion or its spatial relationship to other requirements (Dasmann 1964). Our estimates of plant cover were based on spatial interpolation from transect point samples. Problems associated with spatial mapping errors and error propagation (Berry 1995) should be recognized when using mapped data. Our interpolated maps of aquatic plant cover should have provided good estimates for quantifying the amount of cover at each site, but since interpolation would tend to blend out patchiness of plant cover at the individual sampling site scale of analysis, it would have been inappropriate to address spatial arrangements of habitats with our data at that scale.

Analysis of site habitat - fish population interactions was confounded by a "lake effect" which was not removed in our analysis. Littoral habitats within the study lakes were less variable than among the study lakes. Similarly, Rundle and Jackson (1996) observed less variation in littoral zone fish communities within lakes than among lakes. Sampling sites are not totally independent of each other, especially in lakes with smaller surface areas. As a result, higher catch observations in sites with poor habitat might reflect adjacent sites with better habitat and vice versa. In our site scale analyses, we worked on the hypothesis that fish sampled at a site reflected the local habitat conditions to a greater extent than that of the lake. Separating a site effect from a lake effect is problematic; however, for species with relatively small home ranges and narrow habitat requirements, site habitats should explain most of their occurrence. Fish and Savitz (1983) documented primary occupation areas of 0.25 to 0.50 ha for largemouth bass, bluegill, pumpkinseed, and yellow perch. On the other hand, the occurrence of a species that ranges over a large area and is a habitat generalist is more likely related to habitat at the "lake" and "watershed" scales than at the site scale. By combining analyses at the site scale and the lake and watershed scales, influences at all scales can be examined simultaneously. The cumulative effect of all habitats in a lake are likely related to whole lake fish populations; however, habitat conditions at individual sites are more likely to reflect the distribution of fish within a lake as depicted in spatial models of bluegill catches shown in Figure 17. Our site scale analyses also was hindered by the lack of replications at each site which adds a considerable amount of unexplained sampling error to the analysis (Hamley and Howley 1985), masking the strength of relationships between fish abundances and habitat characteristics. Nonetheless, we assumed that strong associations would stand out from background variability.

Management and Research Implications

Results of management actions such as the manipulation of vegetation and watershed connections on fish populations are predictable. Lake Class 24 lakes are usually managed for largemouth bass and bluegill fisheries which are dependent upon aquatic plant cover to sustain their populations. Consequentially, efforts to maintain fisheries in these lakes should focus on maintaining stable plant communities that provide adequate amounts of cover. Limitations to aquatic plant growth due to natural and anthropogenic factors should be clearly identified. This necessarily includes sound information concerning the affects of watersheds and lake ecosystems on plant growth (i.e. alkalinity, nutrient loading, turbidity, common carp and black bullhead populations, and water level fluctuations) as well as site specific limitations to the development of plant cover (i.e. fetch, slope, aspect, bottom substrates, and human shoreline development). Watershed linkages are important to recognize because it is easier to manage terrestrial sources of stress on aquatic habitats than lake sources (Crowder et al. 1996). The most efficient way to assemble and analyse this information for problem solving is to use a GIS so that descriptive inventories can be tied together spatially. Development of complete GIS's for individual lake ecosystems would empower managers with information that could be used to link plant population dynamics to fish population dynamics, and to direct habitat protection and restoration efforts (examples: aquatic management area acquisitions and revegetation efforts) more specifically to problem areas. More specifically, this information could be used to limit the amount of aquatic plant removal permitted or to identify appropriate areas for revegetation efforts or the acquisition of aquatic management areas. Also, this information could be used to predict the condition of lake habitats and corresponding fish populations present before degradation by human activities so that appropriate goals are identified in habitat restoration programs.

Additional research is needed to fine-tune our knowledge of fish response to lake habitat. At the watershed scale of analysis, more detailed, spatially linked information on soils, animal livestock units, and road density would be useful. Also, models of sediment and nutrient runoff for each lake's watershed would be invaluable to provide detailed information not only on the amount of sediment and runoff but also the location. Finally, hydrographic data with stream and open water body connectivity and more information on fish movements are needed to understand fish populations in more connected lake ecosystems. At the lake scale, seasonal three-dimensional spatial distributions of dissolved oxygen and temperatures could be used to help define suitable habitat volumes in lakes, especially useful during periods of summer and winter anoxia. More and improved spatial data on aquatic plant communities and cover types are needed to obtain a more complete analysis of fish - plant interactions which appear to be the key factor influencing fish populations in many central Minnesota centrarchid lakes. For example, more information is needed on ecological gradients (edge, juxtaposition, and patch size) in relation to fish community composition and performance indicators of individual fish stocks (growth, recruitment, and mortality rates). Several investigators have attempted to manipulate plant communities in lakes in order to improve the size structure of bluegill populations by increasing predation on small bluegill with mixed success (Cross and McInerny, 1992; Radomski et al. 1995; Potthoven et al. 1999, and Unmuth et al. 1999). However, optimal habitats for maintaining good bluegill size structure in lakes are perhaps better identified by relating existing plant community structures in lakes to performance indicators of corresponding bluegill populations.

Relative abundances of littoral fish species estimated by RTA performed with environmental lake and watershed variables is a useful tool for identifying key "habitat" related factors affecting populations of littoral sport and forage fish species. Similarly, Emmons et al. (1999) determined that results from classification tree analysis were easily interpreted. This type of analysis expanded to other individual Minnesota lake classes may provide valuable management insight into explanatory habitat factors associated with net catch indices from standardized lake surveys. As such, it could help guide management efforts, such as those directed at stocking and regulating fish harvests, by providing rationale based on the productivity of fish habitats. Classification tree models could also aid in setting and communicating appropriate goals for individual fish species based on habitat suitability in lakes. For example, limitations in lake size and plant cover for walleye and largemouth bass identified by regression tree analysis might be useful to the public and a fish manager interested in the potential of stocking walleye or regulating largemouth bass harvest to improve populations.

Finally, spatial models of habitat suitability for aquatic plant and fish communities are needed to assess environmental damage, determine potential for habitat restorations, and improve sampling efforts. The potential for combining spatial information on lake morphometry (fetch, aspect, and depth), shoal bottom substrates, and watershed characteristics (size, edaphic properties, and connections), as well as other factors in a GIS to identify habitat suitability for aquatic plant growth was demonstrated by Remillard and Welch (1993). They showed spatial variables describing depth and sedimentation predicted 90% of the observed distribution of aquatic plant cover in a South Carolina Reservoir. As such, spatial models of plant cover could be used to identify and prioritize locations for habitat acquisition or identify areas of environmental damage. In addition, spatial models can be used to connect these areas to controlling factors in the watersheds that may need management attention. Spatial models of fish communities would help in constructing a sampling design for estimating lakewide fish abundance, since sampling of poor habitats tends to yield underestimates and sampling of good habitats tends to yield overestimates according to Wilde and Fisher (1996). Meals and Miranda (1991) and Toepfer et al. (2000) recommend accounting for the influence of habitat quality variation on fish abundance estimates.

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Appendix I. Common and scientific names of fish species captured during standardized MNDNR lake survey trap netting in Lake Class 24 lakes (1980-1997).

Common name	Taxonomic name
Longnose gar	*Lepisosteus osseus*
Shortnose gar	*Lepisosteus platostomus*
Bowfin	*Amia calva*
Gizzard shad	*Dorsoma cepedianum*
Rainbow trout	*Oncorhynchus mykiss*
Cisco	*Coregonus artedi*
Northern pike	*Esox lucius*
Muskellunge	*Esox masquinongy*
Common carp	*Cyprinus carpio*
Golden shiner	*Notemigonus crysoleucas*
Common shiner	*Notropis cornutus*
Spottail shiner	*Notropis hudsonius*
Quillback	*Carpoides cyprinus*
White sucker	*Catostomus commersoni*
Longnose sucker	*Catostomus catostomus*
Bigmouth buffalo	*Ictiobus cyprinellus*
Smallmouth buffalo	*Ictiobus bubalus*
Silver redhorse	*Moxostoma anisurum*
Golden redhorse	*Moxostoma erythrurun*
Shorthead redhorse	*Moxostoma macrolepidotum*
Black bullhead	*Ameiurus melas*
Yellow bullhead	*Ameiurus natalis*
Brown bullhead	*Ameiurus nebulosus*
Channel catfish	*Ictalurus punctatus*
Tadpole madtom	*Noturus gyrinus*
Flathead catfish	*Pylodictus olivaris*
White bass	*Morone chrysops*
Rock bass	*Ambloplites rupestris*
Green sunfish	*Lepomis cyanellus*
Pumpkinseed	*Lepomis gibbosus*
Bluegill	*Lepomis macrochirus*
Hybrid sunfish	*Lepomis X Lepomis*
Smallmouth bass	*Micropterus dolomieu*
Largemouth bass	*Micropterus salmoides*
White crappie	*Pomoxis annularis*
Black crappie	*Pomixis nigromaculatus*
Yellow perch	*Perca flavescens*
Walleye	*Stizostedion vitreum*
Freshwater drum	*Aplodinotus grunniens*

Appendix II. Regression tree models of trap net CPE for selected fish species and species richness in Lake Class 24 lakes using seven selected physical and chemical watershed-lake variables (watershed area, mean depth, Secchi depth, forested land cover, cultivated land cover, lake area, and alkalinity). The proportional reduction in error term (PRE) for each model is listed in parenthesis. Boldface type denotes mean trap net CPE within each classification (n=113).

Bluegill June (PRE = 0.60)
- I. Watershed area < 4529 ha
  - A. Cultivated land cover < 19% - **(124.6)**
  - B. Cultivated land cover ≥ 19%
    - 1. Secchi < 1.8 m **(39.7)**
    - 2. Secchi ≥ 1.8 m **(107.9)**
- II. Watershed area ≥ 4529 ha
  - A. Watershed area < 27733 ha **(20.6)**
  - B. Watershed area ≥ 27733 ha **(57.6)**

Bluegill July-August (PRE = 0.67)
- I. Cultivated land cover < 57%
  - A. Cultivated land cover < 7% **(118.7)**
  - B. Cultivated land cover ≥ 7%
    - 1. Lake area < 194 ha **(46.2)**
    - 2. Lake area ≥ 194 ha
      - a. Watershed area < 10186 ha **(30.9)**
      - b. Watershed area ≥ 10189 ha **(8.5)**
- II. Cultivated land cover ≥ 57%
  - A. Mean depth ≥ 5.9 m **(25.6)**
  - B. Mean depth < 5.9 m **(6.0)**

Pumpkinseed June (PRE = 0.49)
- I. Watershed area < 853 ha. **(6.29)**
- II. Watershed area ≥ 853 ha.
  - A. Lake area ≥ 114.8.
    - 1. Cultivated land cover ≥ 39.3%. **(6.40)**
    - 2. Cultivated land cover < 39.3%. **(2.93)**
  - B. Lake area < 114.8.
    - 1. Mean depth ≥ 5.4 m. **(0.77)**
    - 2. Mean depth < 5.4 m.
      - a. Total alkalinity ≥ 135 mg/l $CaCO_3$. **(3.65)**
      - b. Total alkalinity < 135 mg/l $CaCO_3$. **(1.63)**

Pumpkinseed July-August (PRE = 0.43)
- I. Cultivated land cover ≥ 56.9%. **(0.57)**
- II. Cultivated land cover < 56.9%.
  - A. Mean depth ≥ 6.7 m. **(6.93)**
  - B. Mean depth ≥ 3.42 m and < 6.7 m. **(2.41)**
  - C. Mean depth < 3.42 m. **(0.52)**

Black Crappie (PRE = 0.25)
- I. Secchi ≥ 1.52 m. **(4.97)**
- II. Secchi < 1.52 m.
  - A. Mean depth < 5.6 m. **(16.50)**
  - B. Mean depth ≥ 5.6 m. **(3.57)**

Black bullhead (PRE = 0.46)
- I. Secchi < 0.91 m. **(19.51)**
- II. Secchi ≥ 0.91 m.
  - A. Watershed area ≥ 32,433 ha. **(22.44)**
  - B. Watershed area < 32,433 ha.
    - 1. Secchi ≥ 1.55 m. **(1.20)**
    - 2. Secchi ≥ 0.91 m. and < 1.55 m.
      - a. Watershed < 1361 ha. **(0.64)**
      - b. Watershed ≥ 1361 ha. and < 6138 ha. **(11.76)**
      - c. Watershed ≥ 6138 ha. and < 32433 ha. **(2.21)**

Yellow bullhead (PRE = 0.24)
- I. Secchi ≥ 3.35 m. **(9.30)**
- II. Secchi < 3.35 m.
  - A. Watershed area ≥ 1455 ha. **(1.81)**
  - B. Watershed area < 1455 ha.
    - 1. Cultivated land cover > 6.4%. **(5.24)**
    - 2. Cultivated land cover < 6.4%. **(1.68)**

Yellow Perch (PRE = 0.44)

- I. Secchi ≥ 1.22 m. **(0.51)**
- II. Secchi < 1.22 m.
  - A. Lake area < 74.6 ha. **(0.25)**
  - B. Lake area ≥ 74.6 ha.
    - 1. Watershed area ≥ 7980 ha. **(0.84)**
    - 2. Watershed area < 7980 ha.
      - a. Cultivated land cover < 19.6%. **(4.61)**
      - b. Cultivated land cover ≥ 19.6% and < 54.1%. **(1.05)**
      - c. Cultivated land cover ≥ 54.1% **(3.99)**

Walleye (PRE = 0.46)

- I. Cultivated land cover < 38%. **(0.20)**
- II Cultivated land cover ≥ 38%.
  - A. Cultivated land cover ≥ 77.8. **(1.72)**
  - B. Cultivated land cover < 77.8.
    - 1. Lake area < 124 ha. **(0.34)**
    - 2. Lake area ≥ 124 ha.
      - a. Mean depth ≥ 4.3 m. **(0.57)**
      - b. Mean depth < 4.3 m. **(1.30)**

Common Carp (PRE = 0.49)

- I. Cultivated land cover ≥ 77.8%. **(7.02)**
- II. Cultivated land cover < 77.8%.
  - A. Secchi ≥ 1.25 m. **(0.37)**
  - B. Secchi < 1.25 m.
    - 1. Watershed size < 1361 ha. **(0.29)**
    - 2. Watershed size ≥ 1361 ha.
      - a. Mean depth ≥ 3.9 m. **(1.13)**
      - b. Mean depth < 3.9 m. **(2.63)**

PC1 Factor Loading (PRE = 0.57)

- I. Cultivated land cover < 38%.
  - A. Mean depth < 3.4 m. **(0.369)**
  - B. Mean depth ≥ 3.4 m. **(-0.620)**
- II. Cultivated land cover ≥ 38%.
  - A. Secchi < 0.82 m. **(1.383)**
  - B. Secchi ≥ 0.82 m.
    - 1. Cultivated land cover ≥ 67.2%. **(1.291)**
    - 2. Cultivated land cover ≥ 38% and < 67.2%.
      - a. Mean depth < 5.2 m. **(0.353)**
      - b. Mean depth ≥ 5.2 m. **(-0.768)**

Trap Net Species Richness (PRE = 0.36)

- I. Watershed area < 3055 ha.
  - A. Cultivated land use < 4.4%. **(11.92)**
  - B. Cultivated land use ≥ 4.4%. **(10.06)**
- II. Watershed area ≥ 3055 ha.
  - A. Secchi ≥ 1.55 m. **(11.15)**
  - B. Secchi < 1.55 m.
    - 1. Lake area < 384 ha. **(12.28)**
    - 2. Lake area ≥ 384 ha. **(14.11)**

Appendix III. Regression tree models of trap net CPE for selected fish species and species richness in Lake Class 24 lakes using seven selected physical and chemical watershed-lake variables (watershed area, mean depth, Secchi depth, forested land cover, cultivated land cover, lake area, and alkalinity) and 4 additional variables from lake surveys (fine-leaf plant occurrence, emergent plant occurrence, gravel shoal substrate occurrence, and total phosphorus). The proportional reduction in error term (PRE) for each model is listed in parenthesis. Boldface type denotes mean trap net CPE within each classification (n=53).

Bluegill (PRE = 0.57)

- I. Fine-leaf vegetation occurrence in < 17.5% of transects. **(7.0)**
- II. Fine-leaf vegetation occurrence in ≥ 17.5% of transects.
  - A. Cultivated land cover < 14.3% **(109.9)**
  - B. Cultivated land cover < 14.3% **(40.2)**

Pumpkinseed (PRE = 0.54)

- I. Fine-leaf vegetation occurrence in < 22.5% of transects.
  - A. Cultivated land cover < 44.8%. **(1.75)**
  - B. Cultivated land cover ≥ 44.8%. **(0.13)**
- II. Fine-leaf vegetation occurrence in ≥ 22.5% of transects.
  - A. Emergent vegetation occurrence in < 6.0% of transects. **(7.93)**
  - B. Emergent vegetation occurrence in ≥ 6.0% of transects.
    - 1. Mean depth ≥ 4.2 m. **(3.21)**
    - 2. Mean depth < 4.2 m. **(1.05)**

Black Crappie (PRE = 0.58)

- I. Secchi ≥ 1.5 m. **(2.59)**
- II Secchi < 1.5 m.
  - A. Alkalinity < 139 mg/l. **(7.55)**
  - B. Alkalinity ≥ 139 mg/l.
    - 1. Lake area ≥ 372 ha. **(9.30)**
    - 2. Lake area < 372 ha.
      - a. Gravel occurrence in ≥ 51% of transects **(37.11)**
      - b. Gravel occurrence in < 51% of transects **(14.70)**

Black bullhead (PRE = 0.52)

PRE = 0.52

- I. Fine-leaf vegetation occurrence in < 22.3% of transects. **(43.3)**
- II. Fine-leaf vegetation occurrence in ≥ 22.3% of transects.
  - A. Mean depth ≥ 4.4 m. **(1.74)**
  - B. Mean depth < 4.4 m.
    - 1. Total phosphorus ≥ 0.10 mg/l. **(23.95)**
    - 2. Total phosphorus < 0.10 mg/l. **(3.37)**

Yellow bullhead (PRE = 0.56)

PRE = 0.56

- I. Emergent vegetation occurrence in ≥ 57.0% of transects.
  - A. Lake area ≥ 902 ha. **(3.19)**
  - B. Lake area < 902 ha. **(7.93)**
- II. Emergent vegetation occurrence in < 57.0% of transects.
  - A. Emergent vegetation occurrence in < 4.0% of transects. **(0.47)**
  - B. Emergent vegetation occurrence in ≥ 4.0% of transects.
    - 1. Fine-leaf vegetation occurrence in ≥ 46.8% of transects. **(4.05)**
    - 2. Fine-leaf vegetation occurrence in < 46.8% of transects. **(1.44)**

Yellow Perch (PRE = 0.40)

- I. Lake area < 98.4 ha. (0.39)
- II. Lake area ≥ 98.4 ha. and < 131.2 ha. (2.94)
- III. Lake area ≥ 131.2 ha. (0.86)

Walleye (PRE = 0.60)

- I. Cultivated land cover ≥ 67.2%. **(2.13)**
- II. Cultivated land cover < 67.2%.
  - A. Fine-leaf vegetation occurrence in < 25% of transects.
    - 1. Fine-leaf vegetation occurrence in < 15% of transects. **(0.50)**
    - 2. Fine-leaf vegetation occurrence in ≥ 15% of transects. **(1.26)**
  - B. Fine-leaf vegetation occurrence in ≥ 25% of transects.
    - 1. Mean depth ≤ 4.5 m. **(0.61)**
    - 2. Mean depth > 4.5 m. **(0.21)**

Common Carp (PRE = 0.76)
PRE = 0.76

- I. Cultivated land cover ≥ 67.2%. **(8.77)**
- II. Cultivated land cover < 67.2%.
  - A. Fine-leaf vegetation occurrence in ≥ 27.5% of transects.
    - 1. Lake area ≥ 354 ha. **(1.71)**
    - 2. Lake area < 354 ha. **(0.36)**
  - B. Fine-leaf vegetation occurrence in < 27.5% of transects.
    - 1. Cultivated land cover ≥ 44.2% and < 67.2%. **(3.62)**
    - 2. Cultivated land cover < 44.2%. **(0.63)**

PC1 Factor Loading (PRE = 0.67)

- I. Fine-leaf vegetation occurrence in < 27.5% of transects.
  - A. Emergent vegetation occurrence in < 12.0% of transects. **(1.801)**
  - B. Emergent vegetation occurrence in ≥ 12.0% of transects. **(0.214)**
- II. Fine-leaf vegetation occurrence in ≥ 27.5% of transects.
  - A. Mean depth < 4.5 m. **(0.440)**
  - B. Mean depth ≥ 4.5 m. **(-0.649)**

Trap Net Species Richness (PRE = 0.65)

- I. Watershed area < 3055 ha.
  - A. Emergent vegetation occurrence in < 85.9% of transects.
    - 1. Watershed area < 1862 ha. **(10.2)**
    - 2. Watershed area ≥ 1862 ha. **(8.27)**
  - B. Emergent vegetation occurrence in ≥ 85.9% of transects. **(11.24)**
- II. Watershed area ≥ 3055 ha.
  - A. Lake area < 384 ha.
    - 1. Emergent vegetation occurrence in < 50.0% of transects. **(11.45)**
    - 2. Emergent vegetation occurrence in ≥ 50.0% of transects. **(13.12)**
  - B. Lake area ≥ 384 ha. **(13.73)**

Appendix IV. Regression tree models of largemouth bass electrofishing CPE (number/h) in Lake Class 24 lakes using seven selected physical and chemical watershed-lake variables (watershed area, mean depth, Secchi depth, forested land cover, cultivated land cover, lake area, and alkalinity). The proportional reduction in error term (PRE) was 0.61. Boldface type denotes mean electrofishing CPE within each classification (n=43).

- I. Cultivated land cover ≥ 62.5%. **(2.35)**
- II. Cultivated land cover < 62.5%.
  - A. Secchi < 0.98 m. **(9.09)**
  - B. Secchi ≥ 0.98 m.
    - 1. Total alkalinity < 112 mg/l $CaCO_3$. **(61.37)**
    - 2. Total alkalinity ≥ 112 mg/l $CaCO_3$.
      - a. Watershed area < 5212 ha. **(34.24)**
      - b. Watershed area ≥ 5212 ha. **(12.12)**

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