Effects of residential shoreline development on near shore aquatic habitat in Minnesota lakes

A Thesis
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

Jennifer R. Keville

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Bruce Vondracek

June 2013

Acknowledgements

I would like to thank my advisor, Bruce Vondracek for his support and guidance throughout my graduate school career. I also want to acknowledge and thank my committee members Raymond Newman and Martin Jennings for their advice and contribution to this research.

This project would not have been possible without financial support from the Legislative-Citizen Commission on Minnesota Resources and the Environment and Natural Resources Trust Fund (ENRTF). A very special thank you to our Minnesota DNR collaborators Donna Dustin and Cindy Tomcko who helped to design the original study of which this thesis is a part, and provided support, conducted fieldwork, and gave valuable advice throughout the entirety of this project. Thank you to Jason Vinje for his fieldwork and coordination efforts. I would also like to acknowledge Linnea Henkels, Alex Gee, and other DNR interns for their hard work in the field.

I would especially like to acknowledge my friend and lab-mate, Jessie Lepore for her insight and support over the past few years. Ray Valley provided valuable advice regarding methods and statistical analyses. Thank you to Donna Perleberg and Paul Radomski for providing additional data to the project. Special thanks to Jacob Jungers and Marcus Beck for their statistical and moral support throughout this process. Also, thank you to David Andersen and Hattie Saloka with the USGS Co-op unit at the University of Minnesota for their logistical guidance.

Finally, thank you to my friends and family for their encouragement and understanding over these past couple of years. I couldn't have done it without them.

Abstract

The littoral zone contains all of the vegetation within a lake and is critical to the physical and biological integrity of lentic water bodies. Aquatic macrophytes stabilize the shoreline and support macroinvertebrate and fish communities by providing spawning substrate, feeding area, and refuge from predators. Riparian alterations associated with shoreline residential development have been shown to decrease aquatic vegetation and coarse woody structure (CWS). As the extent of lakeshore development increases, understanding the consequences of site- and lake-level shoreline alterations is necessary to better guide management decisions. The intensity and type of alterations may be an important factor regarding the extent of effects on littoral habitat. We investigated site-scale effects of lakeshore development on near-shore habitat across 10 northern Minnesota lakes using the Minnesota Department of Natural Resource's Score Your Shore (SYS) survey, to assess development intensity. We also examined lake-wide effects of development density. Study lakes were of similar size, class, and geology and represented a range of shoreline development. Developed sites had significantly lower macrophyte species richness than undeveloped sites. Emergent and floating-leaf macrophyte biovolume was also lower at developed sites. Coarse woody structure (CWS) density was lower at developed sites than undeveloped sites. SYS score was a significant factor in models of most macrophyte community variables, supporting the hypothesis that site-scale development intensity is related to littoral vegetation. Negative effects of lake-wide development were not detected in whole lake macrophyte and fish community metrics.

Table of Contents

Acknowledgements…………………………………………………………… i

Abstract…...………………………………………………………………...ii

List of Tables…….…………………………………………………………v

List of Figures……………………………………………………………..vi

INTRODUCTION……………………………………………………………1

METHODS…………………………………………………………………….. 5

RESULTS………… ……………………………………………………... .11

DISCUSSION……….……………………………………………………….. 13

REFERENCES……….……………………………………………………..20

Tables…………………..……………………………………….......................25

Figures…………………………………………………………........................33

List of Tables

Table 1. Development and limnological characteristics for 10 study lakes. …………………………………………………………………………………………25

Table 2. Score Your Shore (SYS) score sheet used to assign point values to sites 26

Table 3. Summary of all explanatory variables and distributions used to model each site-scale habitat response variable. ……………………………………………………….27

Table 4. Mean and standard error values (mean ± SE) for site-scale response variables by site type (Developed vs. Undeveloped)..……27

Table 5. Top supported models for site-scale littoral habitat response variables. Models were compared using AIC. All models include "Lake" as a random effect in the error term………………………………………………………………………………...28

Table 6. Parameter estimates for the top-supported generalized linear mixed models (GLMM, lme4, Bates et al. 2012) of structural habitat response variables. Substrate is a categorical variable with four levels: Fine, Sand, Mix and Coarse. All models were created in R version 2.15.2……………………………………………………….…...29

Table 7. Parameter estimates for top linear mixed models (LMM, nlme, Pinheiro 2012) of littoral habitat variables. Both submerged and floating biovolume were square root transformed. Substrate was a categorical variable with 4 levels: Fine, Sand, Mix, and Coarse. All models were created using R version 2.15.1……………………………..…30

Table 8. Best-supported linear models for lake-wide macrophyte and fish response variables. Models were compared using AIC. ....…..…31

Table 9. Parameter estimates for top linear models of lake-wide macrophyte and fish response variables. All models were created using R version 2.15.2………….……….32

List of Figures

Figure 1. Map of Northern Lakes and Forests Ecoregion (grey) with 10 study lakes (black dots) ………………………………………………………………….......33

Figure 2. Mean values for littoral habitat response variables that were significantly different between developed and undeveloped site types (Mann-Whitney-Wilcoxon, alpha=0.05). Whiskers represent 95% confidence intervals. **A**. Mean emergent species richness. **B.** Mean floating-leaf species **C.** Mean sensitive species richness **D.** Mean emergent biovolume **E.** Mean floating-leaf biovolume. **E.** Mean CWS site totals..34

Figure 3. Probability of presence of emergent macrophytes with SYS from best-supported model estimates. Dotted lines represent 95 % confidence intervals. Substrate was set to fine and the mean value for site floating–leaf biovolume was used to obtain the estimates. 35

Figure 4. Model predictions for floating leaf species richness. Substrate type was set at fine. The solid line represents estimates from the best-supported model for floating-leaf species richness with SYS score. Dotted lines represent 95% confidence intervals...36

Figure 5. Model estimates from the best-supported model for emergent species richness with SYS score. Substrate was set to fine. Dotted lines represent 95% confidence intervals………………………………………………………….........37

Figure 6. Model estimates from the best-supported model of sensitive species richness with SYS score. Substrate was set to fine. Dotted lines represent 95% confidence intervals……..38

Figure 7. Parameter estimates for top linear models of lake-wide macrophyte and fish response variables. All models were created using R version 2.15.2. ……………… 39

Introduction

Littoral habitat is a critical component of lake ecosystems. Defined by the zone of a lake in which rooted aquatic plants (macrophytes) are able to grow, littoral areas are influenced by a variety of factors including lake morphometry, chemistry, and geology. The littoral zone may be highly variable, both within and among lakes, due to structural differences attributed to substrate type, aquatic macrophyte growth, and coarse woody structure (CWS) recruitment. Structural complexity (heterogeneity of macrophyte and CWS forms and coverage) within the littoral zone provides important microhabitats for numerous biota as well as other vital ecosystem services.

Structurally complex littoral zones offer habitat to many aquatic species, dissipation of wave energy, flood protection, maintenance of water quality, and dispersal corridors for plants and animals (Carpenter and Lodge 1986; Graneli and Solander 1988). The nearshore littoral area contains the majority of lake vegetation, which stabilizes sediments and can prevent excessive algae growth (Sondergaard and Moss 1998). Macrophytes are also an important habitat and nutrient source for macroinvertebrates and zooplankton (Burks et al. 2002, Jeppesen et al. 1998). Littoral-dwelling fish species rely on aquatic vegetation for feeding, as well as protection from predators (Randall et al. 1996; Sass et al. 2006). Studies have indicated that fish species richness is generally higher in more complex and vegetated littoral areas than areas lacking structure (Jennings et al. 1999, Trial et al. 2001).

Coarse woody structure (CWS), another important feature of the littoral zone, increases the structural heterogeneity of near-shore ecosystems, providing refuge and habitat for fish and macroinvertebrate species (Gurnell et al. 2005). CWS supplies a stable substrate for invertebrates, bacteria and algal films, thereby offering food and forage sites for fish and protection for nests and young (Benke and Wallace 2003, Cochran and Cochran 2005, Sass 2006).

Lakes in Minnesota and throughout the Upper Midwest are popular destinations for residential development and recreation. Residential development around Minnesota lakes has increased significantly since the mid-1960s (Radomski and Goeman 2001). Additionally, many lots that once held small, seasonal cabins are being converted into large, year-round estates. Development of lake shorelines has the potential to affect the near shore littoral zone ecosystem in a number of ways. The degree to which the littoral area is affected depends upon both the extent of development (number of developed lots) surrounding a lake, as well as the development practices employed at individual lots. This linkage between lake riparian zone characteristics and littoral zones has been addressed in a number of studies but is not yet completely understood.

Riparian alterations can affect water quality by changing run-off patterns (Groffman et al. 2003) and increasing water temperature through the decrease of shaded areas (Johnson and Jones, 2000). Nutrient and contaminant inputs, as well as increased erosion, are also linked to shoreline alterations (Downing and McCauley, 1992). In studies of Wisconsin lakes, Christensen et al. (1996) and Marburg et al. (2006) concluded that developed shorelines had significantly less CWS than undeveloped shorelines. Additionally, coverage of aquatic macrophytes was reduced at developed sites when compared to undeveloped ones (Alexander et al. 2008; Cheruvelil and Soranno 2008;

Jennings et al. 2003). Developed shorelines had 66% less floating-leaf and emergent macrophyte coverage than undeveloped shorelines in a study of Minnesota lakes (Radomski and Goeman 2001).

Previous studies that addressed the effects of shoreline development on near-shore habitat typically categorized shorelines as developed or undeveloped based upon presence of a dock or dwelling. Other studies have assessed riparian vegetation coverage or focused on specific in-water structures such as break-walls or riprap (Alexander et al. 2008, Jennings et al. 1999). Studies have not generally assessed site-wide development practices as a whole. The decisions that shoreline landowners make with respect to the development of their lot may affect the extent of change in the near-shore aquatic ecosystem. Common shoreline development practices include removal of emergent and floating-leaf vegetation, replacement of riparian vegetation with lawn, clearing or thinning of trees and the addition of impervious surfaces. How many and which of these practices landowners adopt is likely to influence the degree to which development affects near-shore aquatic habitat. Understanding the effects of development behaviors and their various combinations on the littoral zone would allow those who manage lakes and shorelines to better advise landowners.

This thesis is part of a larger study involving 100+ lakes in north-central Minnesota that investigated the cumulative effects of shoreline development on littoral habitat. Within the larger study, my goal was to examine the effects of development on aquatic macrophyte communities and CWS at the individual lot/site scale. Rather than solely comparing developed vs. undeveloped sites, I also wanted to examine whether varying residential shoreline development practices affected littoral habitat characteristics to different degrees. I used the Minnesota Department of Natural Resource's (DNR) Score Your Shore (SYS) citizen shoreline description survey to assess site-scale shoreline development practices in more detail (Perleberg et al. 2012). This survey was originally developed as an education tool for landowners to learn about their development impacts but we used the SYS survey to provide a relatively quick but detailed assessment of site shoreline development practices for our study. Using the SYS survey, shoreline sites are scored based upon various development characteristics or lack thereof. The less intensively developed a site, the higher the score it receives.

My first objective for this study was to confirm the relationship established in previous research between developed and undeveloped sites and macrophyte and CWS variables. I expected to see the same negative relationship between site-scale development and local plant community and CWS variables within our study lakes. My second objective was to examine the link between those habitat metrics and site SYS score as a more detailed indicator of development intensity. I hypothesized that SYS score would be positively related to site-level macrophyte and CWS variables and would be a useful indicator of detrimental levels of development to littoral habitat impacts for lake managers and landowners. My third objective was to determine whether the effects of development density at the whole-lake scale would be detectable in lake-wide plant and fish communities. I hypothesized that lake plant and fish communities would respond negatively to increasing lake-wide development density.

Methods

Study Lake and Site Selection

We used stratified random sampling to select 12 study lakes from a group of 100+ candidate lakes. Candidate lakes were selected to have similar limnological characteristics to isolate the effects of lakeshore development. Study lakes were located in the Northern Lakes and Forests Ecoregion of Minnesota and had two or fewer upstream catchments. All lakes were mesotrophic with total phosphorus levels from 12 to 38 parts per billion. Watershed land use was restricted to at least 85% forested with no more than 10% agriculture (cultivated and pasture), based on land use classification in the National Land Cover Database (NLCD 2001). Lake dock density was determined using geo-referenced aerial photographs from the U.S. Department of Agriculture Farm Service Agency. Candidate lakes were ranked and separated into 5 development categories based on dock densities. Dock densities ranged from <1 dock/km shoreline to 70 docks/km shoreline in the candidate lakes. Six lakes from each category were selected to compose a set of 30 study lakes representing a range of shoreline development densities. These 30 lakes were part of the larger study and were assessed for plant and fish assemblages. From these 30 lakes, a representative subsample of 12 lakes was selected to receive intensive site-scale and whole lake littoral habitat surveys. After visiting two of the lakes for field work, we determined that their natural water chemistry and natural littoral habitat characteristics were too dissimilar to the other study lakes, thus we removed those lakes from future analyses, leaving 10 lakes (Table 1, Figure 1).

Using ArcGIS, we divided the shoreline of each study lake into 20m sections. With recent aerial photography, each section was designated as developed or undeveloped based on the presence of a dock. Shoreline sites around each lake were selected using a stratified random sampling design. Half of the sites were developed and half were undeveloped. The number of sites was dependent upon the length of shoreline of each lake. Each lake had a minimum of 15 developed and 15 undeveloped sites. At least 15 undeveloped sites were sampled on lakes with little or no development (Thistledew Lake and Elk Lake, Table 1).

Site Shoreline Assessment: Score Your Shore

Sites on all 10 lakes were visited in July through September 2012. Each site was located via GPS and assessed from a boat using the SYS survey (Perleberg et al. 2012, Table 2). The SYS survey divides a site/lot into "Upland", "Shoreline" and "Aquatic" zones. We used the "Upland" and "Shoreline" zone portions of the survey, which assign points to a site based on various characteristics reflecting development practices (Table 2). The highest possible score for a site is 100.

Field Methods

At each site we established 3 equally spaced transects perpendicular to shore. Transects were approximately 8 meters apart. At developed sites, transects were sometimes moved to accommodate docks or other in-water structures. We recorded all macrophyte species present within a $0.5m^2$ diameter buoyant sampling ring at three water depths (0.3m, 0.6m, and 0.9m) along each transect. Biovolume was estimated using a view-tube individually for each of three structural forms of macrophytes: emergent, submerged and floating-leaf. Biovolume was defined as the percentage of the water column within the sampling ring taken up by macrophytes. We estimated biovolume for submerged macrophytes between 0 and 100 percent at increments of 5 percent. Biovolume for floating-leaf macrophytes was estimated as the percentage of the water surface within the sampling ring that was covered with floating leaves. Estimates were between 0 and 100 percent in increments of 5 percent. Where coverage of submersed or floating-leaf macrophytes was very sparse, but greater than 0, a biovolume of 1 was assigned. Emergent macrophytes are typically thin stems such as bulrush (*Scirpus spp.*) or cattail (*Typha spp.*) and have a low biovolume. Therefore, we estimated biovolume for emergent macrophytes based upon stem counts within the sampling ring: 0: absent (0), 1: sparse (< 4 stems), 2: 4-9 stems, 3: 10-19 stems, 4: 20-30 stems, 5: dense (>30 stems) (personal comm. Ray Valley, Minnesota DNR).

Total macrophyte species richness was determined for the entire site using the sampling point data. Species richness was also determined for each macrophyte structural type (emergent, floating-leaf and submersed). We counted the number of sensitive macrophyte species at each site based upon the sensitive species list used by Beck et al. (2010) to calculate the Minnesota lake macrophyte IBI. Macrophyte species with coefficient of conservatism values (C) greater than 7, were called sensitive (Nichols 1999). The nine sampling point biovolume estimates were averaged for each structural type to obtain mean site biovolumes. We also counted all pieces of CWS >10cm in diameter and >60cm in length within the site area designated by the 20m of shoreline and to a water depth of 0.9m. We classified substrate by particle size at the center sampling point (0.6m depth) for each site into one of four categories: fine (silt/muck), sand, mix (cobble with sand), and coarse (rocks/boulders).

Macrophyte point intercept sampling was also conducted on each of the 10 study lakes following the Minnesota DNR's standard protocol (Minnesota Department of Natural Resources 2008) We calculated macrophyte Index of Biotic Integrity (IBI) scores (Beck et al. 2010) and Floristic Quality Index (FQI) scores for each lake (Rooney and Rogers 2002). FQI data were also available for many of the larger set of 114 study lakes from the Minnesota DNR. Lake-wide macrophyte species richness was also determined for these lakes.

The percentage of disturbed land (agriculture, commercial, residential) within each lake watershed was determined using National Land Cover database layers in ArcGIS (NLCD 2001). We determined dock density (number of docks/km of shoreline) for each lake using aerial photographs. Fish were collected on the larger set of 30 lakes according to the Minnesota DNR protocol to calculate an index of biotic integrity (Drake and Pereira 2002). Fish IBI data were also available for 26 additional lakes within the larger set of 114 study lakes (Minnesota DNR). Lake-wide fish species richness was determined from these data.

Statistical Analysis Methods

Site Type analysis

I used Mann-Whitney-Wilcoxon tests to compare macrophyte and CWS response variables between developed and undeveloped sites (R Statistical Program, alpha = 0.05). Response variables included total macrophyte species richness, emergent species richness, submersed species richness, floating-leaf species richness, sensitive species richness, emergent macrophyte biovolume, submersed macrophyte biovolume, floating-leaf macrophyte biovolume, and CWS count at a site.

SYS analysis

I examined relationships between littoral habitat response variables and a main effect of SYS score to determine whether effects of a range of development intensities would be reflected through differences in littoral habitat structure and diversity. I modeled both submersed and floating-leaf biovolume site means as a function of SYS score using restricted maximum likelihood with linear mixed models (LMM) in Program R (square-root transformed, package nlme). Lake was included as a random effect in all mixed-effects models to account for variation between lakes; random effects are associated with model error terms (Zuur et al. 2009). I compared all models using

Akaike's information criteria (AIC). For emergent macrophytes, I used presence/absence of emergent macrophytes as a response variable rather than estimated emergent biovolume because emergent vegetation was not present in many sites. I used generalized linear mixed models (GLMM, R package lme4, family=binomial) to model the probability of presence of emergent macrophytes at a site with SYS score. Additional explanatory variables in the biovolume models included substrate type as well as emergent, submerged, and floating-leaf biovolume, depending on the response variable (Table 3). The biovolume variables were included as explanatory variables in models to account for potential competition or mutualism between the macrophyte structural types.

I used generalized linear mixed models (GLMM, R package lme4; family=Poisson) to investigate the relationship between species richness response (total, submersed, emergent, floating-leaf and sensitive) and site SYS total scores. Similar to the emergent biovolume model, I used GLMMs to model the probability CWS presence at a site with SYS total score (family = binomial).

Finally, I modeled lake-wide macrophyte species richness and Floristic Quality Index (FQI) scores as a function of human disturbance (% of watershed disturbed and dock density), lake morphometry (lake depth, lake area, % littoral area), and lake chemistry (Trophic State Index) covariates using least squares regression in program R. Trophic State Index (TSI) values were calculated using total phosphorous concentrations for each lake, obtained from the Minnesota DNR (Carlson 1977). Fish response variables (IBI and species richness) were each modeled as a function of the aforementioned human disturbance, morphometry and chemistry variables using least squares regression. FQI was also included as an explanatory variable in fish response models as a habitat covariate. All statistical assumptions were verified through visual inspection of residual plots and all models were created in Program R (R Core Development Team, 2011).

Results

Site Scale: developed vs. undeveloped sites

I analyzed and modeled responses to residential development using data from 317 sites on 10 lakes. Within the 10 study lakes, I found significantly higher floating-leaf ($W=24793.5$, $p<0.001$), emergent ($W=25583$, $p<0.001$), and sensitive ($W=25424.5$, $p<0.001$) macrophyte species richness at undeveloped sites compared to developed sites (Figure 2 A-C). Mean values for all response variables at developed and undeveloped sites are shown in Table 4. There was no difference in total and submersed species richness between site types ($W=33861.5$, $p= 0.28$). Average floating-leaf ($W=23898$, $p<0.001$) and emergent ($W=23898$, $p<0.001$) macrophyte biovolume was higher at undeveloped sites than at developed sites (Figure 2 D and E). Submersed macrophyte biovolume was higher at undeveloped sites than developed sites ($W= 24065$, $p<0.001$, not shown). Coarse woody structure (CWS) density was higher at undeveloped sites than developed sites ($W=22250.5$, $p<0.001$, Figure 2 F; Table 4).

Mixed Effects Models – SYS Total

The best-supported model for probability of emergent macrophyte presence at a site contained: SYS score, substrate type and floating-leaf macrophyte biovolume (Table 5). The probability of emergent macrophyte presence increased with an increase in site SYS total ($p<0.05$) and as site substrate type became finer (Table 6, Figure 3). Emergent macrophyte presence was positively associated with floating-leaf biovolume. Similarly, the best-supported model for floating-leaf biovolume contained SYS total score ($p<0.05$) and substrate type as covariates (Table 5). Floating-leaf biovolume was also related to emergent and submerged biovolume (Table 7). Substrate type, emergent, and floating biovolume were covariates in the best-supported model for submersed biovolume (Tables 5 and 7). Submersed biovolume was not related to SYS score.

The best-supported models for floating-leaf and emergent species richness both contained the main effect of SYS score ($p<0.05$ and $p<0.001$) as well as substrate type (Tables 5 and 6). For each model, floating and emergent species richness at a site increased as SYS score increased (Table 6, Figures 4 and 5). Best-supported models, based on AIC, were similar for sensitive and total species richness with both SYS total score ($p<0.001$ and $p<0.001$, respectively) and substrate as covariates (Tables 5 and 6). Sensitive species richness and total species richness increased with SYS total in model predictions (Figure 6). The best-supported model for submersed species richness included substrate type but did not contain the main effect of SYS score (Tables 5 and 6).

CWS presence was significantly related to SYS score in the best-supported model (Table 5). CWS was more likely to be present as site SYS scores increased ($p < 0.001$; Table 6; Figure 7).

Lake-Scale Analyses

I modeled macrophyte (n=103) and fish (n= 55) response variables in a larger group of lakes within the Northern Lakes and Forests Ecoregion as a function of lake area, percentage littoral area, TSI, dock density (docks/km), and percentage of the watershed disturbed. The best-supported model for FQI included percentage littoral area as an explanatory variable (Tables 8 and 9). Similarly, the top model for lake-wide plant species richness contained percentage littoral area but no other variables (Tables 8 and 9). The best-supported model for lake-wide fish species richness included human development variables: dock density and percent watershed disturbed, as well as lake morphometry variables: lake area (hectares) and maximum depth (m) (Table 8). There was a positive relationship between fish species richness and both human disturbance covariates: dock density and percent watershed disturbed (Table 9). Interestingly, the best-supported model for lake-wide fish IBI score contained only FQI; IBI scores were negatively related to FQI (Tables 8 and 9).

Discussion

In the subset of small freshwater lakes we studied, I found littoral zone structural habitat variables, including macrophyte species richness, macrophyte biovolume, and CWS, to be negatively associated with residential development at the site scale. Higher species richness and biovolume of all structural types were associated with finer substrates. This link between residential development and macrophyte biovolume is consistent with previous studies (Radomski and Goeman 2001; Jennings et al. 2003, Elias and Meyer 2003). In our study, emergent and floating-leaf biovolume were reduced at developed sites compared to undeveloped sites. This reduction in macrophyte biovolume may be attributed to use of the littoral zone for recreation, including swimming and boating activities, physical removal of vegetation, as well as effects of runoff or increased erosion from developed sites (Asplund and Cook 1997; Downing and McCauley 1992). Ness (2006), observed similar declines in macrophyte cover densities at developed site access points such as docks. That study also included fetch and littoral slope to explain variation in macrophyte cover. Fetch and littoral slope are important factors dictating extent of macrophyte presence and density and should be included as explanatory variables in future studies (Duarte and Kalff 1990).

Few studies have investigated effects of site-scale development on species richness. However, Elias and Meyer (2003) and Hicks and Frost (2011) each observed decreases in mean total macrophyte species richness at developed sites when compared with undeveloped sites. We found similar results but also examined emergent, floating-leaf, and sensitive species richness individually; all of which were decreased at developed sites compared to undeveloped sites. Substrate type was also significantly related to all macrophyte variables with finer substrates generally associated with greater biovolume and species richness values. Although the results are not discussed here, certain species were associated with specific substrate types (e.g. bulrush and sand). Our substrate classifications were done at a relatively coarse scale through visual assessment at one point per site. It would be beneficial for future studies to conduct more detailed substrate assessments in order to gain more insight as to individual macrophyte species preferred habitats (Borman 2007).

The decrease in CWS habitat observed at developed sites compared to undeveloped sites is also consistent with previous studies (Francis and Schindler 2006). Christensen et al. (1996) found significantly lower CWS densities at developed sites than forested sites on 16 Wisconsin lakes. The decrease in CWS at developed sites may be due to a number of mechanisms. Landowners often remove CWS in front of their property for aesthetic or recreational reasons and shoreline development practices typically involve the thinning or complete removal of trees from the shoreline or upland areas. Because shoreline and upland trees are the eventual recruitment source of CWS to the lake, this removal of trees combined with the extraction of existing CWS from the littoral zone is the likely explanation for the significant difference in CWS density between developed and undeveloped sites. Alexander et al. (2008) found percent coverage of riparian trees to be positively related to CWS density at a site, providing evidence that availability of trees for recruitment is an important factor in CWS habitat density.

This study was the first to investigate the ability of a quick shoreline survey such as SYS to provide more information about the development practices at a site and their relationship with littoral habitat. The higher the SYS score, the more natural or less intensively developed the site. Our objective was to determine whether nearshore littoral habitat was negatively associated with more intensive development practices at a site (as assessed through SYS). Positive relationships were found between most of the site-scale, nearshore macrophyte community variables and SYS score. These results supported the hypothesis that development practices employed at a site influence the nearshore littoral habitat and provided some insight as to whether such an indicator could be used by lake managers to assess areas of need and demonstrate to landowners the effects of intensive development practices. Although statistically significant relationships existed between SYS score and littoral habitat variables, the relationships were not strong. Whereas lake managers may not be able to use the survey to assess littoral habitat effects, SYS could continue to be used to educate landowners about the effects their development practices have on important habitat.

A study by Christensen et al. (1996) observed a link between lake-wide development and CWS density around an entire lake. Undeveloped lakes had significantly higher densities of CWS than lakes with shoreline development. Our larger study, of which this thesis is a part, also investigated lake-wide CWS density and development and found a significant and negative relationship between lake-wide CWS density and dock density (Lepore 2013, unpublished). Other studies have detected similar cumulative effects of development with regard to lake macrophyte communities.

Jennings et al. (2003) observed a decrease in emergent and floating vegetation with higher lake dwelling densities in Wisconsin lakes. In another study of small northern Wisconsin lakes, Hatzenbeler et al. (2004) found lake-wide macrophyte metrics including FQI, species richness and sensitive species richness, to be negatively related to dock density. We found no significant correlations between lake FQI or macrophyte species richness and development variables, such as dock density or percentage of watershed disturbed. Due to a lack of point intercept data for many of our study lakes, we were not able to calculate macrophyte IBI scores for the larger group of lakes. Unlike FQI, the macrophyte IBI incorporates metrics involving occurrence etc. rather than species richness information alone. It is possible that development density would have had more of a detectable effect on those metrics, and therefore macrophyte IBI scores, than what I observed with FQI and species richness. Our study lakes were selected to represent a range of shoreline development densities but watershed disturbance was held to 20% or less. Had we included lakes with more highly disturbed watersheds, we may have observed a relationship between macrophyte community variables and percent of watershed disturbed.

The importance of the structural habitat provided by macrophytes and CWS to fish has been examined in a number of studies. Sass et al. (2006) found that higher CWS densities were correlated with a higher prey consumption rate in smallmouth bass (*Micropterus dolomieu*), along with increased time spent in littoral habitat. Scheuerell and Schindler (2003) observed a significant decrease in the spatial aggregation of fishes with increased shoreline development, likely reflecting a loss of refugia and habitat heterogeneity. Other studies have indicated that intermediate macrophyte densities are optimal for fish species aggregation and growth (Dibble et al. 1996; Crowder and Cooper 1992).

As part of our larger study, fish were sampled at nearshore sites around 29 lakes, however, no clear relationships were found between macrophyte biovolume/species richness and fish species richness or abundance. Relationships between fish richness and site development type or SYS score were also inconclusive. However, with our sampling methods fish were more easily captured at sites where macrophytes had been cleared rather than at sites with dense macrophyte growth or sites with CWS, which may have influenced the results. It may also be that the edge habitat at developed sites is as valuable to fish as the denser macrophyte biovolume typical of undeveloped sites, resulting in no significant difference in fish communities between site types. These reasons may also help to explain why, at the lake-wide scale, fish species richness was positively correlated with dock density. Jennings et al. 2009 examined fish species richness in response to development and connectivity variables and found that gamefish species richness in particular, tended to increase with moderate riparian development. The study observed that anthropogenic factors such as stocking of gamefish as well as connectivity of water bodies may have a stronger influence on fish species composition than shoreline development. Inclusion of such factors as well as more intensive sampling using different methods may be needed to better understand lake and site-scale relationships between fish species richness and development densities as well as between fish response variables and macrophyte community variables.

Conclusion

Our site-scale analysis confirmed findings from previous studies and supplements existing knowledge with the addition of a more specific development indicator. We found macrophyte biovolume and richness to be significantly lower at developed sites compared to undeveloped sites. CWS structure was also lower at developed sites. SYS allowed us to examine a range of site-scale shoreline development intensities and how these different levels of development affected littoral structural habitat. We observed significant and negative relationships between most macrophyte structural and diversity variables as site-scale shoreline development intensity (as determined by SYS) increased. The probability of CWS presence also decreased with decreases in SYS score, or as sites became more intensively developed. The variance in habitat variables explained by SYS, however, was relatively low, indicating that several variables may influence these littoral metrics. Although the SYS survey provided us with information about how shoreline land use at a site may affect littoral habitat, future studies should focus on elucidating specific mechanisms through which residential development affects nearshore habitat structure while also considering other important geomorphic and chemical factors.

References

Alexander, M. L., M.P. Woodford, and S. C. Hotchkiss. 2008. Freshwater macrophyte communities in lakes of variable landscape position and development in northern Wisconsin, USA. Aquatic Botany 88:77-86.

Asplund, T. R., and C. M. Cook. 1997. Effects of motor boats on submerged aquatic macrophytes. Lake and Reservoir Management 13:1-12.

Beck, M. W., L. K. Hatch, B.Vondracek, and R. D. Valley. 2010. Development of a macrophyte-based index of biotic integrity for Minnesota lakes. Ecological Indicators 10:968-979.

Benke, A., and J. B. Wallace. 2003. Influence of wood on invertebrate communities in streams and rivers i*n* Gregory, S.V.; Boyer, K.L; Gurnell, A.M. eds. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37: Bethesda, Maryland. p. 149-177.

Borman, S.C., 2007. Aquatic plant communities and lakeshore land use: Changes over 70 years in northern Wisconsin lakes. Thesis. University of Minnesota.

Bryan, M. D., and D. L. Scarnecchia. 1992. Species richness, composition, and abundance of fish larvae and juveniles inhabiting natural and developed shorelines of a glacial Iowa lake. Environmental Biology of Fishes 35:329-341.

Burks, R., D. Lodge, E. Jeppesen, and T. Lauridsen. 2002. Diel horizontal migration of zooplankton: costs and benefits of inhabiting the littoral. Freshwater Biology 47:343-365.

Carpenter, S. R., and D. M. Lodge. 1986. Effects of submersed macrophytes on ecosystem processes. Aquatic Botany 26:341-370.

Carlson, R.E. 1977. A trophic state index for lakes. Limnology and Oceanography. 22:2 361-369.

Cheruvelil, K. S., and P. A. Soranno. 2008. Relationships between lake macrophyte cover and lake and landscape features. Aquatic Botany 88:219-227.

Cheruvelil, K. S., N.A. Nate, P.A. Soranno, and M.T. Bremigan. 2005. Lack of a unimodal relationship between fish growth and macrophyte cover in 45 north temperate lakes. Archiv für Hydrobiologie, 164:5, 193-215.

Christensen, D. L., B.R. Herwig, D.E. Schindler, and S. R. Carpenter. 1996. Impacts of lakeshore residential development on coarse woody debris in north temperate lakes. Ecological Applications 6:1143-1149.

Cochran, J. L., and P. A. Cochran. 2005. Use of fallen trees for spawning by the spotfin shiner (Cyprinella spiloptera) in the upper Mississippi River. Journal of Freshwater Ecology. 20:4; 771-773.

Crowder, L. B. and W. E. Cooper. 1982. Habitat structural complexity and the interaction between bluegills and their prey. Ecology. 63:6; 1802-1813.

Dibble, E. D., and S. Harrel. 1997. Largemouth bass diets in two aquatic plant communities. Journal of Aquatic Plant Management 35:74-78.

Downing, J. A., and E. McCauley. 1992. The nitrogen: phosphorus relationship in lakes. Limnology and Oceanography 37:5; 936-945.

Drake, M. T., and D. L. Pereira. 2002. Development of a fish-based index of biotic integrity for small inland lakes in central Minnesota. North American Journal of Fisheries Management 22:4; 1105-1123.

Duarte, C. M., and J. Kalff. 1990. Patterns in the submerged macrophyte biomass of lakes and the importance of the scale of analysis in the interpretation. Canadian Journal of Fisheries and Aquatic Sciences 47:2; 357-363.

Elias, J. E., and M. W. Meyer. 2003. Comparisons of undeveloped and developed shorelands, northern Wisconsin, and recommendations for restoration. Wetlands 23:4; 800-816.

Francis, T. B. and D. E. Schindler. 2006. Degradation of littoral habitats by residential development: woody debris in lakes of the Pacific Northwest and Midwest, United States. AMBIO: A Journal of the Human Environment, 35:6; 274-280.

Granéli, W., and D. Solander. 1988. Influence of aquatic macrophytes on phosphorus cycling in lakes. Hydrobiologia 170:245-266.

Groffman, P. M., D.J. Bain, L.E. Band, K.T. Belt, G.S. Brush., J.M. Grove, R.V. Pouyat, I.C. Yesilonis, and W. C. Zipperer. 2003. Down by the riverside: urban riparian ecology. Frontiers in Ecology and the Environment 1:315-321.

Gurnell, A., K. Tockner, P. Edwards, and G. Petts. 2005. Effects of deposited wood on biocomplexity of river corridors. Frontiers in Ecology and the Environment 3:377-382.

Hatzenbeler, G. R., J. M. Kampa, M. J. Jennings, and E. E. Emmons. 2004. A comparison of fish and aquatic plant assemblages to assess ecological health of small Wisconsin lakes. Lake and Reservoir Management 20:211-218.

Hicks, A. L., and P.C. Frost. 2011. Shifts in aquatic macrophyte abundance and community composition in cottage developed lakes of the Canadian Shield. Aquatic Botany, 94:1, 9-16.

Homer, C. C. Huang, L. Yang, B. Wylie and M. Coan. 2004. Development of a 2001 National Landcover Database for the United States. Photogrammetric Engineering and Remote Sensing. 70:7, 829-840.

Jennings, M. J., M. A. Bozek, G. R. Hatzenbeler, E. E. Emmons, and M. D. Staggs. 1999. Cumulative effects of incremental shoreline habitat modification on fish assemblages in north temperate lakes. North American Journal of Fisheries Management 19:18-27.

Jennings, M. J., E. E. Emmons, G. R. Hatzenbeler, C. Edwards, and M. A. Bozek. 2003. Is littoral habitat affected by residential development and land use in watersheds of Wisconsin lakes? Lake and Reservoir Management 19:272-279.

Jennings M.J., G.R. Hatzenbeler, M.A. Bozek, and C. Edwards. 2009. Natural and human influences on fish species richness in small north temperate lakes: Implications for bioassessment. Journal of Freshwater Ecology 24:1; 7-18.

Jeppesen, E., T. L. Lauridsen, T. Kairesalo, and M. R. Perrow. 1998. Impact of submerged macrophytes on fish-zooplankton interactions in lakes. pages 91-114 *in* The structuring role of submerged macrophytes in lakes. Springer.

Johnson, S. L., and J. A. Jones. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Canadian Journal of Fisheries and Aquatic Sciences 57:30-39.

Lepore, J.A. 2013. Local and cumulative influences of docks on littoral habitat structure. Thesis. University of Minnesota.

Marburg, A. E., M. G. Turner, and T. K. Kratz. 2006. Natural and anthropogenic variation in coarse wood among and within lakes. Journal of Ecology 94:558-568.

Ness, K. L. 2006. The effects of shoreline development on lake littoral and riparian habitats: Are shoreline protection regulations enough? Thesis. University of Maine.

Nichols, S., 1999. Floristic quality assessment of Wisconsin lake plant communities with example applications. Lake and Reservoir Management. 15, 133–141.

Perleberg, D., Radomski, P., Simon, S. 2012. Score Your Shore: Citizen Shoreline Description Survey Version 2. Minnesota Department of Natural Resources: Division of Ecological and Water Resources.

R Development Core Team. 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Randall, R. G., Minns, C. K., Cairns, V. W., and J.E. Moore. 1996. The relationship between an index of fish production and submerged macrophytes and other habitat features at three littoral areas in the Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences, 53:S1, 35-44.

Radomski, P., and T. J. Goeman. 2001. Consequences of human lakeshore development on emergent and floating-leaf vegetation abundance. North American Journal of Fisheries Management 21:46-61.

Radomski, P. 2006. Historical changes in abundance of floating-leaf and emergent vegetation in Minnesota lakes. North American Journal of Fisheries Management 26:932-940.

Rooney, T. P., and D. A. Rogers. 2002. The modified floristic quality index. Natural Areas Journal 22:340.

Sass, G. G., J. F. Kitchell, S. R. Carpenter, T. R. Hrabik, A. E. Marburg, and M. G. Turner. 2006. Fish community and food web responses to a whole-lake removal of coarse woody habitat. Fisheries 31:321-330.

Sass, G., C. Gille, J. Hinke, and J. Kitchell. 2006. Whole-lake influences of littoral structural complexity and prey body morphology on fish predator–prey interactions. Ecology of Freshwater Fish 15:301-308.

Sass, L. L., M. A. Bozek, J. A. Hauxwell, K. Wagner, and S. Knight. 2010. Response of aquatic macrophytes to human land use perturbations in the watersheds of Wisconsin lakes, USA. Aquatic Botany 93:1-8.

Schupp, D. H. 1992. An ecological classification of Minnesota lakes with associated fish communities. Minnesota Department of Natural Resources, Fisheries Investigational Report 417, St. Paul.

Scheuerell, M. D., and D. E. Schindler. 2004. Changes in the spatial distribution of fishes in lakes along a residential development gradient. Ecosystems. 7:98-106.

Søndergaard, M., and B. Moss. 1998. Impact of submerged macrophytes on phytoplankton in shallow freshwater lakes. Pages 115-132 *in* The structuring role of submerged macrophytes in lakes. Springer.

Trial, P. F., F.P. Gelwick and M.A. Webb. 2001. Effects of shoreline urbanization on littoral fish assemblages. Lake and Reservoir Management 17:2, 127-138.

Zuur, A., E. N. Ieno, N. Walker, A. A. Saveliev, and G. M. Smith. 2009. Mixed effects models and extensions in ecology with R. Springer, New York.

Table 1: Development and limnological characteristics for 10 study lakes. # of sites = the number of shoreline sites sampled on each lake. (TSI: Trophic State Index).

Lake	Docks/km	% WS Disturbed	Lake class[a]	Area (Hectares)	TSI (P)	Max Depth (m)	# Sites
Elk	0.4	0.7	23	122.14	48.07	28.4	20
Thistledew	0.8	2.8	23	130.36	46.24	13.7	20
Upper Cullen	7.3	13.1	29	173.82	50.95	12.2	37
Portage	13.4	7.4	23	110.90	42.22	25.6	26
Gilbert	20.7	10.9	25	158.78	54.15	13.7	49
Horseshoe	24.8	7.8	23	104.13	56.63	15.5	30
Hand	24.9	4.3	25	115.68	49.39	17.4	40
Gladstone	34.4	3.7	29	174.82	45.85	11.0	29
Bass	39.1	3.6	23	77.28	43.22	16.8	30
Girl	46.0	4.8	25	171.27	45.94	24.7	50

[a] Lake class from Schupp (1992)

Table 2: Score sheet for Score Your Shore Survey.

.			Maximum Score	
Land Zones	FEATURE	Potential Points	Zone Score	Total Land Score
Upland	1. Percent of lot frontage with Trees	0-25	65	100
	2. Percent of lot frontage with Shrubs	0-20		
	3. Percent of lot frontage with Natural Ground Cover	0-20		
Shoreline	4. Percent of lot frontage with Trees/Shrubs	0-20	35	
	5. Percent of lot frontage with Natural Ground Cover	0-15		

Table 3. Summary of all explanatory variables and distributions used to model each site-scale habitat response variable (Bv = biovolume).

Response	Explanatory Variables	Family	Link	#Lakes
Pres/abs Emergent	SYS Score, SubBv, FloatBv, Substrate	Binomial	logit	10
Float Biovolume	SYS Score, EmBv, SubBv, Substrate	Gaussian	sqrt	10
Submersed Biovolume	SYS Score, EmBv, FloatBv, Substrate	Gaussian	sqrt	10
Float Species	SYS Score, Substrate	Poisson	ln	10
Emergent Species	SYS Score, Substrate	Poisson	ln	10
Submersed Species	SYS Score, Substrate	Poisson	ln	10
Total Species	SYS Score, Substrate	Poisson	ln	10
Sensitive Species	SYS Score, Substrate	Poisson	ln	10
Pres/abs CWS	SYS Score	Binomial	logit	10

Table 4. Mean ± standard error values for site-level response variables by site type.

Response	Developed	Undeveloped
Species Richness		
Floating-leaf	1.25 ± 0.10	1.68 ± 0.11
Emergent	2.01 ± 0.15	2.98 ± 0.21
Intolerant	0.92 ± 0.08	1.46 ± 0.10
Submersed	9.79 ± 0.28	9.58 ± 0.29
Total	13.05 ± 0.43	14.24 ± 0.47
Biovolume		
Floating-leaf	6.71 ± 0.84	10.87 ± 1.15
Emergent	0.69 ± 0.06	1.21 ± 0.09
Submersed	4.65 ± 0.35	5.64 ± 0.23
CWS		
CWS Total	0.79 ± 0.15	3.17 ± 0.32

Table 5. Top supported models for littoral habitat response variables. Models were compared using AIC. All models include "Lake" as a random effect in the error term.

Response	Model	Parameters	AIC
Emergent Presence	Intercept+SYS Score+Substrate+Floating Biovolume	6	262
	Intercept +SYS Score+Substrate	5	272
Emergent Species Richness	Intercept+SYS Score+Substrate	5	449
	Intercept+Substrate	2	542
Floating Species Richness	Intercept+SYS Score+Substrate	5	410
	Intercept+Substrate	2	355
Total Species Richness	Intercept+SYS Score+Substrate	5	489
	Intercept+Substrate	2	502
Sensitive Species Richness	Intercept+SYS Score+Substrate	5	354
	Intercept+Substrate	2	397
Floating Biovolume	Intercept+SYS Score+Substrate+Emergent Biovolume	6	1176
	Intercept+SYS Score+Substrate	5	1226
Submerged Biovolume	Intercept+Substrate+Emergent Biovolume+Floating Biovolume	6	565
	Intercept +Substrate+ Floating Biovolume	5	595
CWS Presence	Intercept +SYS Score	2	377
	Intercept only	1	414

Table 6. Parameter estimates (transformed) for the best-supported generalized linear mixed models (GLMM, lme4, Bates et al. 2012) of structural habitat response variables. Substrate is a categorical variable with four levels: Fine, Sand, Mix, and Coarse.

Response	Variable	Estimate	SE	Z- value	p-value
Emergent Macrophyte Presence	Intercept (SubstrateCoarse)	-2.104	0.971	-2.166	0.030
	SYS Score	0.014	0.007	2.094	0.036
	SubstrateFine	4.342	1.060	4.095	<0.001
	SubstrateSand	2.188	0.796	2.747	0.006
	SubstrateMix	1.190	0.765	1.556	0.120
	Floating-leaf biovolume	0.090	0.032	2.831	0.005
Emergent Species Richness	Intercept (SubstrateCoarse)	-1.050	0.450	-2.331	0.020
	SYS Score	0.009	0.002	5.554	<0.001
	SubstrateFine	1.578	0.422	3.741	<0.001
	SubstrateSand	1.144	0.425	2.693	0.007
	SubstrateMix	0.578	0.427	1.355	0.176
Floating Species Richness	Intercept (SubstrateCoarse)	-0.875	0.533	-1.642	0.101
	SYS Score	0.005	0.002	2.76	0.006
	SubstrateFine	0.956	0.478	1.999	0.046
	SubstrateSand	0.472	0.481	0.982	0.326
	SubstrateMix	-0.051	0.484	-0.106	0.915
Sensitive Species Richness	Intercept (SubstrateCoarse)	-1.291	0.506	-2.552	0.011
	SYS Score	0.008	0.002	3.51	<0.001
	SubstrateFine	1.219	0.467	2.61	0.009
	SubstrateSand	0.577	0.475	1.215	0.225
	SubstrateMix	0.354	0.475	0.746	0.456
Total Species Richness	Intercept (SubstrateCoarse)	1.681	0.166	10.114	<0.001
	SYS Score	0.002	0.001	3.609	<0.001
	SubstrateFine	0.862	0.137	6.272	<0.001
	SubstrateSand	0.702	0.138	5.087	<0.001
	SubstrateMix	0.463	0.137	3.378	<0.001
CWS Presence	Intercept	-2.196	0.564	-3.895	<0.001
	SYS Score	0.031	0.005	5.583	<0.001

Table 7. Parameter estimates (transformed) for top linear mixed models (LMM, nlme, Pinheiro 2012) of littoral habitat variables. Both submerged and floating biovolume were square root transformed. Substrate was a categorical variable with 4 levels: Fine, Sand, Mix, and Coarse. All models were created using R version 2.15.1

Response	Variable	Estimate	SE	df	T-value	p-value
Floating Biovolume	Intercept(SubstrateCoarse)	-0.096	0.652	312	-0.147	0.884
	SYS Score	0.007	0.003	312	1.996	0.047
	SubstrateFine	0.796	0.495	312	1.608	0.109
	SubstrateSand	0.052	0.477	312	0.108	0.914
	SubstrateMix	-0.176	0.460	312	-0.383	0.702
	Emergent Biovolume	0.457	0.098	312	7.146	<0.001
	Submerged Biovolume	0.154	0.021	312	4.676	<0.001
Submerged Biovolume	Intercept(SubstrateCoarse)	1.331	0.179	317	7.444	<0.001
	SubstrateFine	1.015	0.188	317	5.408	<0.001
	SubstrateSand	0.691	0.181	317	3.827	<0.001
	SubstrateMix	0.515	0.179	317	2.884	0.004
	Emergent Biovolume	-0.063	0.036	317	-1.768	0.078
	Floating Biovolume	0.020	0.003	317	7.302	<0.001

Table 8. Best-supported linear models for lake-wide macrophyte and fish variables. Models were compared using AIC.

Response	Model	AIC	# of Lakes
FQI	Intercept+Littoral Area	599	103
	Intercept only	600	
Plant Spp	Intercept+Littoral Area	659	103
	Intercept only	659	
Fish IBI	Intercept+FQI	484	55
	Intercept+FQI+maxDepth(m)	485	
Fish Spp	Intercept+%WatershedDisturbed+Docks/km+Area(hectares)+maxDepth(m)	501	55
	Intercept+%WatershedDisturbed+Docks/km+Area(hectares)+maxDepth(m)+TSI	501	

Table 9. Parameter estimates for top linear models of lake-wide macrophyte and fish response variables. All models were created using R version 2.15.2.

Response	Variable	Estimate	SE	DF	T	p-value
FQI	Intercept	28.26	1.38	101	20.49	<0.001
	%Littoral	0.05	0.03	101	1.63	0.107
PlantSppRichness	Intercept	21.25	1.84	101	11.55	<0.001
	%Littoral	0.04	1.64	101	1.64	0.104
FishIBI	Intercept	154.27	16.51	55	9.34	<0.001
	FQI	-1.61	0.54	55	-2.99	<0.05
FishSpp	Intercept	7.84	0.75	55	10.43	<0.001
	%WatDisturbed	0.11	0.04	55	2.81	<0.05
	Docks_km	0.07	0.02	55	3.06	<0.05
	Area_hectares	0.01	0.00	55	2.85	<0.05
	maxDepth_m	0.07	0.04	55	1.69	0.093

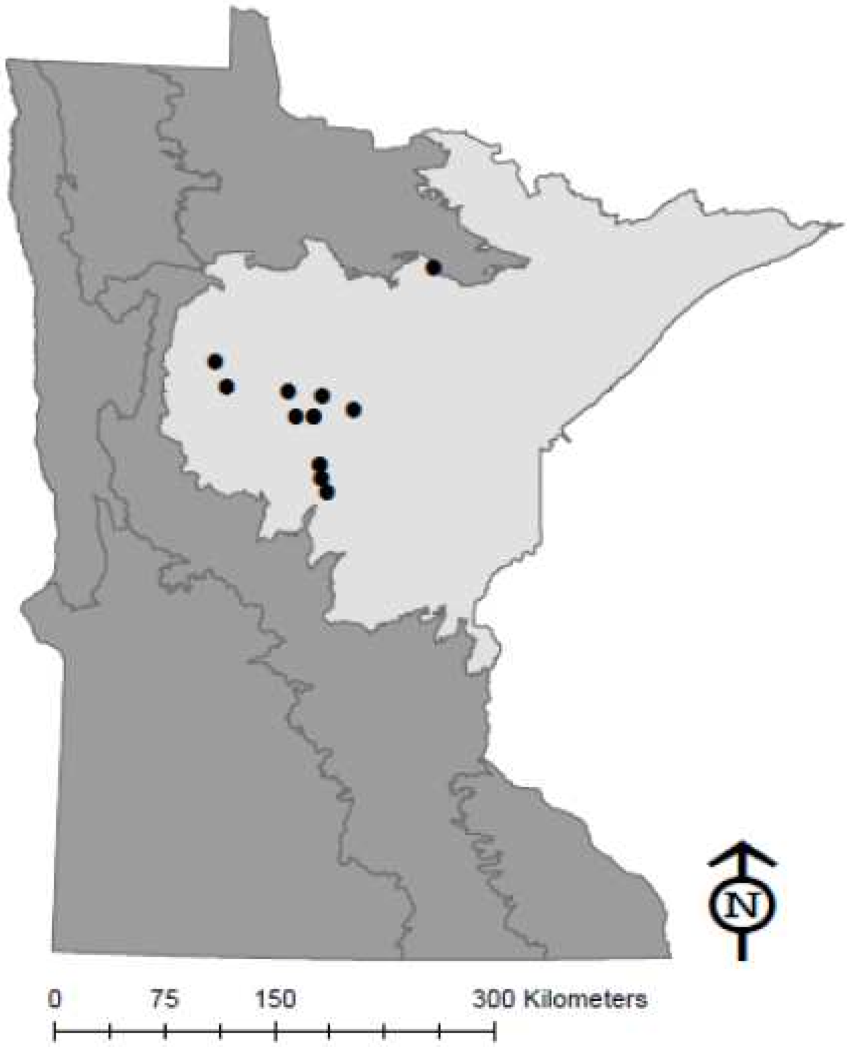

Figure 1. Locations of 10 study lakes within the Northern Lakes and Forests Ecoregion of Minnesota (modified from Lepore 2013).

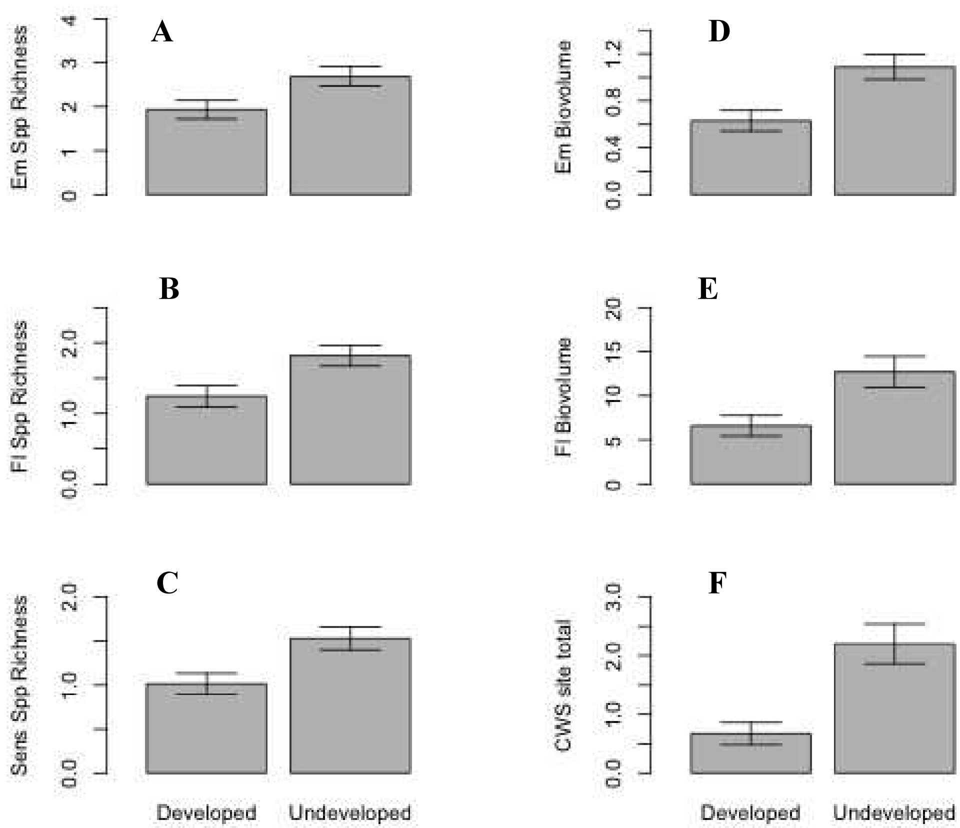

Figure 2. Mean values for littoral habitat response variables that were significantly different between developed and undeveloped site types (Mann-Whitney-Wilcoxon, alpha=0.05). Whiskers represent 95% confidence intervals. **A**. Mean emergent species richness. **B.** Mean floating-leaf species **C.** Mean sensitive species richness **D.** Mean emergent biovolume **E.** Mean floating-leaf biovolume. **E.** Mean CWS site totals.

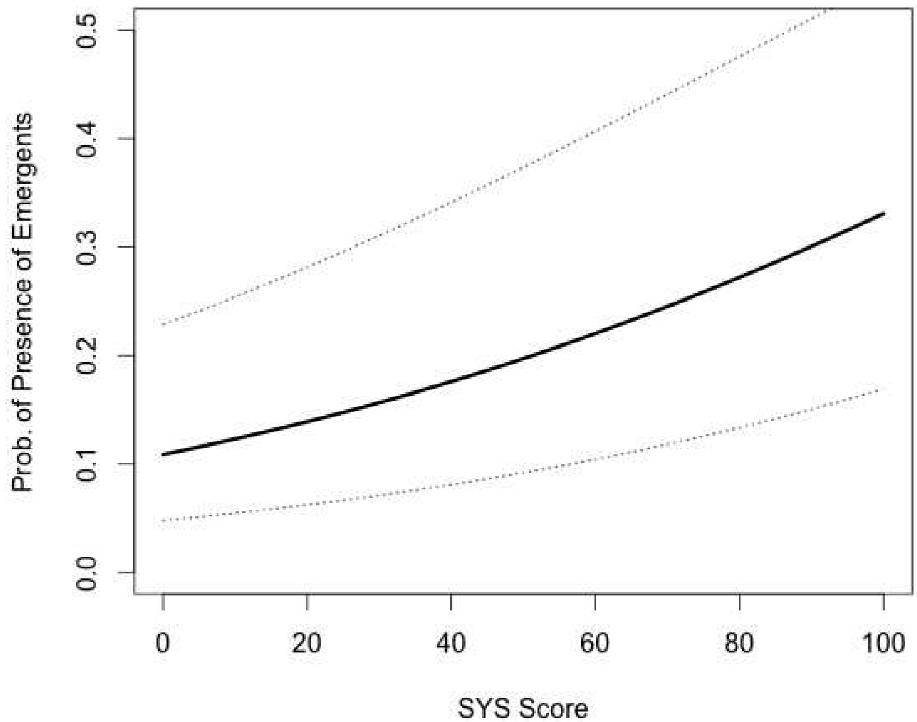

Figure 3. Probability of presence of emergent macrophytes with SYS from best-supported model estimates. Dotted lines represent 95 % confidence intervals. Substrate was set to fine and the mean value for site floating–leaf biovolume was used to obtain the estimates.

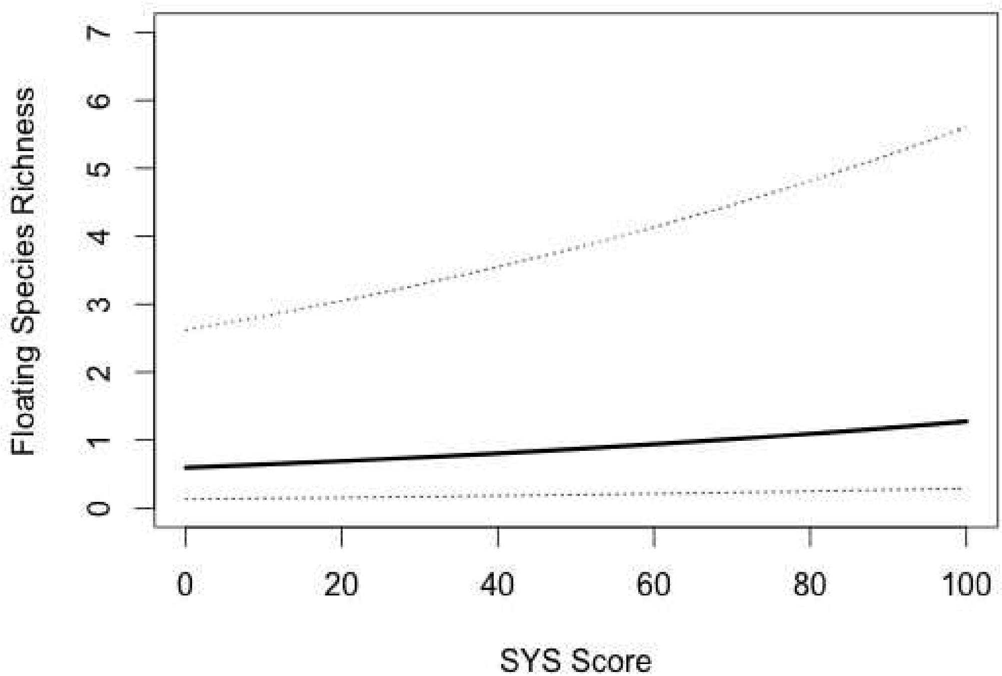

Figure 4. Model predictions for floating leaf species richness. Substrate type was set at fine. The solid line represents estimates from the best-supported model for floating-leaf species richness with SYS score. Dotted lines represent 95% confidence intervals.

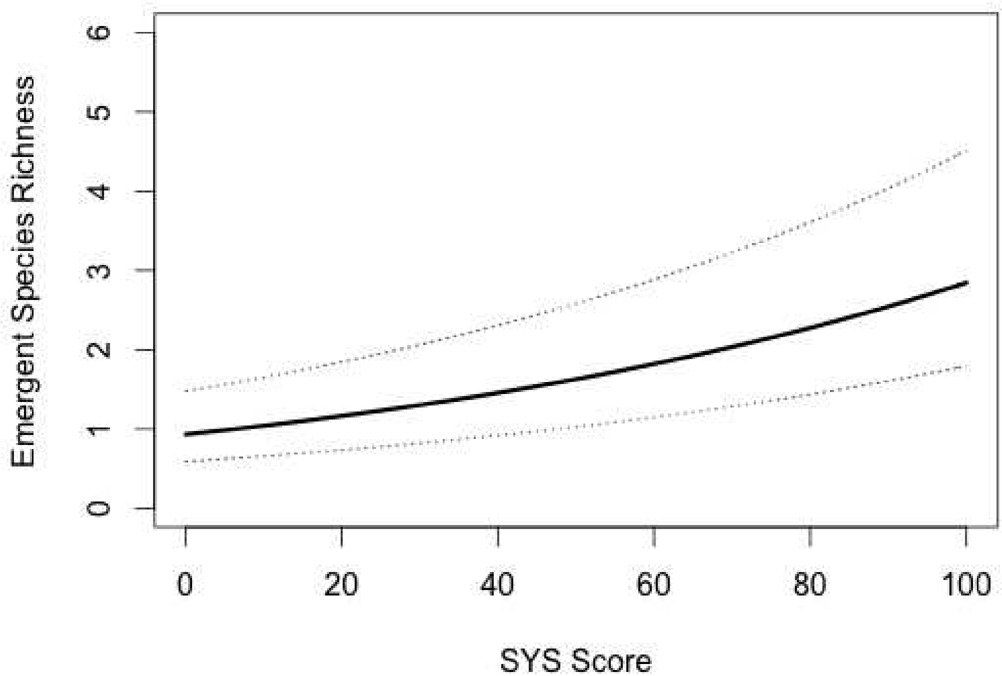

Figure 5. Model estimates from the best-supported model for emergent species richness with SYS score. Substrate was set to fine. Dotted lines represent 95% confidence intervals.

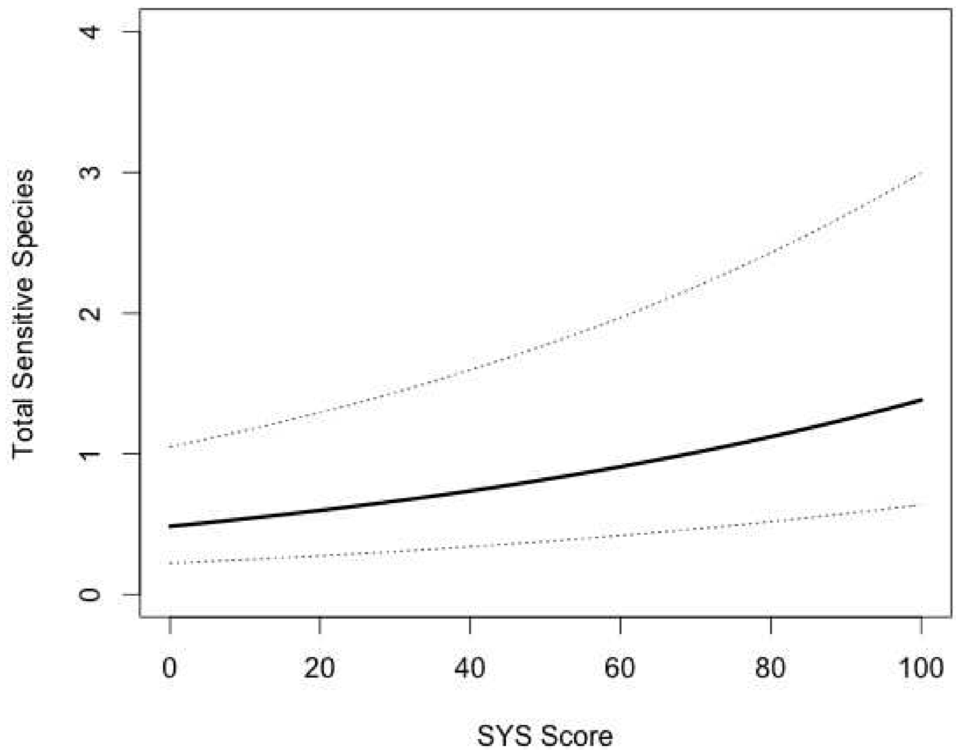

Figure 6. Model estimates from the best-supported model of sensitive species richness with SYS score. Substrate was set to fine. Dotted lines represent 95% confidence intervals.

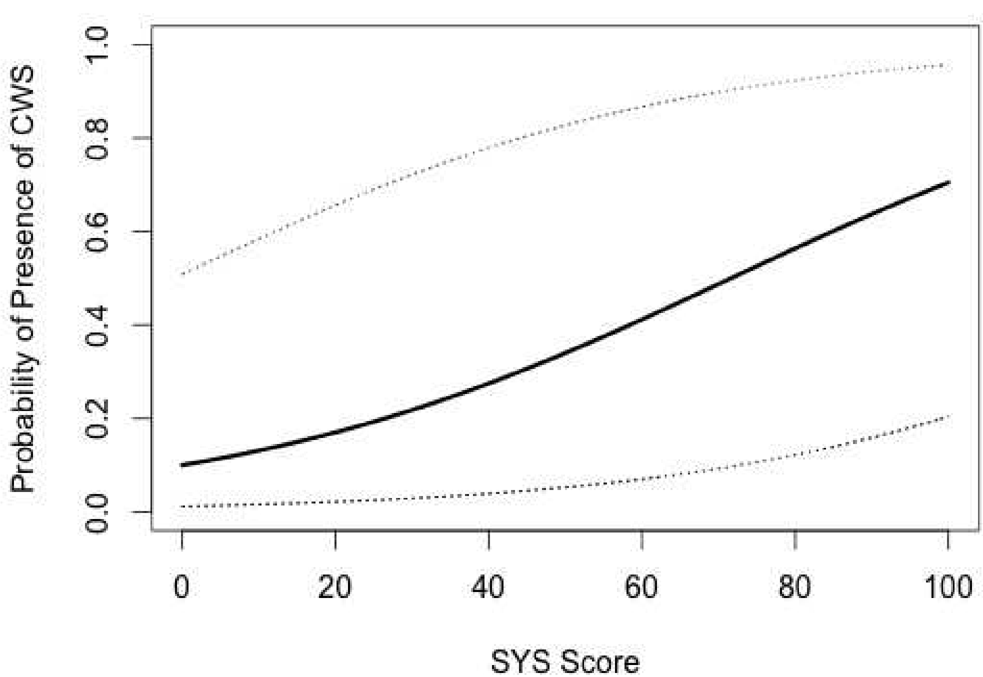

Figure 7. Model estimates for the probability of presence of CWS at a site as SYS score increases. Dotted lines represent 95 % confidence intervals.