2013 Project Abstract
For the Period Ending June 30, 2012

PROJECT TITLE: Assessing Cumulative Impacts of Shoreline Development
PROJECT MANAGER: Bruce Vondracek
AFFILIATION: US Geological Survey, Minnesota Cooperative Fish and Wildlife Research Unit
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FUNDING SOURCE: Environment and Natural Resources Trust Fund)
LEGAL CITATION: 2013

APPROPRIATION AMOUNT: $300,000

<u>Overall Project Outcome and Results</u>
The littoral zone contains all of the vegetation within a lake and is critical to the physical and biological integrity of lakes. Aquatic macrophytes and coarse woody structure (CWS) provide refuge, foraging area, and spawning substrate for many fish species. The goal of this study was to evaluate shoreline development by measuring a number of variables that reflect human activity including, terrestrial vegetation, physical alterations and in-lake structures. Previous studies have found reductions in abundance of aquatic vegetation and CWS; however, few studies have quantified the specific influence of docks on aquatic habitat structure. CWS and three measures of macrophyte abundance increased with distance to the nearest dock structure. Presence of CWS and emergent species were significantly and negatively related to lake-wide dock density. We intensively investigated effects of lakeshore development on nearshore habitat across 11 northern Minnesota lakes using the Minnesota Department of Natural Resources' Score Your Shore (SYS) survey to assess development intensity. Developed sites (a residence and dock present) had lower macrophyte species richness, emergent, and floating-leaf macrophytes and CWS than undeveloped sites (no residence, no dock). 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. A fish Index of Biological Integrity decreased as the density of docks increased for the 11 intensively studied lakes. Development density across 29 lakes and 114 lakes were also examined, but less intensively. Effects of development in these less intensively studied lakes were less apparent for most lake macrophyte and fish community variables than for the intensively studied lakes. These findings suggest that riparian management on residential lots and reduced removal of aquatic macrophytes and CWS could improve fish habitat at both local and lake-wide scales of development.

<u>Project Results Use and Dissemination</u>
1. How has information from your project been used and/or disseminated?

The project was conducted in conjunction with the Minnesota Department of Natural Resources and several meetings to disseminate our findings took place with Jacquelyn Bacigalupi, the Lake IBI Coordinator with MNDNR and colleagues.

2. *What communications and outreach activities have been done in relation to your project?*

Presentations:

Lepore, J., J. Keville, D. Dustin, C. Tomckko, and B. Vondracek . 2011. Cumulative impacts of residential lakeshore development on littoral habitat. 44th Annual meeting of the Minnesota Chapter of the American Fisheries Society, 8-9 February, Sandstone, Minnesota. (Poster)

Lepore, J., J. Keville, D. Dustin, C. Tomko, B. Vondracek. 2011. Cumulative Impacts of Residential Lakeshore Development on Littoral Habitat. Minnesota Water Resources Conference, 18-19 October, St. Paul, Minnesota. (Poster)

Lepore, J. and J. Keville. 2011. Cumulative effects of shoreline development on nearshore habitat. DNR Fisheries Research Meeting, 16-18 November, Cloquet Forestry Center

Keville, J., J. Lepore, D. Dustin, C. Tomko, B. Vondracek. 2012. Cumulative Impacts of Residential Lakeshore Development on Littoral Habitat. 142nd Annual meeting of the American Fisheries Society, 19-23 August, St. Paul, Minnesota. (POSTER)

Lepore, J. and J. Keville. 2012. Cumulative effects of shoreline development on nearshore habitat. Department of Natural Resources, Fisheries Research Winter 2012 meeting, Lake Itasca Biological Station, 25-26 October

Lepore, J, J. Keville, D. Dustin, C. Tomcko, and B. Vondracek. 2012. Cumulative impacts of lakeshore residential development on littoral habitat. Minnesota Water Resources Conference, 16-17 October 2012, St. Paul, Minnesota. (Poster)

Lepore, J. A., J. R. Keville, and B. Vondracek. 2013. Localized and cumulative impacts of lakeshore residential development on littoral habitat. Annual meeting of the Minnesota Chapter of the American Fisheries Society, 12-13 March, St. Cloud, Minnesota.

Theses:

Lepore, J. Local and cumulative influences of docks on littoral habitat structure. MS Thesis, University of Minnesota. Defended 13 May 2013

Keville, J. Effects of residential shoreline development on near shore aquatic habitat in Minnesota lakes. MS Thesis, University of Minnesota. Defended 30 May 2013

2010 Environment and Natural Resources Trust Fund (ENRTF) Work Program Final Report

Date of Report: August 15, 2013
Date of Next Progress Report: Final Report
Date of Work Program Approval:
Project Completion Date: 30 June 2013

I. PROJECT TITLE: Assessing Cumulative Impacts of Shoreline Development

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Location: Aitkin, Becker, Cass, Crow Wing, Douglas, Hubbard, Morrison, Otter Tail, Todd

Total ENRTF Project Budget:	**ENRTF Appropriation**	**$**	**300,000**
	Minus Amount Spent:	**$**	**252,948**
	Balance:	**$**	**47,052**

Legal Citation: M.L. 2010, Chp. 362, Sec. 2, Subd. 5h

Appropriation Language:
$300,000 is from the trust fund to the Board of Regents of the University of Minnesota to evaluate near-shore, in-water habitat impacts from shoreline development activities to assist in the design and implementation of management practices protecting critical shorelands and aquatic habitat. This appropriation is available until June 30, 2013, by which time the project must be completed and final products delivered.

II. PROJECT SUMMARY AND RESULTS: Human structures related to shoreline development, such as docks, boatlifts, and other structures, and disturbance from recreational activity may have a cumulative impact on aquatic ecosystems. Near-shore areas (less than 4 meters deep) often contain most of the vegetation and are generally the spawning area for fish. Few studies have addressed the effects of incremental changes on lake ecosystems despite ongoing concerns about the rate and extent of near-shore, in-water habitat alterations, and expansion of in-lake structures. The lack of scientific knowledge on the cumulative effects of human activities on aquatic habitat, water quality, and fish populations has hindered regulatory authorities and lake managers who need better information to guide landowners toward lower impact practices. To address this lack of information, we will assess the extent of near-shore vegetation and fish along a gradient of shoreline development and develop a framework to assess cumulative impacts on whole lake systems. We will use aerial photos and existing DNR data to measure whole lake disturbances of ~100 lakes in the Northern Lakes and Forests Ecoregion. We will also conduct assessments of a subset of lakes (~30) at the individual lot scale, to quantify impacts to vegetation and fish along a gradient of shoreline development and shoreline types. We will use our research develop a model to predict the cumulative impact of development on aquatic ecosystems, providing a tool to guide lake managers toward sustainable near-shore, in-water development.

II. PROGRESS SUMMARY

PROGRESS SUMMARY AS OF January 15, 2013

We completed data entry for the Fish-IBIs, near-shore macrophyte species richness and biovolume, Score Your Shore, coarse woody structure (CWS) collected during the past summer and have begun data analysis on the data collected in summer 2011 and 2012. In addition to the proposed work plan, we conducted a standard macrophyte point-intercept survey, following the protocol of the Minnesota Pollution Control Agency, of the entire littoral zone and hydroacoustic sampling of macrophyte volume to evaluate the overall littoral habitat for comparison to our detailed nearshore data. The data for the intensive lakes have been processed and are currently being analyzed in ArcGIS by our DNR collaborator. We also calculated a macrophyte-based index of biotic integrity (M-IBI) based on the point-intercept data following Beck et al. (2010).

We found a slight negative relationship between dock density and fish IBI scores that we will explore further as our analysis continues.

Our DNR collaborator is in the process of conducting a GIS based analysis of shoreland buffer land use and land cover.

PROGRESS SUMMARY AS OF September 15, 2012

The dock shape file for the 114 lakes was updated by adding historical data for each lake and reorganized. The GIS buffer analysis was continued and an existing, but not previously analyzed, data set was discovered that predicts shoreline development intensity with good accuracy.

We completed data collection for all the lakes in our study design that included: Fish-IBIs, near-shore macrophyte species richness and biovolume, Score Your Shore, coarse woody structure (CWS). All "extensive lakes" included point-intercept sampling of macrophytes at 77 to 142 points, depending on lake size, in the littoral area of a lake. In addition, we conducted point-intercept surveys and acoustic surveys to quantify macrophyte biovolume between 1.5 meters in depth to the maximum extent of vegetation in the littoral zone.

We modified the extensive lake sampling methods for the 2012 field season. We used stratified random sampling to add 20m sites on the 12 extensively sampled lakes, in addition to the 10 or more sites previously selected, rather than sampling single transects spaced around the lakeshore as in 2011. In addition, we extended the analysis of Coarse Woody Structure (CWS) and macrophyte biovolume as follows: We documented CWS and estimated macrophyte biovolume along 18 closely-spaced transects extending outward from the edge of the dock. Nine transects were oriented parallel to each side of the dock and extended from the shoreline to the end of the dock with the first, closest transect located along the edge of the dock. Subsequent transects were spaced every meter. Transect length varied depending on the length of the dock. Transcription of data and data analysis is underway.

Amendment Request (09/15/2012):

We propose modifying the budget for three line items. We propose decreasing the budgeted amount for an undergraduate research assistant $11,838. Initially, we anticipated that an undergraduate student would assist in data collection during the summer and then process samples, primarily macroinvertebrates, during the academic year; however, we amended the proposal to eliminate macroinvertebrate collections (amended 01/15/2011), and thus the need to process them. We further propose transferring the $11,838 from the undergraduate research assistant line to increase the line for a Research Assistant (Lepore) by $2,000 to cover the anticipated stipend and to increase the line for mileage for a University vehicle by $9,838, as the actual mileage exceeded the budgeted amount.

PROGRESS SUMMARY AS OF January 15, 2012
Transcribed all data and began analysis for surveys for Fish-IBIs, near-shore macrophytes, Score Your Shore, coarse woody structure for 10-17 sites for nine lakes and for six lakes where we conducted point-intercept surveys, acoustic surveys to quantify macrophyte biovolume, CWS that included the diameter, length, branching complexity, and maximum depth located approximately every 50 to 120 feet of shoreline, depending on the size of the lake.

PROGRESS SUMMARY AS OF September 15, 2011
We completed Fish IBI evaluations, near-shore macrophyte surveys, Score Your Shore surveys, coarse woody structure (CWS) description for 10-17 sites for nine lakes.

In addition at six lakes we conducted point-intercept surveys, acoustic surveys to quantify macrophyte biovolume, CWS that included the diameter, length, branching complexity, and maximum depth located approximately every 50 to 120 feet of shoreline, depending on the size of the lake. We also noted the shaded area provided by overhanging trees and shrubs. Docks, boatlifts and other in-water structures were described and marked with GPS waypoints.

PROGRESS SUMMARY AS OF January 15, 2011
We have acquired aerial photographs for 114 lakes to assess the number buildings and in-water structures per kilometer of shoreline and assess the coverage of aquatic vegetation. The first field season was a pilot study to train the research staff and to determine the time required for each task to better plan sampling trips during the summers of 2011 and 2012.

Amendment Request (01/15/2011):
We determined that collecting macroinvertebrates would be too time-consuming and provide limited information (few species and low numbers). Thus, we request that the study design be amended. To compensate for removing macroinvertebrates from the work program, we would provide a more detailed analysis of aquatic plants and vegetation along the shore. Specifically, we request to implement Score Your Shore Surveys at 10 random evenly spaced sites around the lake. Scores are assigned for each upland, shoreline and aquatic zone in the sites. At each of the 10 Score Your Shore sites per lake, we will evaluate the nearshore aquatic habitat. Beginning at the edge of the 50 ft site (or whatever size we happen to decide on) we will evaluate vegetation at depths of one, two, and three feet. At each point, we will record the plant species present (based on sight and/or rake throw), substrate composition and a biovolume estimate. Finally, we propose to conduct point-estimate plant surveys at a subset of 12 lakes along with hydroacoustic sampling of plant biovolume, which will be joined with the nearshore biovolume estimates. The proposed amendment will provide more quantitative information on aquatic vegetation than initially proposed. The proposed amendment will not affect the overall budget.

Note: Attachment A has been modified to reflect that a DNR employee will not be hired, due to the current state hiring freeze, instead a Research Fellow will be hired as a university employee to perform the tasks initially anticipated for the DNR employee.

Amendment approved: 24 January 2011

IV. OUTLINE OF PROJECT RESULTS*:*

RESULT/ACTIVITY 1: Assess near-shore, in-water habitat on lake ecosystems

Description: We will acquire aerial photographs for ~100 study lakes to assess the number buildings and in-water structures per kilometer of shoreline and assess the coverage of aquatic vegetation. The study lakes will be restricted to the Northern Lakes and Forests Ecoregion to control for the inherent productivity of the lakes and the watersheds. Using existing DNR fishery surveys, we will explore relationships among shoreline development, coverage of aquatic vegetation, and aspects of the fish community.

Summary Budget Information for Result/Activity 1: **ENRTF Budget: $8,816**
Amount Spent: $8,816
Balance: $0

Deliverable/Outcome	Completion Date	Budget
1. Provide a measure of the number and coverage of in-water structures from a subset of lakes with and without shoreline structures in north-central Minnesota.	June 2012	**$4408**
2. Develop and evaluate models that relate the amount of shoreline development to aquatic vegetation and fish communities.	June 2012	**$4408**

Result Completion Date: December 2012

Result Status as of: (Agust 2013)**:**
No new analysis completed.

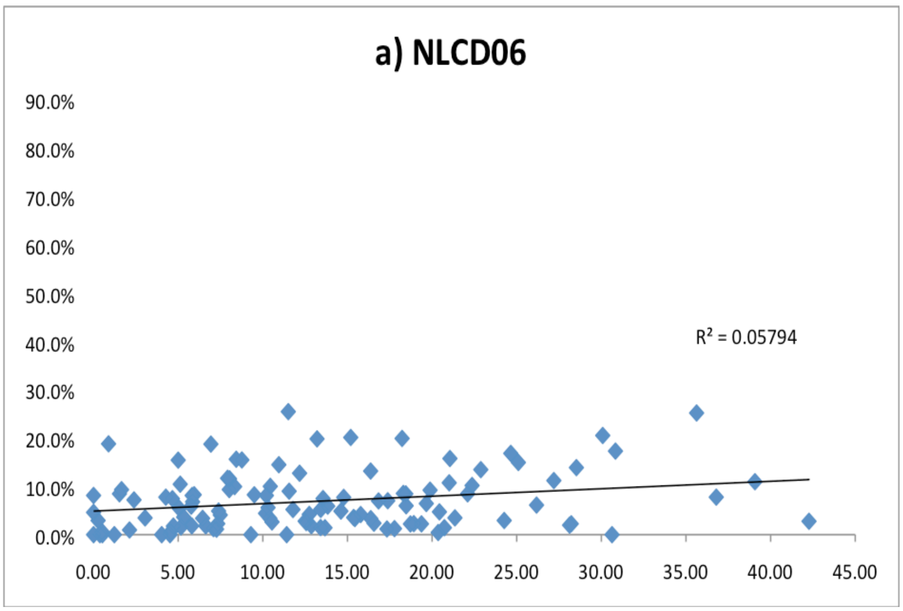
Result Status as of: (January 2013)**:**
No new analysis completed.

Result Status as of:
September 2012
The GIS layer of dock counts created last year was modified and expanded, such that dock descriptions align with other DNR projects. For example, the new dock layer now includes a field for dock class, following the classification system of Radomski et al. (2010). Historic air photos were added and docks were counted for 1991, 2003, 2008 and 2010. Specifically, a single dock location was marked with a new point each year that it was observed.

The number of more complex docks increased over time at all of the lakes except Elk Lake. Although, dock numbers increased over time interpretation is not straightforward, because air photos were taken at various times of year, ranging from April to October. In 1991, photos were taken in the early spring and likely not all docks had been installed, whereas in 2003, 2008 and 2010 photos were taken during the summer growing season. Thus, it is difficult to quantify how much of the increase in dock numbers from 1991 to 2003 was due to development, and how much was due to photographing the lakes in different seasons. Possibly, the dock counts could be supplement with home counts from the 1991 photos since they were taken before leaf-on.

The shoreline buffer analysis begun last year was expanded by analyzing additional GIS layers and comparing the resulting data to manual dock counts for the 114 lakes in our study. The buffer analysis uses a 75 m buffer zone around the perimeter of the lake. The new version of the National Land Cover Database (NLCD2006), an update to the 2001 version was analyzed. The buffer analysis was also done using a data set called Minnesota Land Use and Cover – A 1990's Census of the Land (MNLU90), a Minnesota database that integrates land-use and land-cover.

The MNLU90 data had a higher correlation (r=0.802) for the number of docks counted per shoreline mile in the Northern Lakes and Forests ecoregion than the NLCD data (r=0.24.1; Figure 1). The MNLU90 dataset integrates land use with land cover, and represents developed lakeshore as "developed", whereas the NLCD data categorizes these areas as forest, since the predominate land cover in the 30 m cells is trees. If this study confirms that docks are correlated with changes in structural habitat then this buffer analysis will be able to provide a rapid assessment of habitat conditions across the state.



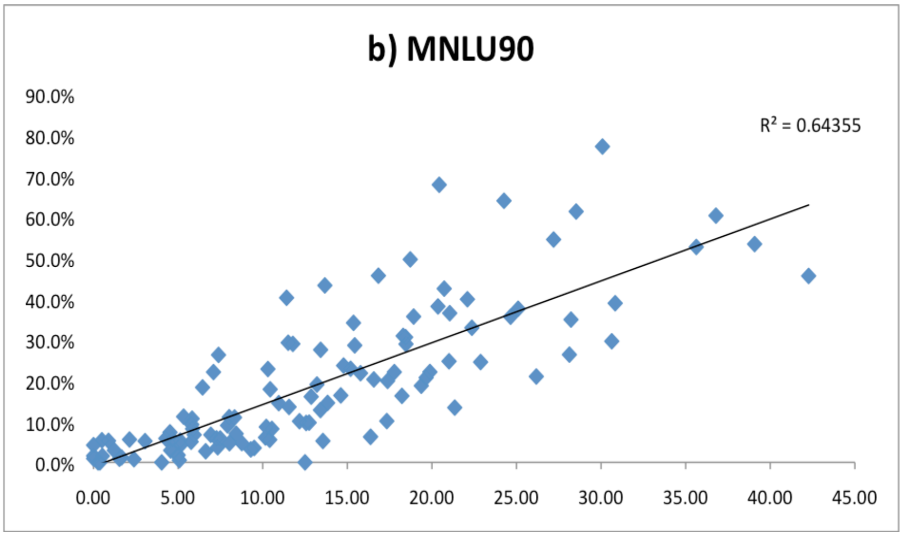


Figure 1. Docks per shoreline mile for 114 lakes in north-central MN vs mean proportion (%) of 75 m buffer zone developed using a) NLCD 2006 data and b) MNLU 90 data.

Result Status as of:
January 2012
No additional work related to aerial photographs for 114 lakes.

Result Status as of:
September 2011
We acquired aerial photographs for 114 lakes and created a point shape file in ArcMap with a point for each dock that was visible on FSA aerial photos in either 2008 or 2009. We calculated docks per mile of shoreline and used this information to rank the lakes from least to most development, and from that list we selected 30 lakes for assessment.

Result Status as of:
January 2011
Description: One hundred fourteen aerial photographs for 2008-2009 were acquired to assess the number buildings and in-water structures per kilometer of shoreline and assess the coverage of aquatic vegetation. The number of docks on all 114 lakes has been counted following the creation of a point shapefile on the lakes using air photographs. The accuracy of the counts varies, as some aerial photographs of the Northeast Minnesota lakes are high-resolution (50 cm) photographs, whereas some photographs are of lower resolution. A project partner, Donna Dustin, with the DNR, accomplished this task. The accuracy of the counts will be addressed in the future.

No progress was made to develop and evaluate models that relate the amount of shoreline development to aquatic vegetation and fish communities.

RESULT/ACTIVITY 2: Assess impacts of shoreline development on near-shore habitat

Description: We will quantify docks, boat lifts, watercraft, rafts, or any other recreational structures in the water in 30 lakes along 30 m transects at a site. We will note and estimate the linear distance of retaining walls or rip-rap along the shore, as well as the note vegetative cover type(s) adjacent to the wall or rip-rap. Coarse woody structure (CWS) will also be inventoried on each lot. We will estimate macrophyte (distribution, density, biovolume, and species composition), and fish (distribution and species composition; and calculate a Fish-Index of Biological Integrity). We will evaluate macrophytes and fish for at least 5 dock sites per lake, plus an additional 10 randomly chosen sites. We will visually estimate plant coverage at each site using the scale: no plants, <10%, 10-40%, 40-70%, 70-100%, and 100%. In addition, we will estimate aquatic vegetation density using stem density and Robel pole cover in digital underwater photographs. We will also collect invertebrates associated with macrophytes from 0.1 m^2 quadrats spaced at 3 m intervals or at selected sites based on the distribution of aquatic macrophytes at a site. All plant material in a quadrat will be clipped at the sediment interface and immediately placed in a sealable bag underwater, returned to a boat, and immediately placed on ice. We will sample the nearshore fish community with a backpack electrofisher and a seine. We will sample fish using a boat electrofisher or visual observations parallel to the shoreline at each site. Transects will be along a 2m depth contour or 60m from the shoreline, whichever is closer.

We will relate the number of structures, rip-rap and CWS to measurements of macrophytes and fish to estimate the effect of near-shore, in-water alterations on the biological community.

Summary Budget Information for Result/Activity 2: ENRTF Budget: $235,395
Amount Spent: $232,607
Balance: $2,786

Deliverable/Outcome	**Completion Date**	**Budget**
1. Develop an index of shoreline development by measuring a number of variables that reflect human activity including buildings, terrestrial vegetation, physical alterations such as riprap, and in-lake structures.	June 2013	**$79,437**
2. Measure characteristics of aquatic vegetation, woody debris, and fish communities at these sites.	June 2013	**$155,958**

Result Completion Date: Data collection completed by September 2012; analysis completed by June 2013

Final Status as of: (August 2013*)***:**

Aquatic Habitat Structure and Proximity to Docks
We performed an additional analysis not anticipated when the project began to reflect human activity. We used ArcGIS to delineate the shoreline of 11 lakes into 20-m segments, or “sites.” Recent aerial photographs from Objective 1 were used to classify shoreline sites as “developed” or “undeveloped”. We classified developed sites as those that contained docks which were simple in shape and at least 20 m from a neighboring dock to avoid sampling in areas influenced by an adjacent dock. Undeveloped sites were also located at least 20 m from a dock structure. From these initial sampling sites, five developed sites were randomly selected from 9 study lakes that contained docks. Five additional dock sites were sampled within the two largest developed lakes (Gilbert and Girl). In total, 55 developed sites were chosen for habitat sampling. Because undeveloped sites were expected to exhibit more variation than developed sites, we randomly selected a minimum of 10 undeveloped sites within 11 study lakes (two sites had only one dock at a public assess). Fourteen undeveloped sites were selected from Gilbert and Girl. Thus, we selected a total of 118 undeveloped sites for sampling. In total, 173 sites were evaluated.

At each selected developed site 18 transects (nine on each side of a dock) were oriented parallel to a dock and extended from the shoreline to the end of the dock; thus, transect length was equivalent to the length of the dock over the water. Transects began at the edge of the dock (distance = 0 m) with subsequent transects spaced every meter until a distance of eight meters was reached (Figure 1). At sites with a boat lift, boat, or other structure that extended from the edge of the dock, sampling began at the edge of the ancillary structure. Thus, transects were not always linear, but conformed to the unique shape of the structure. Transects began along the edges of the dock (Distance= 0m) and were spaced at 1m intervals until a distance of 8m was reached on either side.

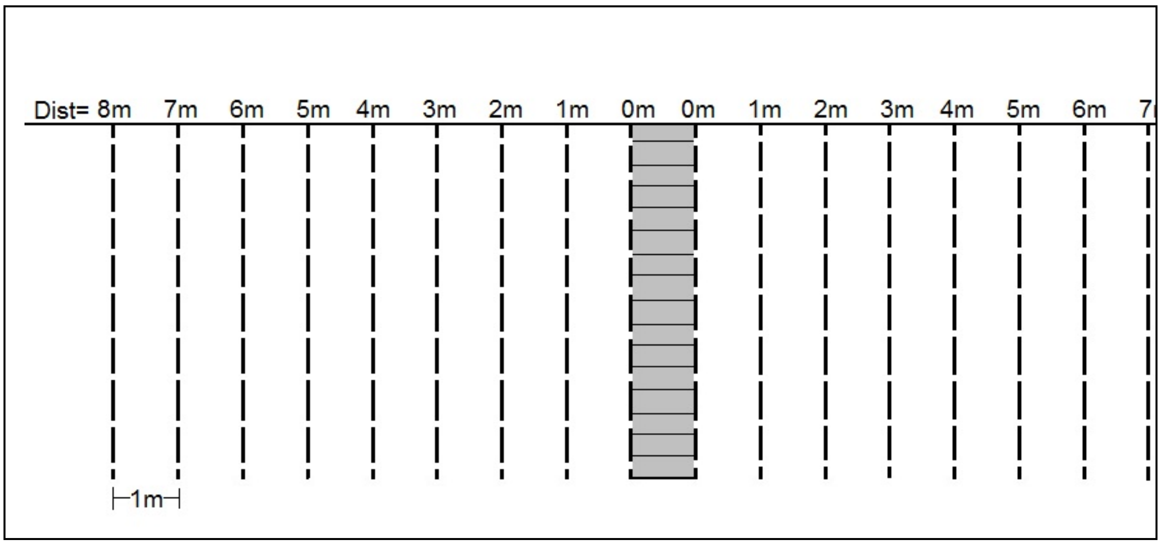


Figure 1. Habitat sampling scheme with the shoreline located at the top of the figure. Nine sampling transects (dashed lines) were sampled on each side of a dock (gray rectangle).

We recorded water depth, substrate type, and macrophyte biovolume estimates every 3 m from shore until the end of the dock was reached along each sampling transect using a buoyant circular sampling ring (50 cm diameter) constructed from foam pipe insulation. We visually classified substrate by particle size for each site into one of four categories: fine (silt/muck), sand, mix (cobble with sand), and coarse (rocks/boulders). Most docks were sampled at three or four depths, with the deepest sampling points aligned with the end of the dock. Macrophyte biovolume was estimated for each of three structural categories: emergent, submerged, and floating-leaf. Emergent biovolume was assigned integer values from 0 to 5 based on the following stem counts: 0: absent (0), 1: sparse (< 4 stems), 2: 4-9 stems, 3: 10-19 stems, 4: 20-30 stems, 5: dense (>30 stems). Submerged biovolume was recorded as a percentage from 0 to 100 in increments of 5 percent, based on the density of vegetation within the water column. In areas where vegetation was sparse, 1 percent biovolume was reported. Coverage of floating-leaf vegetation was recorded as the percentage of the sampling ring covered by floating leaves. Estimates of floating-leaf cover could range from 0 to 100 percent in increments of 5 percent, although 1 percent was noted for areas with minimal cover.

Coarse woody structure (CWS), defined as a piece of wood ≥ 10 cm in diameter along the trunk and ≥ 60 cm in length was documented each time it crossed a transect, but we recorded the total CWS count at each site.

The sampling approach at undeveloped sites was similar to that used at developed sites, i.e., sampling was conducted along transects oriented perpendicular to the shoreline. Three sampling transects were spaced approximately 6.7 m apart and extended from 0.3 to 0.9 m water depth. Macrophyte sampling points were placed along each transect at depths of 0.3, 0.6, and 0.9 m. Macrophyte biovolume was visually estimated in each of the three structural categories as described for developed sites. We counted each piece of CWS within the sampling area defined by the macrophyte transects.

A binomial General Linear Mixed Model (GLMM) was used to investigate the relationship between presence of coarse woody structure and distance to the nearest dock. A nested random effect was used to account for variation between sampling sites within study lakes. Mixed models were used to examine relationships between aquatic macrophyte responses (presence of emergent species, submerged biovolume, and floating-leaf biovolume) and distance to the nearest dock.

We also applied mixed models to identify key drivers of local macrophyte abundance. Each of the macrophyte responses was modeled in response to a suite of physical, biological, and development characteristics. For example, a model for presence of emergent species response included the following five explanatory variables: distance, submerged biovolume, floating-leaf biovolume, substrate, and depth. Each model was refined using backward elimination, which uses Akaike's Information Criterion (AIC) and *P*-values to arrive at the best model.

The presence of emergent species exhibited a positive and significant relationship with distance to the nearest dock (Z= 11.76, P <0.001; Figure 2A). The model intercept was significantly different from zero (Z= -7.43, P <0.001), indicating a 9 percent likelihood of emergent species occurrence at the edge of a dock. Submerged and floating-leaf biovolume were significantly related with distance to the nearest dock. Submerged biovolume increased with distance from a dock (t= 8.01, df=3,177, P <0.001; Figure 2B). Floating-leaf biovolume was also increased with distance to the nearest dock (t= 13.00, df=3,177, P <0.001; Figure 2C).

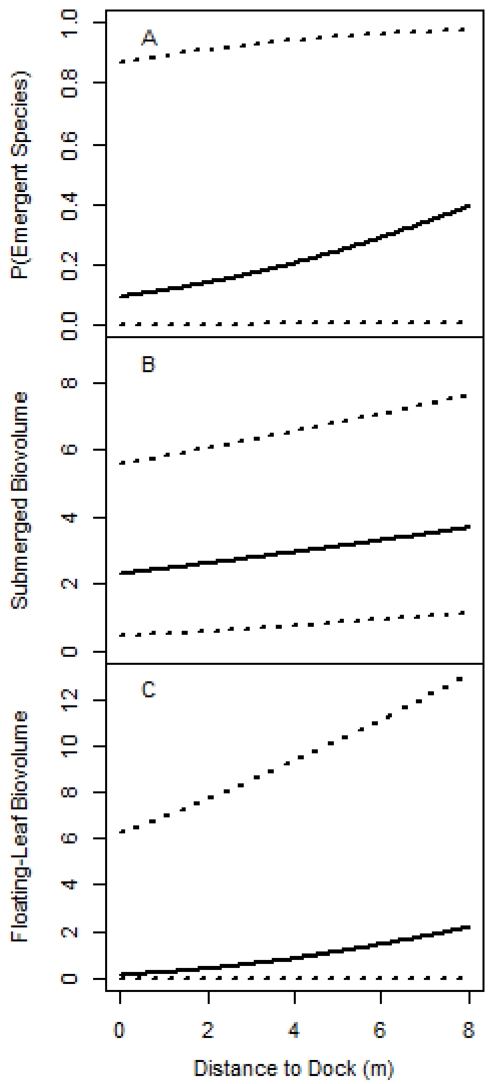


Figure 2. Presence of emergent species (A), submerged biovolume (B), and floating-leaf cover (C) in relation to distance to the nearest dock structure. The solid black lines indicate the model estimates and the dotted lines represent 95% confidence intervals.

Macrophyte responses were not only affected by proximity to docks, but other local physical and biological factors as well. We used AIC to compare the simple proximity models to the more complex models and found that for each macrophyte response, the complex models, which included substrate and depth, accounted for more variation in the response. However, distance remained a significant explanatory variable in each of the models. Presence of emergent vegetation was significantly related to distance to the nearest dock, floating-leaf cover, substrate, and water depth (Table 1). Presence of emergent species was positively related to distance to the dock (Z= 13.35, P <0.001) and negatively associated with floating-leaf cover (Z= -3.03, P= 0.002) and water depth (Z= -17.37, P <0.001). Presence of emergent species was also affected by substrate size; emergent species were most common in fine substrates and least common in coarse substrates.

Table 1. Estimates of the presence of emergent species (logit-transformed) in relation to distance to the nearest dock (Dist), floating-leaf macrophyte cover (Float), substrate: coarse, mix, sand, fine, and water depth (Depth) based on a binomial generalized linear mixed.

	Estimate	SE	*Z*	*P*
Intercept	-2.63	0.44	-5.88	<0.001
Dist (m)	0.32	0.02	13.35	<0.001
Float	-0.02	0.01	-3.03	0.002
Substrate:fine	3.13	0.54	5.80	<0.001
Substrate:mix	1.71	0.34	4.98	<0.001
Substrate:sand	1.64	0.33	5.00	<0.001
Depth (m)	-4.05	0.23	-17.37	<0.001

Submerged biovolume was significantly and positively related to distance to the nearest dock (t= 8.92, df=3,171, P <0.001; Table 2), presence of emergent species (t= 2.46, df=3,171, P <0.001), floating-leaf cover (t= 2.15, df=3,171, P= 0.01), and water depth (t= 27.08, df=3,171, P <0.001). Submerged vegetation was most abundant in fine substrates and least abundant in coarse substrates.

Table 2. Estimates of submerged biovolume (Sub) and floating-leaf macrophyte cover (Float) in relation to distance to the nearest dock (Dist), presence of emergent species (pEm), substrate: coarse, mix, sand, fine, and water depth (Depth) based on linear mixed model.

Response	Predictor	Estimate	SE	df	*T*	*P*
Sub	Intercept	0.24	0.113	3,171	2.09	0.04
	Dist (m)	0.03	0.004	3,171	8.92	<0.001
	pEm	0.07	0.028	3,171	2.46	<0.001
	Float	0.002	0.001	3,171	2.15	0.014
	Substrate:fine	0.59	0.088	3,171	6.73	0.031
	Substrate:mix	0.36	0.055	3,171	6.58	<0.001
	Substrate:sand	0.50	0.041	3,171	10.1	<0.001
	Depth (m)	0.84	0.031	3,171	27.08	<0.001
Float	Intercept	-0.58	0.20	3,171	-2.82	0.005
	Dist (m)	0.13	0.01	3,171	12.79	<0.001
	pEm	-0.23	0.08	3,171	-2.98	0.003
	Sub	0.08	0.01	3,171	7.73	<0.001
	Substrate:fine	1.48	0.24	3,171	6.03	<0.001
	Substrate:mix	0.30	0.15	3,171	1.97	0.049
	Substrate:sand	0.02	0.14	3,171	0.13	0.894
	Depth (m)	0.68	0.09	3,171	7.68	<0.001

Floating-leaf biovolume was positively and significantly related to distance to the nearest dock (t= 12.79, df=3,171, P <0.001; Table 2), submerged biovolume (t= 7.73, df=3,174, P <0.001) and water depth (t= 7.68, df=3,171, P <0.001). Floating-leaf cover was negatively related to presence of emergent vegetation (t= -2.98, df=3,171, P= 0.003). Floating-leaf biovolume was highest in fine substrates, but biovolume in the other three substrate categories (coarse, mix, and sand) were not significantly different from zero ($P \geq 0.05$; Table 2).

Presence of CWS was positively related to distance to the nearest dock (Z= 3.32, P= 0.001; Figure 3), indicating that the probability of CWS presence increased with separation from docks. The model intercept was also statistically significant (Z= -9.46, P <0.001), suggesting that at the edge of a dock (distance = 0 m), the probability of CWS was significantly different from zero.

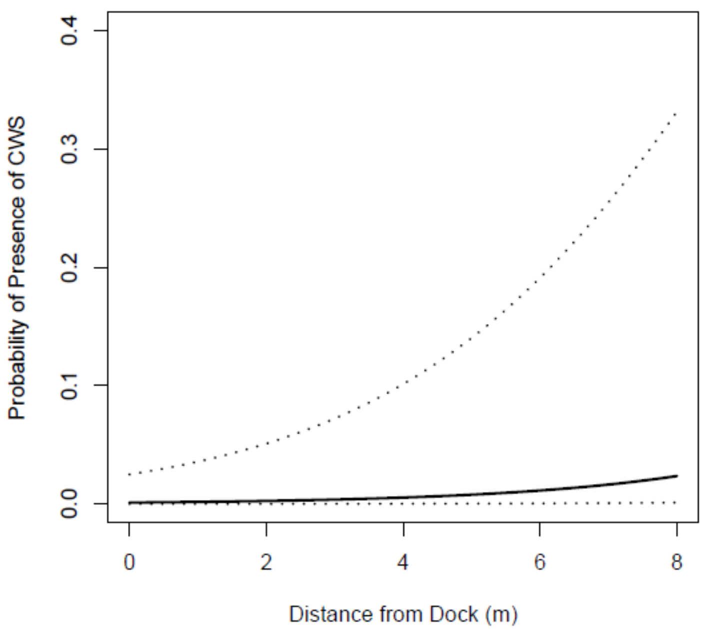


Figure 3. Predicted probability of CWS presence increased with distance to the nearest dock. The solid line is the mean response and dotted lines indicate 95% confidence intervals.

Aquatic Habitat Structure at Developed and Undeveloped Sites

Two types of analyses to evaluate relationships with terrestrial vegetation and physical alterations to the shoreline were conducted to assess aquatic habitat structure at developed and undeveloped sites: (1) aquatic macrophytes and CWS in relation to terrestrial vegetation [Score Your Shore (SYS); Perleberg et al. (2012)] and (2) aquatic macrophytes and CWS relative to the presence or absence of docks. Using ArcGIS, we divided the shoreline of each study lake into 20m sections. With recent aerial photography (objective 1), 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 3). A total of 317 sites were analyzed.

Table 3. 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	Area (ha)	TSI (P)	Max Depth (m)	# Sites
Elk	0.4	0.7	122.14	48.07	28.4	20
Thistledew	0.8	2.8	130.36	46.24	13.7	20
Upper Cullen	7.3	13.1	173.82	50.95	12.2	37
Portage	13.4	7.4	110.90	42.22	25.6	26
Gilbert	20.7	10.9	158.78	54.15	13.7	49
Horseshoe	24.8	7.8	104.13	56.63	15.5	30
Hand	24.9	4.3	115.68	49.39	17.4	40
Gladstone	34.4	3.7	174.82	45.85	11.0	29
Bass	39.1	3.6	77.28	43.22	16.8	30
Girl	46.0	4.8	171.27	45.94	24.7	50

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 4). The highest possible score for a site is 100.

Table 4. Score sheet for Score Your Shore Survey.

Land zones	Feature	Potential points	Zone Score	Total 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		

Three equally spaced transects were established perpendicular to shore at each site. Transects were approximately 8 meters apart. 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 submerged and floating-leaf macrophytes as indicated earlier. We used presence/absence of emergent macrophytes as a response variable rather than estimated emergent biovolume because emergent vegetation was not present in many sites.

Total macrophyte species richness was determined for the entire site using the sampling point data. Species richness was also determined for emergent, floating-leaf and submersed macrophytes. 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

Index of Biological Integrity (IBI). Macrophyte species with coefficient of conservatism values (C) greater than 7, were designated as sensitive (Nichols 1999). The biovolume estimates of the nine sampling points were averaged for each structural type to obtain mean biovolume at a site. We also counted all pieces of CWS.

Relationships between littoral habitat response variables and SYS score were examined to determine whether effects of a range of development intensities would be reflected through differences in littoral habitat structure and diversity. The mean SYS score was significantly higher ($p<0.001$) for undeveloped sites (87) than for developed sites (50). Both mean submersed and floating-leaf biovolume were modeled as a function of SYS using restricted maximum likelihood with linear mixed models (LMM) in Program R (square-root transformed, package nlme). Lake was included as a random effect to account for variation between lakes; random effects are associated with model error terms (Zuur et al. 2009). All models were compared using Akaike's information criteria (AIC). Generalized linear mixed models (GLMM, R package lme4, family=binomial) were used to model the probability of presence of emergent macrophytes at a site with SYS. Additional explanatory variables included substrate type, submerged and floating-leaf biovolume, and emergent presence/absence depending on the response variable. The biovolume variables were included as explanatory variables in models to account for potential competition or mutualism between the macrophyte structural types.

The best-supported model for the 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 fine substrate (Table 6, Figure 4). 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 5 and 6). Best-supported models, based on AIC, were similar for sensitive ($p<0.001$) and total species richness ($p<0.001$) with both SYS total score and substrate as covariates (Tables 5 and 6). Sensitive species richness and total species richness increased with SYS total in model predictions (Figure 7). 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). The presence of CWS was more likely as SYS scores increased ($p< 0.001$; Table 6; Figure 8).

Table 5. Best-supported models for littoral habitat response variables. 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. Estimates of response variables for the best-supported generalized linear mixed models (GLMM, lme4, Bates et al. 2012). Substrate is a categorical variable: 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

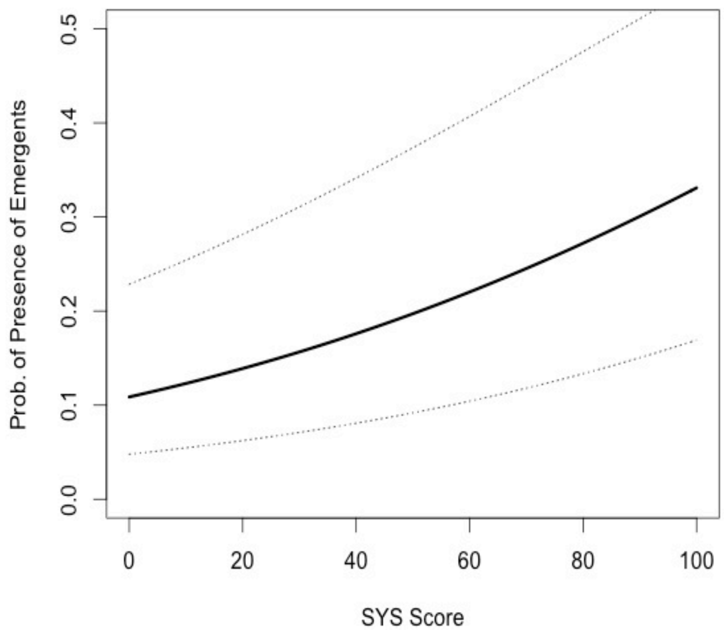


Figure 4. Probability of presence of emergent macrophytes with SYS from best-supported model estimates. Dotted lines represent 95 % confidence intervals. Substrate was set to fine and the mean for floating-leaf biovolume to obtain the estimates.

Table 7. Estimates of response variables (square root transformed) for top linear mixed models (LMM, nlme, Pinheiro 2012) of littoral habitat variables. Substrate was a categorical variable: 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	3,12	-0.147	0.884
	SYS Score	0.007	0.003	3,12	1.996	0.047
	SubstrateFine	0.796	0.495	3,12	1.608	0.109
	SubstrateSand	0.052	0.477	3,12	0.108	0.914
	SubstrateMix	-0.176	0.460	3,12	-0.383	0.702
	Emergent Biovolume	0.457	0.098	3,12	7.146	<0.001
	Submerged Biovolume	0.154	0.021	3,12	4.676	<0.001
Submerged Biovolume	Intercept(SubstrateCoarse)	1.331	0.179	3,17	7.444	<0.001
	SubstrateFine	1.015	0.188	3,17	5.408	<0.001
	SubstrateSand	0.691	0.181	3,17	3.827	<0.001
	SubstrateMix	0.515	0.179	3,17	2.884	0.004
	Emergent Biovolume	-0.063	0.036	3,17	-1.768	0.078
	Floating Biovolume	0.020	0.003	3,17	7.302	<0.001

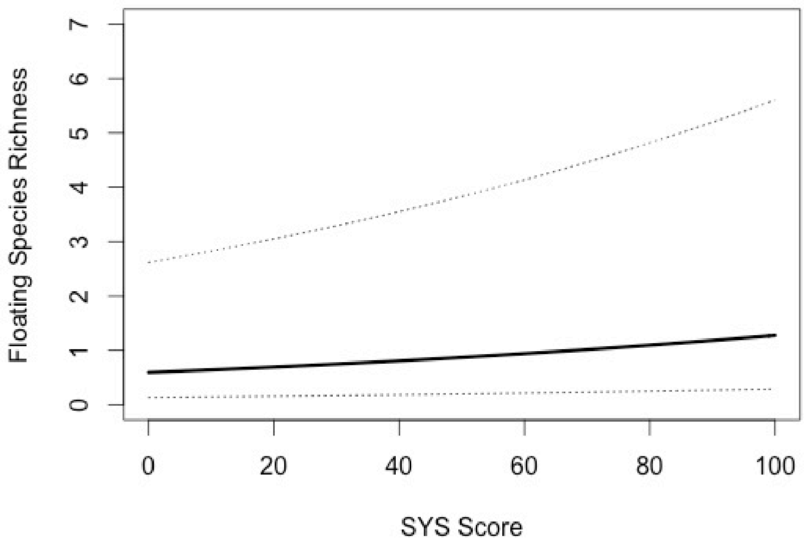


Figure 5. Model predictions for floating leaf species richness in relation to SYS score. The solid line represents the best-supported model for floating-leaf species richness; dotted lines represent 95% confidence intervals. Substrate type was set at fine.

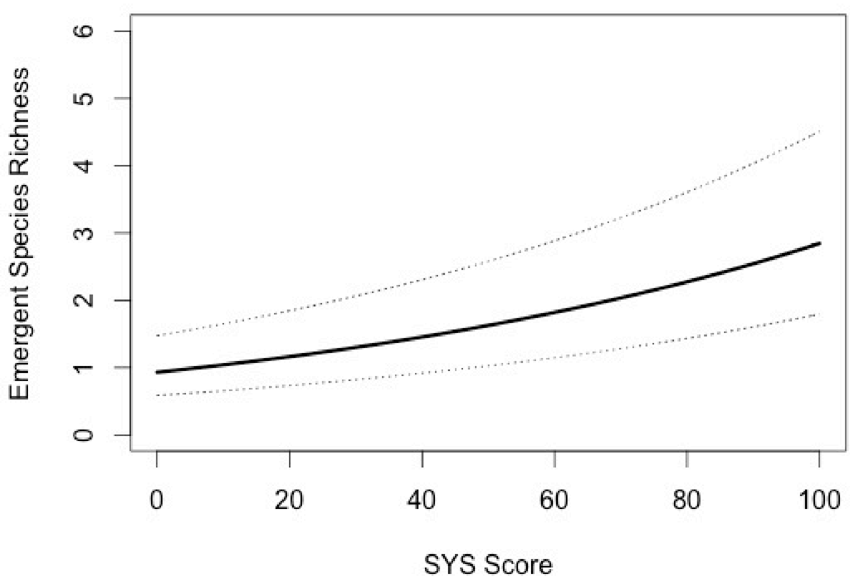


Figure 6. Model estimates from the best-supported model for emergent species Richness in relation to SYS score. The solid line represents the best-supported model leaf species richness; dotted lines represent 95% confidence intervals. Substrate was set to fine.

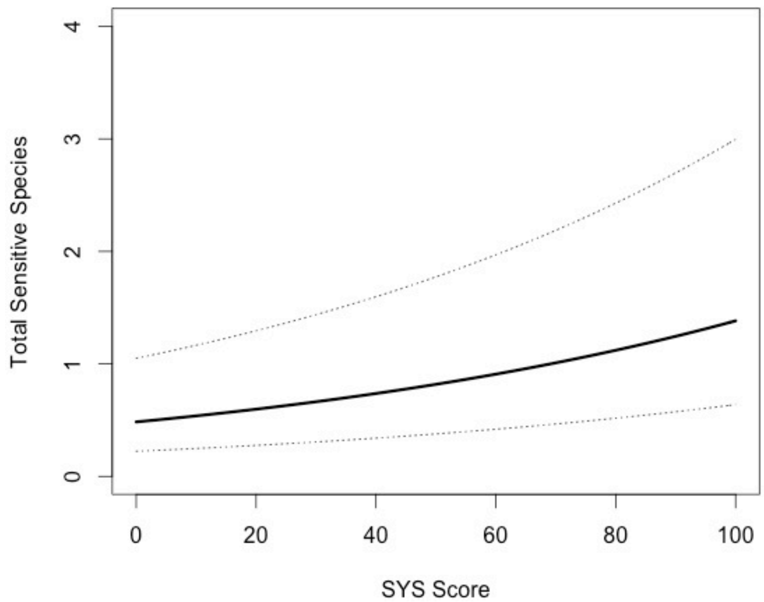


Figure 7. Model estimates from the best-supported model of sensitive species richness with SYS score. Substrate was set to fine. Dotted lines represent 95% confidence intervals.

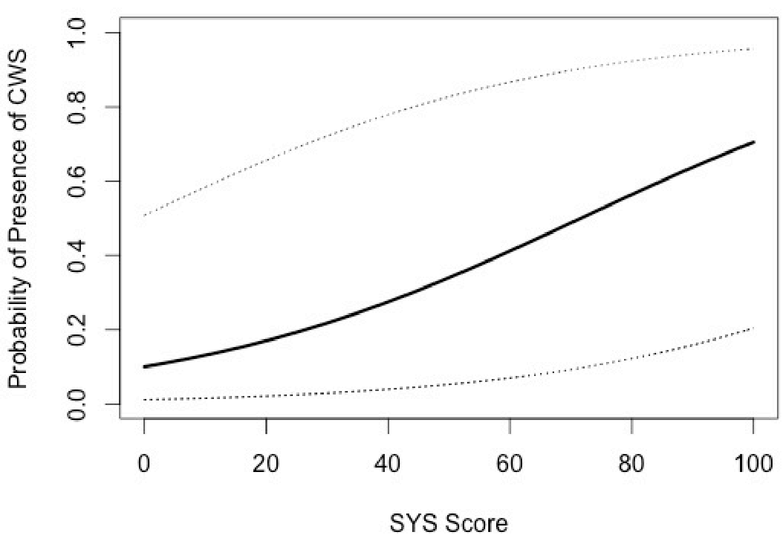


Figure 8. Model estimates for the probability of presence of CWS at a site as SYS score increases. Dotted lines represent 95 % confidence intervals.

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 were significantly higher at undeveloped sites compared to developed sites (Figure 9 A-C). There was no difference in total and submersed species richness between site types ($W=33861.5$, $p= 0.28$). Mean 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 9 D and E). Submersed macrophyte biovolume was higher at undeveloped sites than developed sites (W= 24065, p<0.001, not shown).

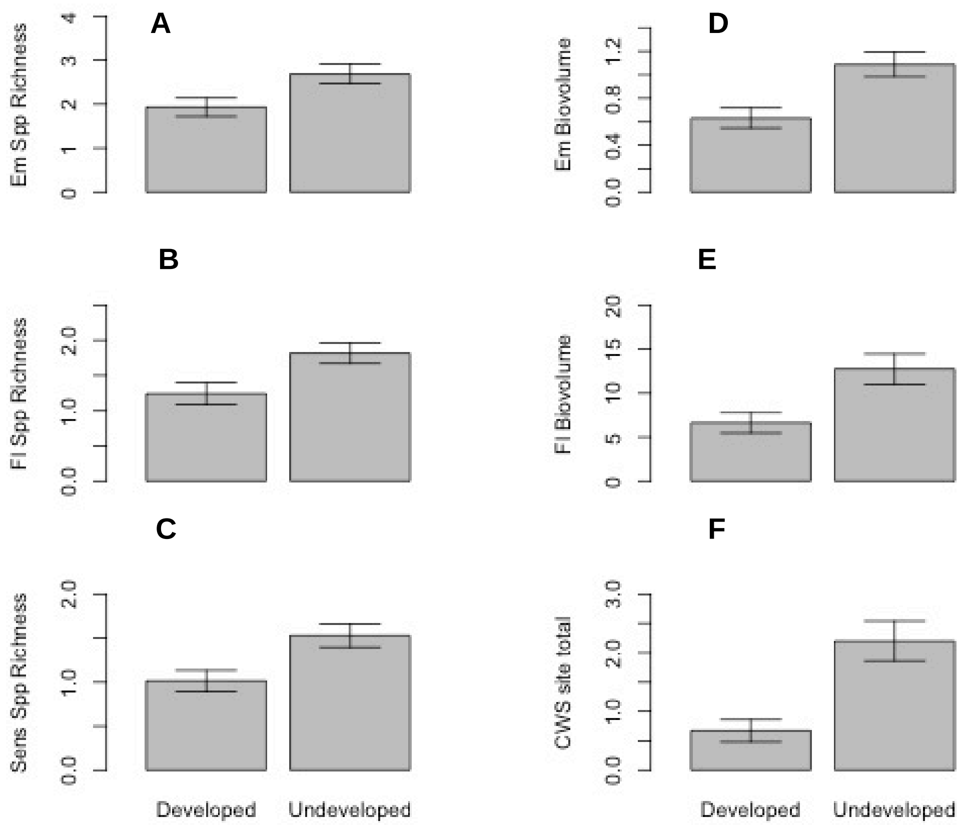


Figure 9. Mean values for littoral habitat response variables that were significantly different between developed and undeveloped site types. **A**. Mean emergent species richness. **B.** Mean floating-leaf species **C.** Mean sensitive species richness **D.** Mean emergent biovolume **E.** Mean floating-leaf biovolume. **F.** Mean CWS site totals. Whiskers represent 95% confidence intervals.

CWS abundance was quite variable among study lakes (Table 8). Portage Lake had particularly high CWS densities, with a mean of 14 pieces per site and a maximum of 91 pieces observed at one site. However, the grand mean CWS abundance across study lakes was 3.2 pieces per site. CWS density was higher at undeveloped sites than developed sites (W=22250.5, p<0.001, Figure 2 F; Table 8).

Table 8. Site-level and estimated lake-wide density of coarse woody structure (CWS; mean ± SE) for each study lake. Undeveloped (U) sites (n= 10-14 per lake) were located at least 20m from a dock. Each developed (D) site (n= 5 per lake) was centered on a residential dock.

Lake Name	Dock Density (docks/km)	CWS (U) (pcs/site)	CWS (D) (pcs/site)	CWS density (pcs/km)
Elk*	0.1	5.70 ± 1.26	NA	284
Thistledew*	0.1	8.40 ± 1.24	NA	411
Upper Cullen	2.8	0.30 ± 0.21	0.00 ± 0.00	13
Portage	5.2	21.90 ± 11.58	0.20 ± 0.20	948
Eagle	7.3	1.22 ± 0.62	0.40 ± 0.24	51
Gilbert	8.0	1.79 ± 0.49	0.60 ± 0.22	71
Horseshoe	9.5	1.00 ± 0.37	1.40 ± 0.60	55
Hand	9.6	1.60 ± 0.76	0.80 ± 0.58	73
Gladstone	13.3	0.80 ± 0.49	0.00 ± 0.00	23
Bass	15.1	2.40 ± 0.86	0.20 ± 0.20	74
Girl	17.7	2.07 ± 1.00	1.90 ± 0.48	99

*Elk and Thistledew lakes only contained one dock at a public access.

Emergent and floating-leaf macrophytes were most abundant at undeveloped sites with fine substrates and least abundant at developed sites with coarse substrates. The highest mean submerged biovolume was 6.76 (SE, 0.45); the lowest mean biovolume was 2.45 (SE, 0.45), which was observed at developed sites with coarse substrate. Submerged biovolume was significantly different across the four substrate categories (Kruskal-Wallis test; H= 52.77, df= 3, P < 0.001). The highest floating-leaf cover was 12.20 (SE, 0.91) at sites with fine substrates, which was higher than the mean coverage for the other three substrate categories, even among undeveloped sites (range 1.07 to 2.90). The estimate of mean floating-leaf cover at developed sites with coarse substrates was near zero. Floating-leaf cover varied significantly across all four substrate groupings (Kruskal-Wallis test; H= 76.21, df= 3, P < 0.001).

Cumulative Effects of Lake-wide Development on Habitat Structure

Probability of presence of emergent vegetation was affected by a combination of site type and lake-wide dock density (Figure 10). Both site types were negatively related to dock density (Z= -2.14, P= 0.03); however, probability of emergent presence was higher at undeveloped sites than developed sites regardless of lake-wide development density.

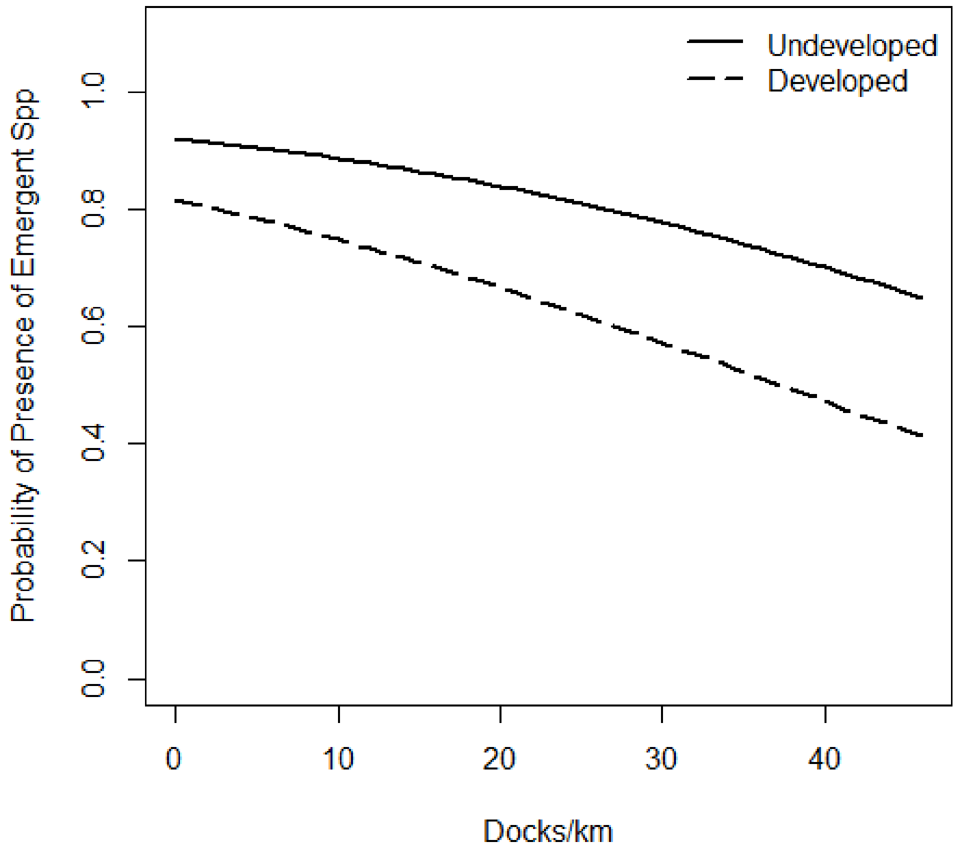


Figure 10. Probability of presence of emergent vegetation in relation to site type (developed/undeveloped) and lake-wide dock density.

Relationships with fish

An index of Biological Integrity for fish (Fish IBI) was calculated for fish collected in the nearshore for the 11 lakes that were intensively evaluated. Drake and Pereira (2002) the Fish IBI in Minnesota using metrics based on measures of human-induced stress (watershed land use patterns and human population density). Karr (1981) originally developed an IBI to assess environmental degradation in streams based on the characteristics of their fish communities. The IBI is a multimetric approach, i.e., the IBI uses a group of metrics that in combination indicate overall biological condition of a waterbody. For example, intolerant species or species that are habitat specialist are sensitive to differences in human-induced stress. Effective sampling of the nearshore fish community is essential to the development and performance of the IBI. Often sampling for fish in the nearshore of a lake is more difficult where there is extensive macrophtye growth; fish are difficult to detect during electrofishing surveys and seines, which may not be effective because they tend to move over rather than through the macrophytes.

The Fish IBI was significantly and negatively related to the density of docks (docks/km) across the 11 intensively studied lakes (P=0.016; Figure 11). The number of fish species was significantly and positively related to the number of plant species across the 11 intensively studied lakes (P=0.033; Figure 12), whereas the Fish IBI was not related to the number of plant species (P=0.150). However, the Fish IBI was negatively related to the macrophyte Floristic Quality Index (FQI) (P=0.025; Figure 13). The FQI is also a multimetric index. The mechanism for the relationship between the Fish IBI and the FQI is not clear, but may be related to the density of plants and the ability to collect fish in the nearshore.

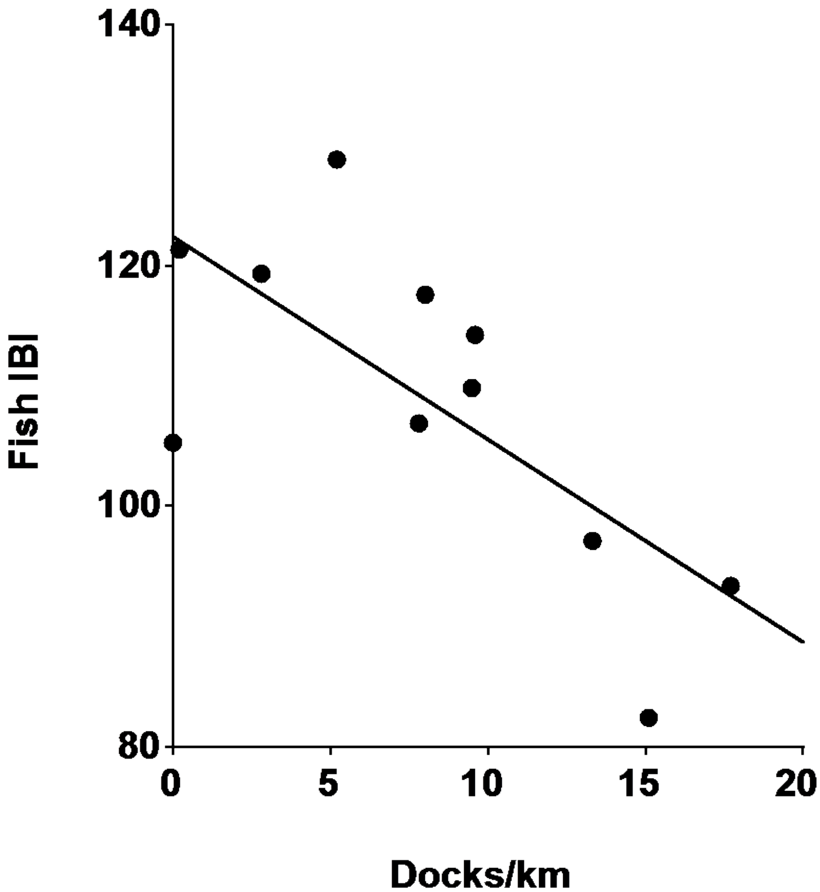


Figure 11. Fish IBI in relation to dock density in the 11 intensively studied lakes.

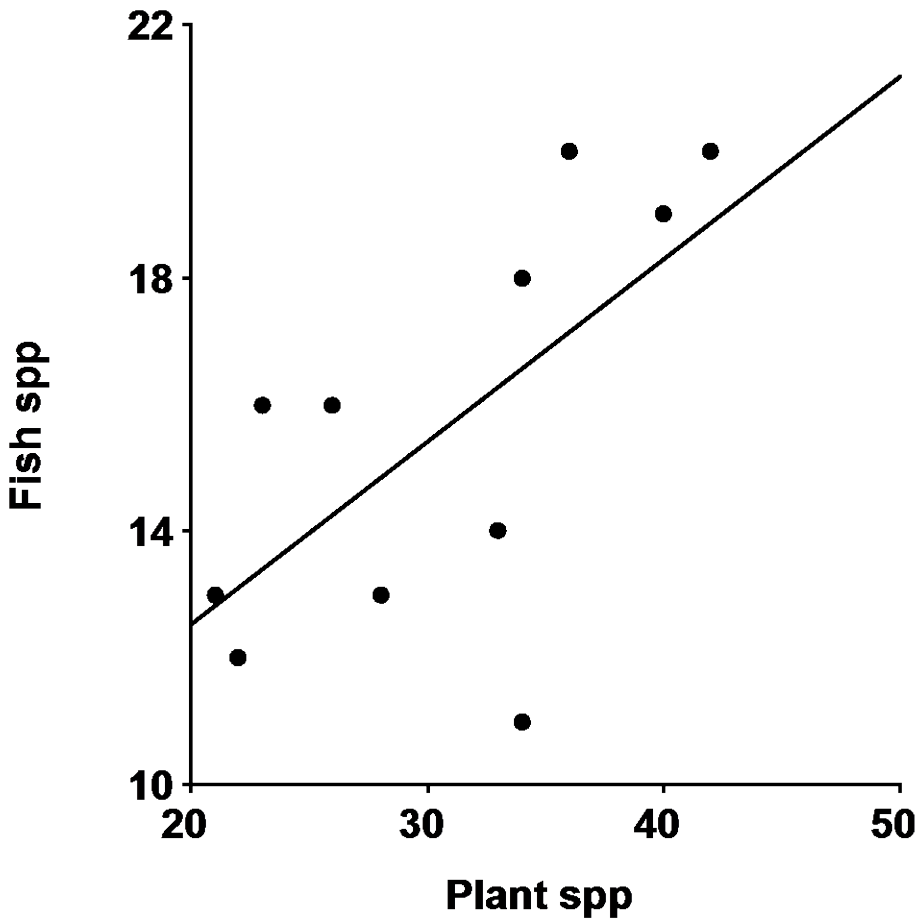


Figure 12. The number of fish species in relation to plant species in the 11 intensively studied lakes.

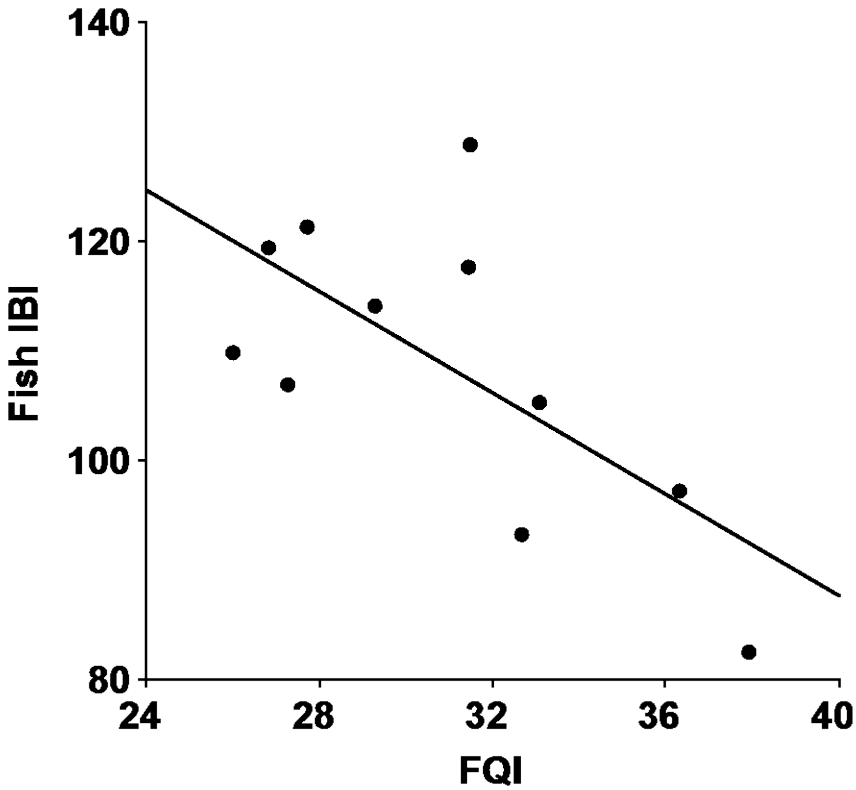


Figure 13. Fish IBI scores in relation to FQI scores in the 11 intensively studied lakes.

Lake-Scale Analyses

In total, 35,052 individuals representing 39 species were collected to calculate Fish IBI scores across (Table 9). There were no significant relationships between dock density and the Fish IBI, the number of fish species, the number of macrophyte species, and the FQI with the density of docks in 29 lakes that were extensively studied. In addition, relationships between the Fish IBI and the number of fish species with the number of plant species and the FQI were not significant.

Table 9. Fish species and number of fish per species (abundance) collected to calculate Fish IBI scores for 29 lakes in the Northern Lakes and Forest Ecoregion.

Species	Abundance
Bluegill	9082
Bluntnose minnow	8050
Largemouth bass	6461
Yellow perch	4232
Mimic shiner	1030
Blackchin shiner	869
Blacknose shiner	842
Banded Killifish	515
Pumpkinseed	499
Golden shiner	466
Johnny darter	418
White sucker	398
Central mudminnow	339
Rock bass	314
Iowa darter	279
Log perch	173
Green sunfish	167
Spottail shiner	158
Black crappie	137
Hybrid sunfish	108
Mottled sculpin	77
Smallmouth bass	76
Tadpole madtom	55
Yellow bullhead	47
Northern pike	36
Common shiner	32
Brook silverside	30
Least darter	30
Pugnose shiner	29
Brook stickleback	22
Walleye	20
Longear sunfish	17
Bowfin	13
Black bullhead	12
Hornyhead chub	10
Brown bullhead	3
Creek chub	3
Fathead minnow	2
Burbot	1
Total	35052

We also conducted an analysis of macrophyte biovolume in conjunction with the Minnesota Department of Natural Resources that was not anticipated in the original workplan. Macrophyte biovolume was assessed along a series of transects using hydroacoustic equipment (similar to commercial fish finders) in water deeper than 1.5-2.0 meters deep to complement the macrophyte data collected in the nearshore in the 11 extensively studied lakes. Biovolume ranged from sparse coverage in Horseshoe Lake to extensive coverage in Gilbert Lake (Figure 14). The macrophyte IBI was significantly correlated with biovolume scaled from 1 for Gilbert Lake to 11 for Horseshoe lake (r=0.696; p=0.010; Figure 115).

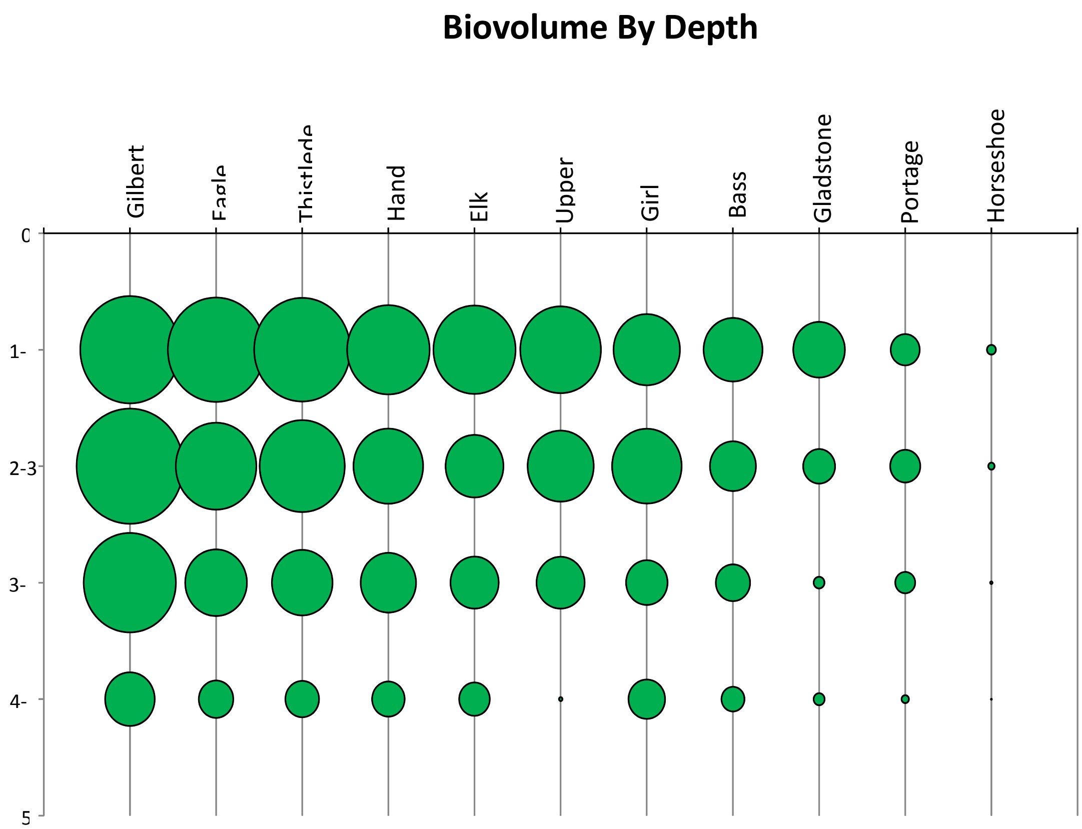


Figure 14. Mean vegetation biovolume by depth for the 11 intensively studied lakes. The size of the circle at each depth represents the mean biovolume for each depth interval. Mean biovolume ranged from 63% at 2-3m in Gilbert Lake to 1% at 4-5 m in Horseshoe Lake.

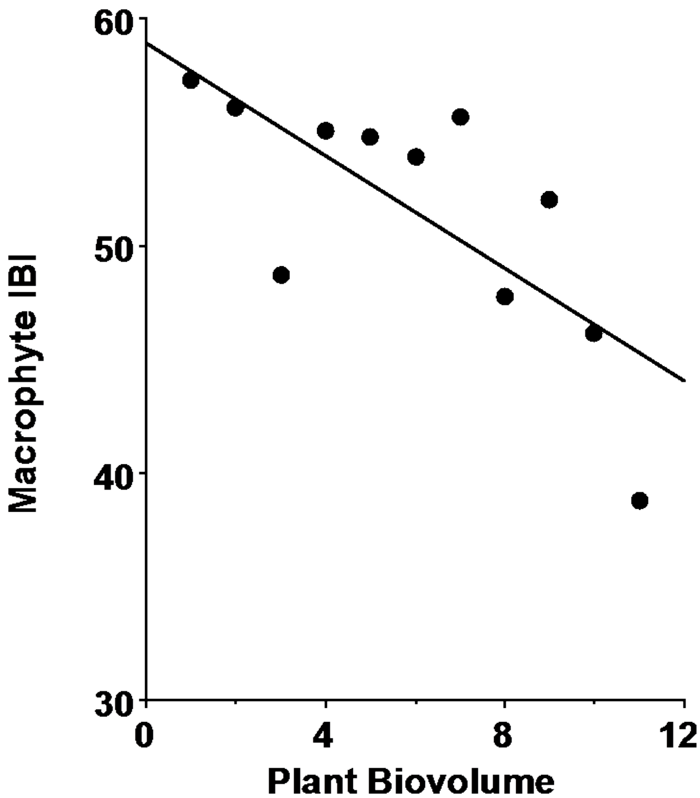


Figure 15. Relationship between macrophyte IBI and macrophyte biovolume (scaled from 1 for Gilbert Lake to 11 for Horseshoe Lake (see Figure 14).

Relationships for macrophytes and fish relative to lake area, percentage littoral area, Trophic State Index (TSI; a measure of phosphorus concentration), dock density (docks/km), and the percentage of the watershed disturbed were evaluated across most of the 114 lakes within the Northern Lakes and Forests Ecoregion in our initial pool of lakes in objective 1. Most macrophyte and fish variables were not measured in all lakes, thus the number of data entries for the statistical models was less than 114 for some analyses. Several models were evaluated and the best-supported model for FQI included the percent littoral area as an explanatory variable (Tables 10 and 11). Similarly, the top model for the number of plant species in a lake contained percentage littoral area but no other variables (Tables 10 and11). The best-supported model for lake-wide number of fish species included human development variables: dock density and percent watershed disturbed, as well as lake morphometric variables: lake area (hectares) and maximum depth (m) (Table 10). Fish species richness and dock density and percent watershed disturbed were positively related (Table 11; Figures 16 and 17). Interestingly, the best-supported model for Fish IBI score contained only FQI; IBI scores were negatively related to FQI (Tables 10 and 11, Figure 18), as was the case for the 11 intensively studied lakes.

Table 10. Best-supported linear models for lake-wide macrophyte and fish variables.

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 11. Parameter estimates for 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

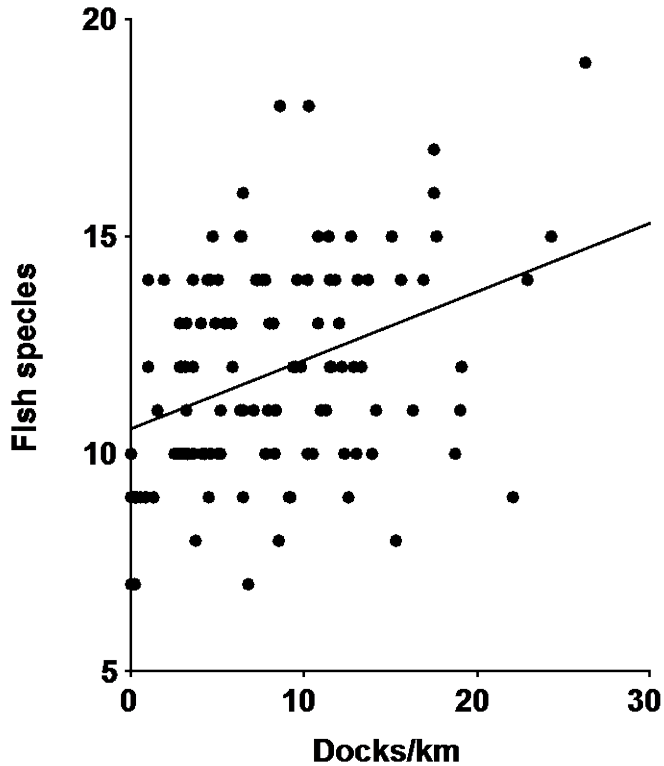


Figure 16. The number of fish species in relation to dock density across 114 lakes within the Northern Lakes and Forests Ecoregion.

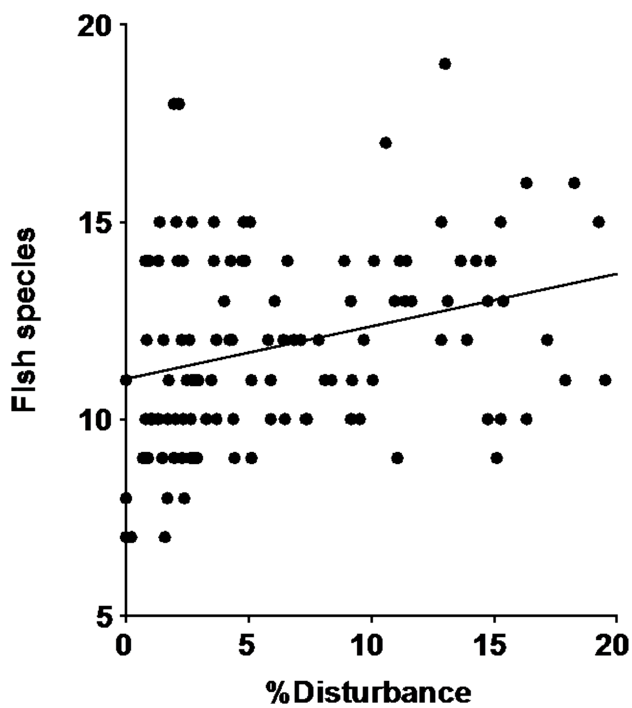


Figure 17. The number of fish species in relation to the percent disturbance in the watershed across 114 lakes within the Northern Lakes and Forests Ecoregion.

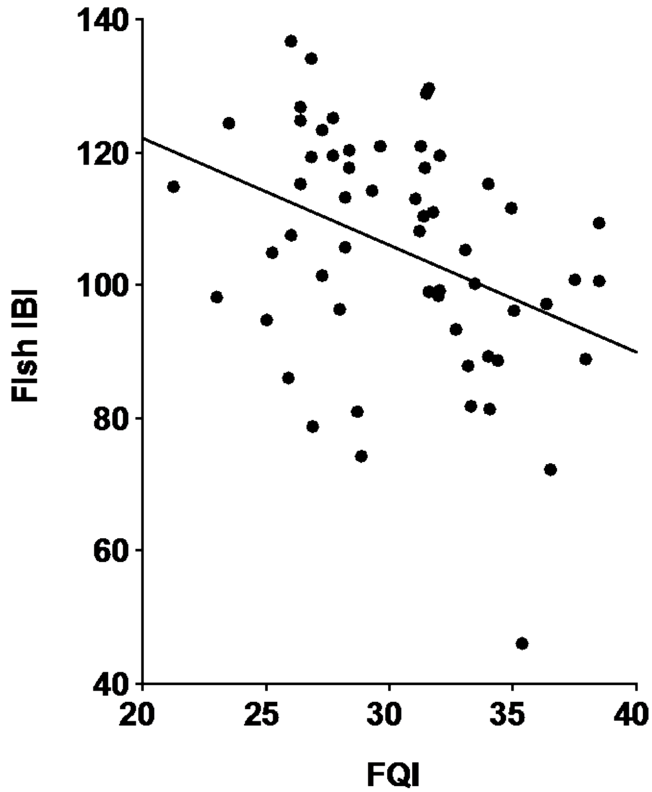


Figure 18. Fish IBI scores in relation to the FQI across 57 lakes within the Northern Lakes and Forests Ecoregion.

Conclusion

Human activities associated with residential docks significantly influence natural aquatic habitat structure. In the subset of small freshwater lakes we studied, We 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. 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. Relationships between nearshore development and fish abundance or the number of fish species was less clear; however, Fish IBI scores were negatively related to dock density in the 11 most intensively studied lakes.

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.

This study was the first to quantify relationships between habitat structure and proximity to a dock, and we found reductions in the presence and abundance of critical habitat components were documented as far as eight meters from docks in this study. Presence of CWS and emergent vegetation, as well as abundance of submerged and floating-leaf macrophytes, were reduced within this 8m zone. These findings are consistent with the 7.6m 'habitat impact zone' suggested by Radomski et al. (2010), which was based on vegetation removal guidelines for recreational development lakes in Minnesota. The site-level and lake-wide relationships between docks and habitat structure are consistent with the results of previous studies, which used cabins, rather than docks, as indicators of lakeshore development.

We observed significant and negative relationships between most macrophyte structural and diversity variables as 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. Submerged macrophytes were least affected by development; site-level development did not significantly affect the abundance of submerged vegetation. This could indicate that submerged growth forms are more tolerant of disturbance than other macrophyte types. Alternatively, landowners may overlook submerged species because they are less conspicuous than highly-visible emergent and floating-leaf species. Similar shifts in macrophyte communities have been reported in Canadian Shield lakes (Hicks and Frost 2011), where declines in emergent and floating-leaf macrophyte coverage were accompanied by increased coverage of submerged vegetation. The loss of emergent vegetation across highly developed lakes could have negative implications for species such as black crappie and other species which nest near emergent macrophyte species. 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 specific mechanisms through which residential development affects nearshore habitat structure while also considering other important geomorphic and chemical factors.

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. 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 stronger relationships between macrophyte community variables and percent of watershed disturbed.

Other local factors, such as substrate texture and water depth, are also key drivers of macrophyte biovolume. Presence of emergent species and coverage of submerged and floating-leaf vegetation was consistently highest in areas with fine substrates. Dock-related impacts to aquatic vegetation are likely to be highest at sites with fine substrates, simply because aquatic plants are naturally more abundant in such areas. Floating-leaf vegetation was particularly abundant in sites with fine substrates. Substrate is an important feature of lakefront properties; sandy areas are typically the most appealing to potential landowners. Landowners may even augment natural substrates with sand to create artificial beaches (Engel and Pederson 1998).

Our estimates of lake-wide CWS density were consistent with previous estimates for lakes of similar development densities in Wisconsin (Christensen et al. 1996, Marburg et al. 2006), and upper Michigan (Francis and Schindler 2008). 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. We found many of the developed sites at lower SYS scores. Shoreline and upland trees are the eventual recruitment source of CWS to the lake, and 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.

Large-scale reductions to littoral CWS have been attributed to declines in yellow perch *Perca flavescens* (Sass et al. 2006), as well as dietary shifts and reduced growth among largemouth bass (Ahrenstorff et al. 2009). Reduced yellow perch abundance was attributed to limited recruitment and high mortality rates associated with loss of spawning substrate and refuge (Sass et al. 2006, Roth et al. 2007, Helmus and Sass 2008). Docks could potentially offer surrogate habitat structure in the absence of natural CWS; however, a recent study by Lawson et al. (2011) found that largemouth bass nests were consistently located nearer to CWS than they were to docks, even in highly developed lakes with low CWS densities. Reed and Pereira (2009) observed that nest site selection by largemouth bass and black crappie were influenced by development practices along the shore; although nests were rarely found near developed shores, they were located in deeper water than nests adjacent to undeveloped sites. Fish IBI was significantly and negatively related to dock density within the 11 study lakes. Although the larger set of lakes followed a similar trend (see Figure 1 in the results status for January 2013), the relationship was not statistically significant. These results, together with our findings, suggest the influences of docks on fish communities may be largely negative. The mechanism is likely the reduction of aquatic macrophytes close to docks and the removal of vegetation, especially trees and shrubs in the riparian area of developed lots.

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 and 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. 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. Jennings et al. (2009) also 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. 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.

Result Status as of: (January 2013***)*:**

We completed data entry for the Fish-IBIs, near-shore macrophyte species richness and biovolume, Score Your Shore, coarse woody structure (CWS) collected during the past summer and have begun data analysis on the data collected in summer 2011 and 2012. We found a slight negative relationship between dock density and fish IBI scores (Figure 1) that we will explore further as our analysis continues.

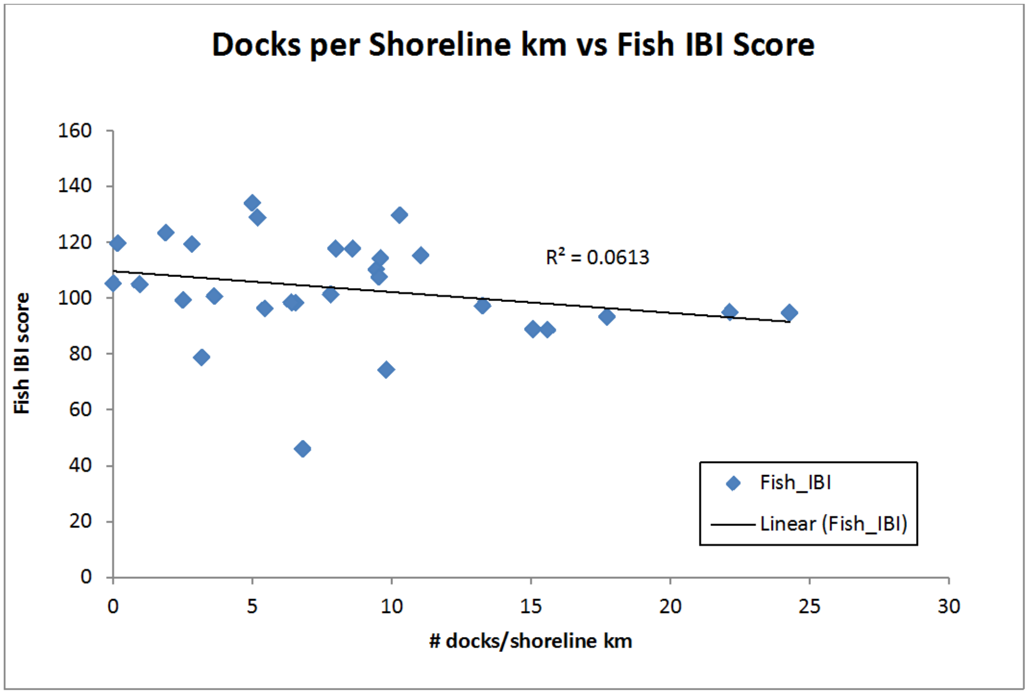


Figure 1. Dock density vs fish IBI scores for 29 lakes (excluding South Twin).

We conducted a standard macrophyte point-intercept survey, following the protocol of the Minnesota Pollution Control Agency, of the entire littoral zone and hydroacoustic sampling of macrophyte volume to evaluate the overall littoral habitat for the 12 extensive lakes to compare with the detailed nearshore data. The macrophyte point-intercept survey and the hydroacoustic sampling of macrophyte volume is an addition to the approved work plan and was conducted by our DNR collaborator. We calculated a macrophyte-based index of biotic integrity (M-IBI) following Beck et al. (2010) based on the point-intercept data (Table 1). We also characterized the composition of the macrophytes collected from the point-intercept surveys (Table 2). The data for the extensive lakes have been processed and are currently being analyzed in ArcGIS.

Table 1. Lake, DOW, date sampled, scaled IBI score (0-100), and the number of native taxa based on point-intercept sampling for the 12 extensive lakes.

Lake Name	DOW	Date Sampled	IBI Score	#Native Taxa
Eagle	29025600	8/10/11	80	26
Hand	11024200	8/16/11	79	33
Elk	15001000	8/9/11	78	21
Bass	11006900	8/18/11	68	23

Portage	11047600	8/17/11	66	22
Horseshoe	11035800	8/17/11	55	22
Gilbert	18032000	7/30/12	82	40
Gladstone	18033800	7/31/12	74	33
Thistledew	31015800	8/14/12	70	28
Upper Cullen	18037600	8/1/12	77	34
Girl	11017400	8/13/12	80	42
South Twin	69042000	8/15/12	51	9

Table 2. Characteristics (%) of the plant community composition in the 12 extensive lakes. Narrow PW = narrow pondweed.

Lake Name	Chara	Rooted	Submersed	Emergent	Floating	Narrow PW	# Taxa/point
Eagle	41	92	91	43	39	15	3.7
Hand	51	98	98	7	45	20	4.1
Elk	22	95	95	38	12	46	3.2
Bass	24	96	96	2	2	38	3.8
Portage	53	91	91	7	2	10	2.2
Horseshoe	72	80	80	7	2	10	1.8
Gilbert	32	95	93	10	27	19	3.9
Gladstone	45	98	98	7	7	7	3.1
Thistledew	33	98	98	30	13	40	4.6
Upper Cullen	38	82	78	37	36	3	3
Girl	29	99	98	15	21	10	4.9
South Twin	0	45	19	30	17	0	0.7

We conducted an analysis for 30-50 sites from the 12 “extensive “ lakes based on stratified random sampling. Half of the sites were developed and half were undeveloped. Macrophytes and CWS were sampled at each site. We used mixed effects models to investigate the effect of shoreline development on the following response variables at the site level: Presence/absence of CWS, total macrophyte species richness, emergent species richness, submerged species richness, and floating species richness. Total Score Your Shore score (SYSTotal) was the primary explanatory variable. Score Your Shore scores across sites ranged from 20 to 100 with lower scores indicating more developed properties (e.g., impervious surfaces, cleared trees etc.) and higher scores indicating more natural shorelines.

The presence/absence of CWS was significantly and positively related to the SYSTotal score ($p<0.001$; Table 3, Figure 1). Emergent and floating macrophyte species richness at the site-level was also significantly, positively related to SYSTotal score ($p<0.001$; Table 2). Neither submerged nor total species richness was significantly related to SYS score.

Table 3. Presence-absence of coarse woody debris (CWS) in relation to the Total Score Your Shore (SYSTotal) based on a Generalized Linear Mixed Model; binomial; random effect=Lake.

CWS	Estimate	SE	Z-Value	p
Intercept	0.098045	0.520786	-4.261	<0.001
SYSTotal	0.507735	0.005298	5.840	<0.001

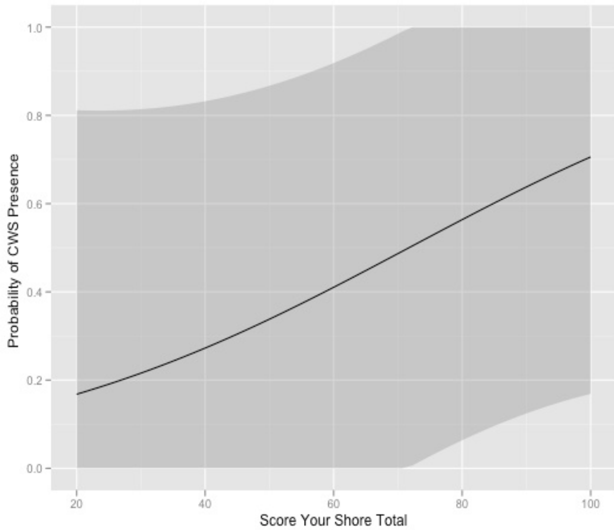


Figure 2. Model projection of probability of CWS presence at a site relate to Total Score Your Shore.

Table 4. Emergent and floating macrophyte species richness in relation to Total Score Your Shore (SYSTotal) based on linear mixed models; random effect=Lake. * Response variables were square-root transformed.

		Estimate	SE	df	t- value	p
Emergent Species Richness*	Intercept	0.491	0.466	342	1.053	0.293
	SYSTotal	0.026	0.004	342	5.978	<0.001
Floating Species Richness*	Intercept	0.548	0.169	342	3.243	0.0013
	SYSTotal	0.005	0.001	342	3.693	0.003

Coarse woody structure was infrequently found within 8 meters of 55 docks; only six percent of the sample transects contained CWS. In addition, CWS complexity did not vary substantially within or across dock locations; over 90 percent of all documented CWS consisted of simple logs (complexity=1). Therefore, we chose to examine the relationship between CWS presence and proximity to docks. Preliminary analysis suggested the frequency of CWS was positively related to distance to the nearest dock. We created a binary variable in which the presence or absence of CWS (pCWS) in a transect was coded as a “1” or “0”. A binomial generalized linear mixed model (GLMM; using the lme4 package in R 2.13.2) was used to examine the relationship between the presence of CWS and distance to the nearest dock. We created a GLMM in which distance to the nearest dock, Dist, was the sole predictor of pCWS. A random effect was included to account for variation between the nested sampling units (dock sites within lakes). The nested random effect essentially allowed each of the dock sites to have a unique slope and intercept. Model assumptions were verified by inspection of residual plots.

The binomial GLMM indicates CWS is likely to be found further from dock structures (Table 5, Figure 3).

Table 5. Presence of CWS (logit-transformed) is predicted to increase with distance to the nearest dock (Dist).

	Estimate	SE	Z	p
(Intercept)	-6.681	0.977	-6.841	<0.001
Dist	0.372	0.143	2.594	0.009

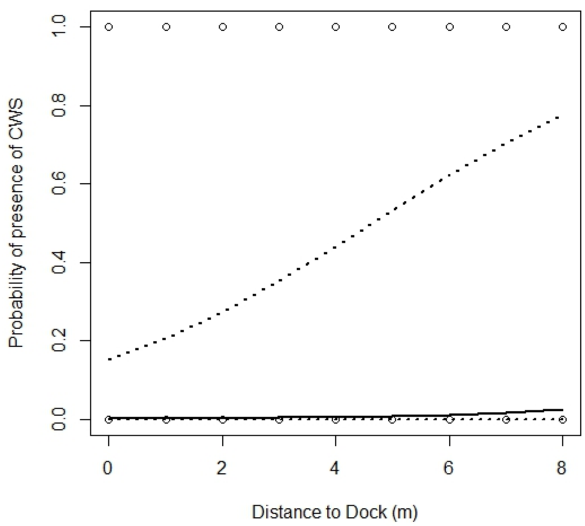


Figure 3. Predicted probability of CWS presence increases with distance to the nearest dock. Observed data are represented by the open circles. The solid line shows the mean response and dotted lines indicate 95% confidence intervals.

Our site-level analyses suggest that abundance of coarse woody structure (CWS) is negatively related to the presence of dock structures (Figure 4). The mean CWS abundance at developed sites containing docks was significantly lower than the mean CWS abundance found at undeveloped sites.

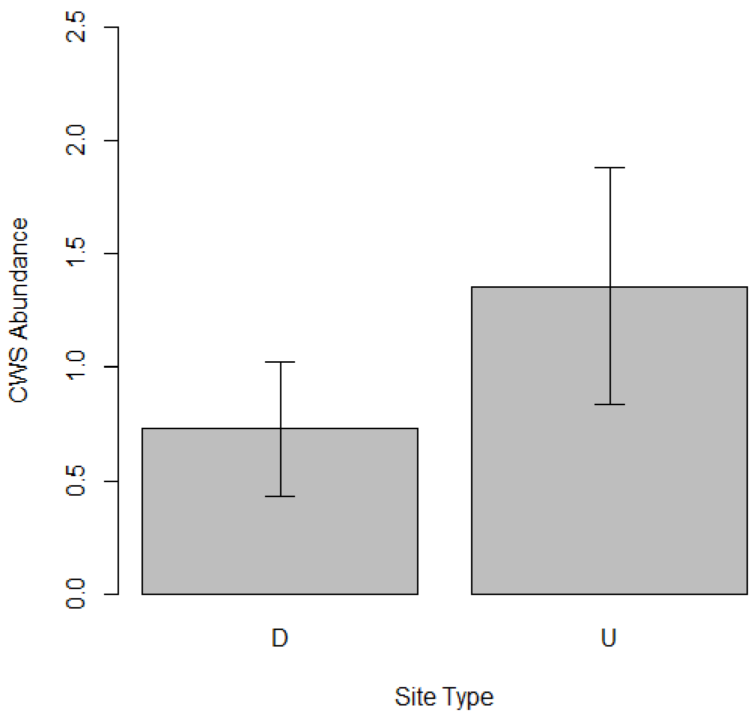


Figure 4. Undeveloped sites (U) had significantly higher mean CWS abundance than developed sites (D). The whiskers represent 95% confidence intervals.

We constructed linear mixed models (LMMs) to examine simple relationships between submerged and floating-leaf biovolume and distance to the nearest dock structure. The models used a nested random effect to account for variation across sampling units and allow the biovolume-distance relationship to vary across individual sites. LMMs were also used to examine relationships between biovolume and site type (developed/undeveloped). Submerged biovolume was modeled in response to site type, with a random effect accounting for variation between study lakes. A separate LMM was used to investigate the response of submerged biovolume to both site type and substrate texture. This model included a nested random effect to account for variation between sites and lakes.

Both submerged and floating-leaf biovolume were significantly and positively related to distance to docks (Figures 5 and 6), suggesting that biovolume increases further from dock structures. Although mean submerged biovolume differed between site types, the difference was not statistically significant (Figure 7).

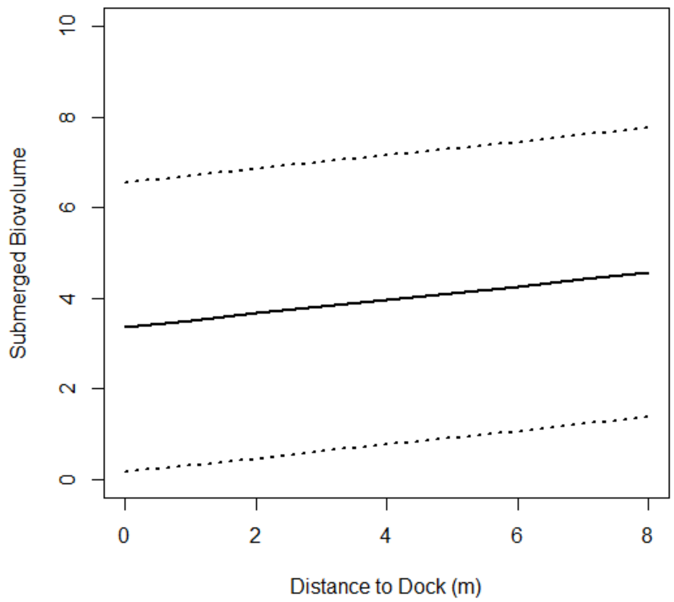


Figure 5. Submerged biovolume increases with distance to docks. Mean response (bold line) and 95% confidence intervals (dotted lines).

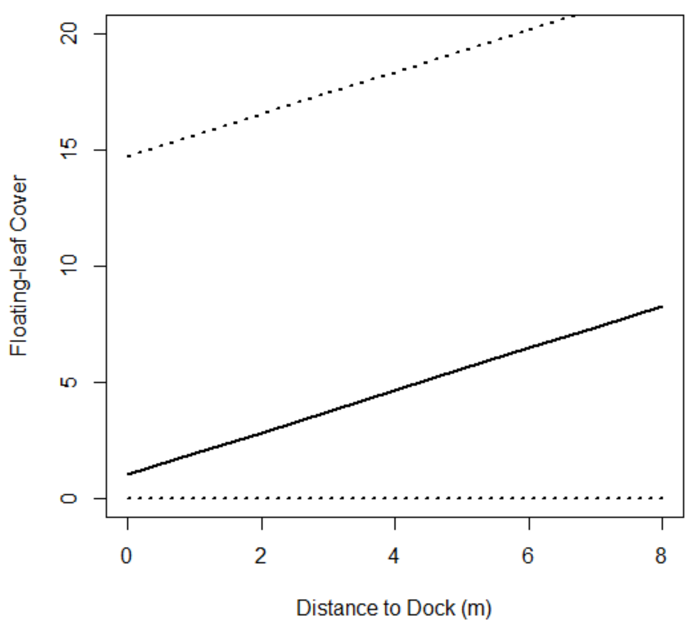


Figure 6. Floating-leaf cover increases with distance to docks. Mean response (bold line) and 95% confidence intervals (dotted lines).

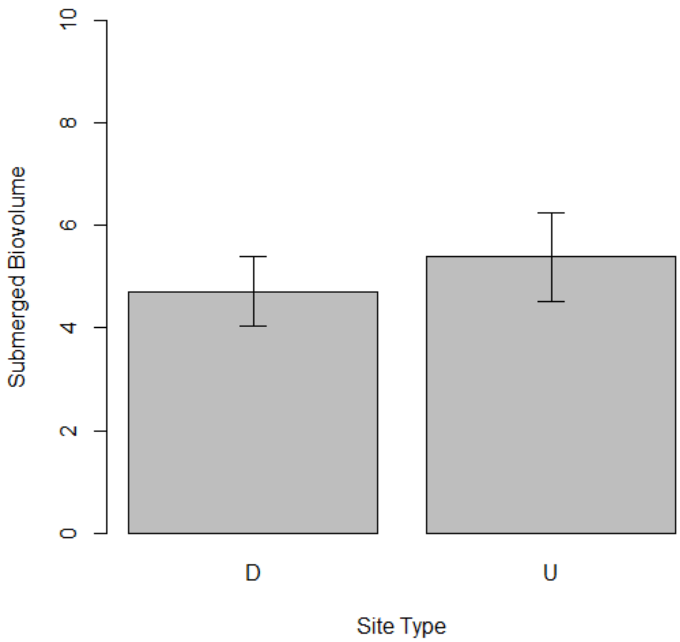


Figure 7. Mean submerged biovolume did not differ significantly between undeveloped (U) sites than developed (D) sites.

The lack of a relationship for submerged biovolume could be an indication that submerged biovolume is highly variable within the site area sampled. Another possibility is that submerged species are less sensitive to disturbance than emergent and floating-leaf species, which are often preferentially removed by homeowners. Submersed species typically colonize deeper areas than emergent-floating species and their vulnerability to shoreline development is expected to be reduced. Substrate texture was also a major predictor of submerged biovolume within the site. In general, undeveloped sites had higher submerged biovolume than developed sites (Figure 8); however, coarse substrates did not conform to this trend. Among developed sites, coarse substrates exhibited the highest submerged biovolume, although there was not a statistically significant difference between coarse and mixed substrates. Overall, submerged biovolume was highest at sites with fine substrates.

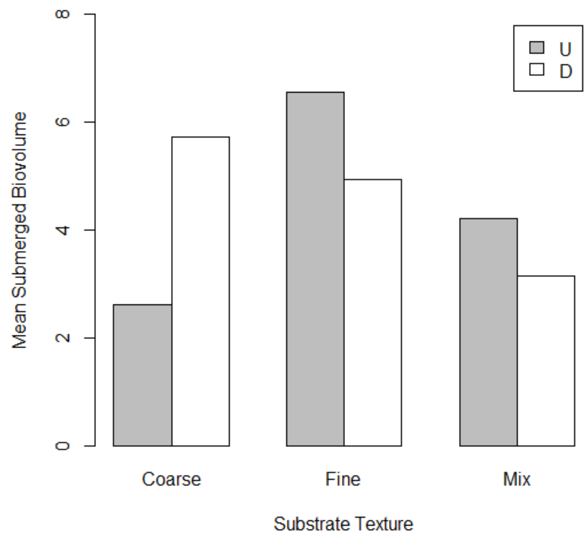


Figure 8. Mean submerged biovolume varied as a function of site type (developed/undeveloped) and substrate particle texture. Undeveloped (U) sites tended to exhibit higher mean biovolume than developed (D) sites; however, this pattern did not hold for areas with coarse substrate. Overall, fine substrates supported the greatest submerged biovolume.

Result Status as of:
September 2012

We completed sampling all 30 lakes in the initial sampling design at two levels of intensity. The number of sites per lake was dependent upon whether lakes were “site lakes (n=30)” or “extensive lakes (n=12)”. All “site lakes” had 10 sites, and included surveys for calculating a Fish-Index of Biotic Integrity (IBI), Score Your Shore, macrophyte taxa and biovolume at nine points (depths of 30, 60, and 90 cm along three transects) at each site, and CWS (Table 1). All “extensive lakes” included point-intercept sampling of macrophytes at 77 to 142 points, depending on lake size, in the littoral area of a lake. Additionally, macrophyte biovolume between 1.5 meters in depth to the maximum extent of vegetation was mapped using hydroacoustic surveys on the 12 “extensive” lakes.

Table 1. Number of sampling sites for Fish-IBI, Score Your Shore, and macrophyte taxa for 17 lakes in summer 2012.

Lake Name	DOW	Sample Type	# Fish/Habitat Sites
Girl	11-0174	Extensive	28
Gilbert	18-0320	Extensive	22
Gladstone	18-0338	Extensive	11
Upper Cullen	18-0376	Extensive	14
Thistledew	31-0158	Extensive	12

South Twin	69-0420	Extensive	10
Little Pine	01-0176	Site	10
Upper Gull	11-0218	Site	10
Child	11-0263	Site	10
Portage	18-0050	Site	10
Island	18-0183	Site	10
Goodrich	18-0226	Site	10
Mitchell	18-0294	Site	10
Eagle	18-0296	Site	10
Crooked	31-0193	Site	10
Rush Island	31-0832	Site	10
Pike	69-0490	Site	10

We evaluated the direct effects of development at the lot scale on lake shorelines with a modified design of the extensive lake sampling methods for the 2012 field season. Rather than sampling single transects spaced around the lakeshore, we used stratified random sampling to add sites around each lake, in addition to the 10 or more sites as in 2011. In all, 30-50 sites were sampled around each of the 12 "extensive" lakes, depending upon the length of shoreline mileage. Half of the sites were developed (contained a dock and/or cabin) and half were undeveloped. We sampled macrophyte taxa and biovolume in three equally spaced transects at three depths per transect in each site, which was similar to sampling in 2011. The total number of macrophyte species encountered in the 12 lakes ranged from 14 species in South Twin to 55 species in Gilbert with a mean of 38.7 species (Figure 2).

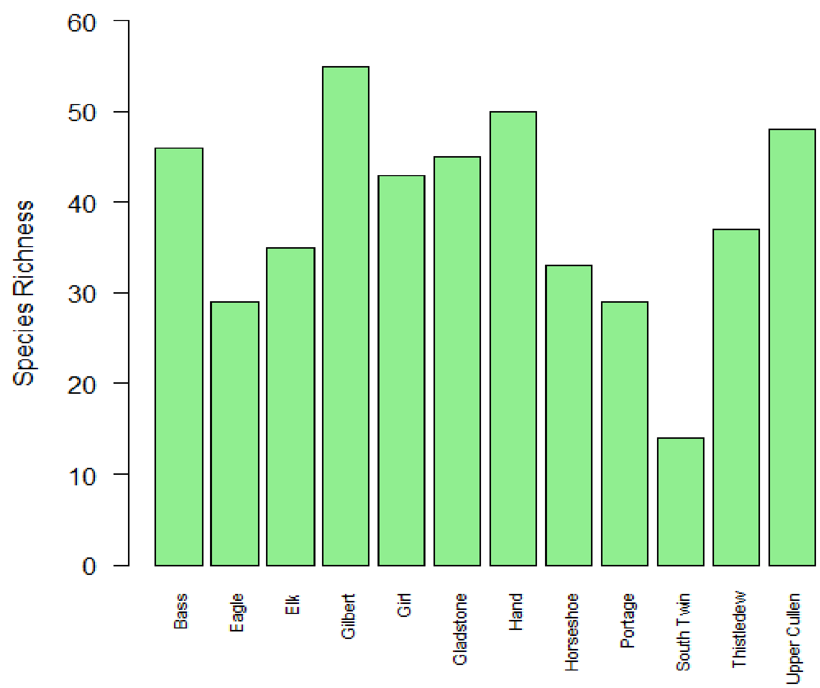


Figure 2. Total number of macrophyte species sampled in nearshore samples in each of the 12 “extensive” lakes in summer 2012.

We also measured characteristics of habitat complexity (macrophyte biovolume and CWS) near docks more intensively to examine the localized influences of docks on littoral habitat structure. We used aerial photographs (2011) to identify all docks on 10 developed ‘extensive’ lakes. We selected candidate docks, which were simple in shape and relatively isolated (over 20 meters from a neighboring dock). A random subset of five docks was chosen for each study lake. Ten docks were sampled on Girl and Gilbert lakes because they are substantially larger than the others. Thus, a total of 60 dock locations were selected to undergo habitat sampling. We recorded water depth, substrate texture, and visual macrophyte biovolume estimates at points along each sampling transect using a circular sampling ring (0.5 m diameter). The sampling points began at the shore and were spaced every 3 meters until the end of the dock was reached. Thus, docks over 6 meters long received sampling along more than three points per transect. Most docks were sampled at 3 or 4 different depths. The final sampling depth was aligned with the end of the dock. Macrophyte biovolume was estimated for each of three structural categories: emergent, submerged, and floating-leaf. Emergent biovolume was assigned a range from 0 to 5 percent in increments of 1 percent; the percentages correspond to the following stem counts: 0: absent (0), 1: sparse (<4 stems), 2: moderate (4-9 stems), 3: 10-19 stems, 4: 20-30 stems, 5: dense (>40 stems). Submerged biovolume estimates were assigned values from 0 to 100 percent in increments of 5 percent, based on the density of vegetation within the entire water column. In areas where vegetation was extremely sparse, 1 percent biovolume was recorded. Cover of floating-leaf vegetation was recorded as the percentage of the sampling ring covered by floating leaves. Thus, estimates of floating-leaf cover could range from 0 to 100 percent in increments of 5 percent, although 1 percent was noted for extremely sparse cover.

All coarse woody structure (CWS) greater than 10 cm in diameter was surveyed at each site for the 12 extensive lakes and a complexity score (1 to 5) was assigned to each piece. A “1” indicates the simplest structural type, typically a simple log with no branches. A “5” indicates a highly complex, branchy tree exhibiting fourth-order branching patterns along the majority of the trunk. CWS density appears to be negatively correlated with development (dock density) around the extensively sampled lakes at a whole lake level (Figure 3).

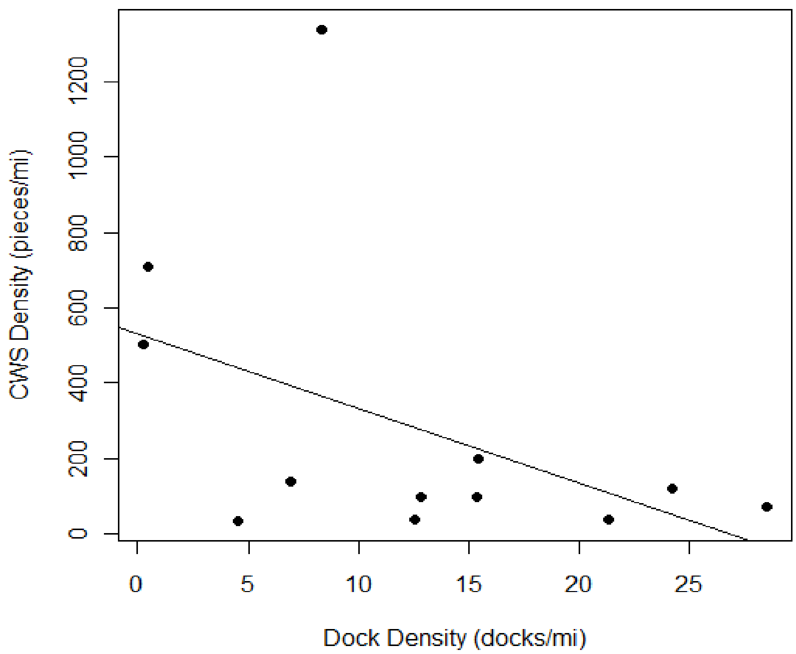


Figure 3: Coarse Woody Structure density in nearshore area (<3 ft depth) of extensive lakes and dock density of the 12 extensive lakes.

At each of the 60 dock locations, we counted every piece of CWS (>10 cm diameter) intersecting the transect lines designated for the macrophyte sampling in 10 developed 'extensive' lakes and assigned each piece a qualitative complexity score from 1 to 5 (as above).

We generated mixed effects models for each of the following response variables collected from the 60 dock locations: Total CWS (TotalCWS), emergent biovolume (Em), submerged biovolume (Sub), and floating-leaf cover (Float). Proximity to dock (Dist) was included as an explanatory variable in all models. Other explanatory variables included: macrophyte biovolume (Em, Sub, Float), water depth (Depth), substrate texture (Substrate), and dock class (Class). In each model, site within lake was included as a nested random effect to account for variation between sampling units. The best models were identified using backward elimination. Generalized linear mixed models with log link functions were created for emergent and submerged biovolume. Linear mixed models were created for floating-leaf cover and total CWS; responses were transformed using square-root and $\log_{10}(y+1)$ transformations, respectively, to meet the statistical assumptions.

Each structural type of macrophyte biovolume was significantly related to proximity to the nearest dock (Tables 2-4). Emergent biovolume was positively related to distance (0.158 ± 0.008, p< 0.001), and negatively related to submerged biovolume (-0.113 ± 0.008, p< 0.001) and floating-leaf cover (-0.022 ± 0.002, p<0.001). Submerged biovolume was also positively related to distance (0.053 ± 0.003, p< 0.001), and negatively related to emergent biovolume (-0.158 ± 0.010, p< 0.001). The three categories of substrate texture were also significantly related to submerged biovolume, with coarse substrate (intercept) supporting the lowest biovolume and fine substrate supporting the highest biovolume. Floating-leaf cover was positively related to distance (0.145 ± 0.010, df=3474, p=0.00) and submerged biovolume

(0.118 ± 0.009, df=3474, p=0.00) and negatively related to emergent biovolume (-0.270 ± 0.03, df=3474, p=0.00).

The CWS model indicated that CWS totals were also significantly related to dock proximity (Table 5). Similar to macrophyte biovolume, CWS counts were positively related to distance (0.003 ± 0.001, df=1021, p=0.00), indicating that CWS density increases as distance from the dock increases.

Table 2. Emergent biovolume model.

	Estimate	SE	z	p
(Intercept)	-1.367	0.374	-3.66	<0.001
Dist	0.158	0.008	19.7	<0.001
Sub	-0.113	0.008	-13.4	<0.001
Float	-0.022	0.002	-9.86	<0.001

Table 3. Results from submerged biovolume model.

	Estimate	SE	z	p
(Intercept)	-0.668	0.234	-2.85	0.004
Dist	0.053	0.003	15.5	<0.001
Em	-0.158	0.01	-15.8	<0.001

Table 4. Results from floating-leaf biovolume model.

	Estimate	SE	df	t	p
(Intercept)	0.065	0.209	3474	0.312	0.755
Dist	0.145	0.01	3474	14.6	<0.001
Em	-0.27	0.026	3474	-10.2	<0.001
Sub	0.118	0.009	3474	13.5	<0.001

Table 5. Results from total CWS model.

	Estimate	SE	df	t	p
(Intercept)	0.0026	0.0058	1021	0.454	0.649
Dist	0.0032	0.0008	1021	4.26	<0.001

Result Status as of:
January 2012

We sampled 13 of the designated 30 lakes at two levels of intensity. The number of sites per lake was dependent upon whether lakes were “site lakes” or “extensive lakes”. All “site lakes” had 10 sites, and included surveys for calculating an Index of Biotic Integrity (IBI), Score Your Shore, macrophyte taxa and biovolume at nine points (depths of 30, 60, and 90 cm along three transects) at each site, and CWS. All “extensive lakes” had 10 to 17 sites, depending on the length of the shoreline and included the same surveys as on the site lakes, but in addition, included point-intercept sampling of macrophytes at 77 to 142 points, depending on lake size, in the littoral area of a lake; macrophyte biovolume between 1.5 meters in depth to the maximum extent of vegetation; and a survey of CWS in a continuous transect around the perimeter of the lake in water less than 90 cm deep. In addition the site sampling on the extensively sampled lakes, we also recorded macrophyte species and biovolume at depths of 30, 60, and 90cm at 50 to 100 additional transects around the 'extensive' lakes, depending upon shoreline length. Macrophyte biovolume was also estimated at three points around every dock in the 'extensively sampled' lakes. Location, size and depth of each dock were also recorded.

Near-shore fish communities were sampled in 13 lakes to calculate an Index of Biotic Integrity (IBI). Fish were sampled using seines and a backpack electrofishing unit. Where habitat and depth permitted, a 15-meter bag seine with 3-mm (1/8 inch) mesh was used. At sites with course woody structure, dense vegetation, boulders, or steep drop-offs, a 4.5-meter bag seine with 3-mm mesh was used. In some instances, sampling with seines was not feasible and only the backpack electrofisher was utilized. Fish were sorted by species and counted, with a proportion of each species being kept as voucher specimens. The average number of fish species captured per lake was 13 (range 8 to 18 species). Overall, 35 different species and 11,952 individuals were captured (Table 1). An IBI score was calculated for each lake by combining the nearshore data with trap net and gill net data from the Minnesota DNR's Lake Survey Module (LSM) database. The LSM data used for the IBI scores was collected from 2005 to 2011. Each IBI score is based on 16 fish population metrics and can have a maximum value of 160. A score of 160 indicates that a lake's fish community is equivalent to that found in a natural, undisturbed lake; thus, a higher IBI score is indicative of a more biologically healthy lake. The fish-IBI scores ranged from 46.04 to 134.04 (Table 2).

Table 1. Total number of fish captured by species and percent frequency for near-shore samples in 13 lakes.

Species	Total	%	Species	Total	%
bluntnose minnow	5605	46.9	spottail shiner	14	0.12
bluegill	1708	14.3	black bullhead	11	0.09
yellow perch	1240	10.4	tadpole madtom	11	0.09
mimic shiner	946	7.9	brook stickleback	9	0.08
blackchin shiner	430	3.6	yellow bullhead	8	0.07
white sucker	369	3.1	mottled sculpin	7	0.06
banded killifish	284	2.4	walleye	7	0.06
largemouth bass	268	2.2	bowfin	4	0.03
rock bass	161	1.4	northern pike	3	0.03
blacknose shiner	131	1.1	creek chub	2	0.02
golden shiner	130	1.1	smallmouth bass	2	0.02
logperch	127	1.1	brown bullhead	1	0.01
Iowa darter	122	1.0	fathead minnow	1	0.01
black crappie	91	0.76	hybrid sunfish	1	0.01
johnny darter	83	0.69	longear sunfish	1	0.01
central mudminnow	81	0.68	unknown chub	1	0.01
pumpkinseed sunfish	66	0.55	unknown minnow	1	0.01
least darter	26	0.22			

Table 2. Fish-IBI scores, number of species, lake size, and number of sites sampled for 13 lakes. The IBI scores include nearshore data and trap net and gill net data from the Minnesota DNR's Lake Survey Module (LSM) database.

Lake	DOW #	County	IBI Score	# of Species	Lake Size (acres)	# of Sites
Bass	3008800	Becker	99.25	15	197	10
Bass	3012700	Becker	78.72	15	128	10
Pickerel	3028700	Becker	98.25	19	361	10
Bass*	11006900	Cass	88.85	18	193	10
Hand*	11024200	Cass	114.16	22	289	17
Horseshoe*	11035800	Cass	107.55	18	260	12
Portage*	11047600	Cass	128.87	20	277	10
Welch	11049300	Cass	123.32	20	195	10
Elk*	15001000	Clearwater	119.6	16	305	10
Eagle*	29025600	Hubbard	101.37	23	424	17
Beatrice	31005800	Itasca	46.04	12	122	10
Loon	31057100	Itasca	134.04	23	231	10
Little Bowstring	31075800	Itasca	96.29	22	327	10

*'extensive' lakes

The mean Score Your Shore values across all 13 lakes surveyed was 69.5; however, all lakes exhibited a range of land use intensities, with low scores indicating extensive terrestrial alteration and high scores (up to 100) indicating natural conditions (Table 3).

Table 3. Mean, minimum, and maximum Score Your Shore values for 13 lakes.

Lake Name	DOW #	Mean	Min.	Max.
Bass -North	3008800	64.36	28	95
Bass - South	3012700	52.7	9	100
Bass *	11006900	57.1	9	100
Beatrice	31005800	70.8	28	100
Eagle*	29025600	68.35	19	100
Elk*	15001000	90.7	36	100
Hand *	11024200	70.82	23	100
Horseshoe*	11035800	73.67	36	100
Little Bowstring	31075800	61.7	18	100
Loon	31057100	67.8	35	100
Pickerel	3028700	70.4	32	100
Portage*	11046700	75.4	28	100
Welch	11049300	80	14	100

*'extensive' lakes

Forty-nine taxa of macrophytes were sampled in the near-shore area in the six extensive lakes. The six extensive lakes exhibited variation in macrophyte assemblages. Macrophyte species richness ranged from 27 species in Horseshoe Lake, to 37 species in Bass Lake (Figure 1); however, there was little difference among lakes for emergent, submergent, or floating macrophytes. Fifty-four taxa were sampled during point-intercept surveys with 39 taxa common to both types of surveys. Macrophyte species richness ranged from 22 species in Horseshoe Lake, to 35 species in Hand Lake (Figure 2); however, there was little difference among lakes for submergent and floating macrophytes.

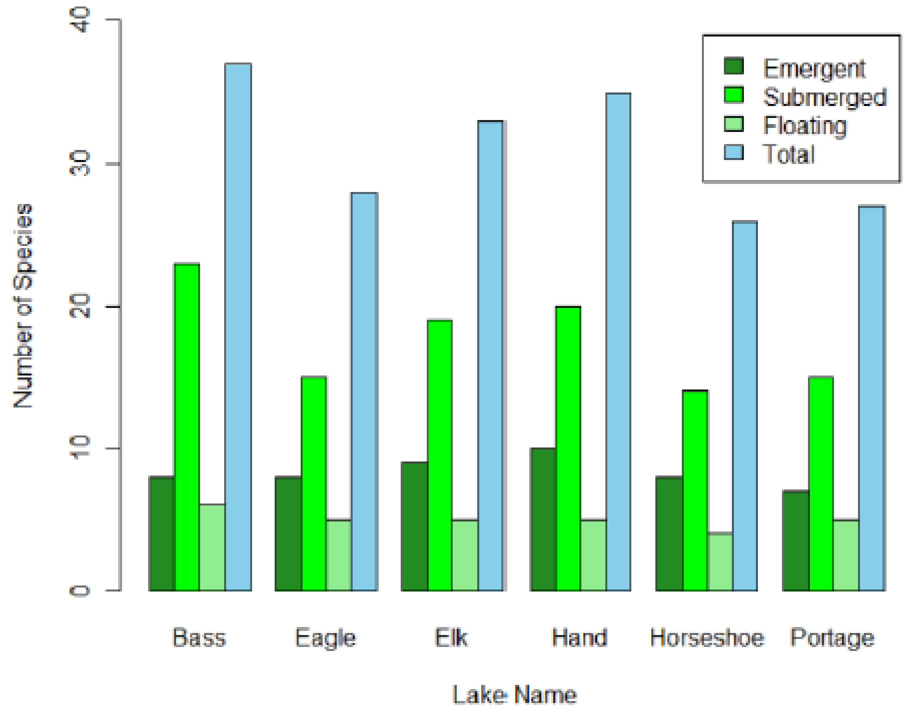


Figure 1. Number of emergent, submergent, floating, and total macrophyte species in the six 'extensive' lakes sampled in the nearshore.

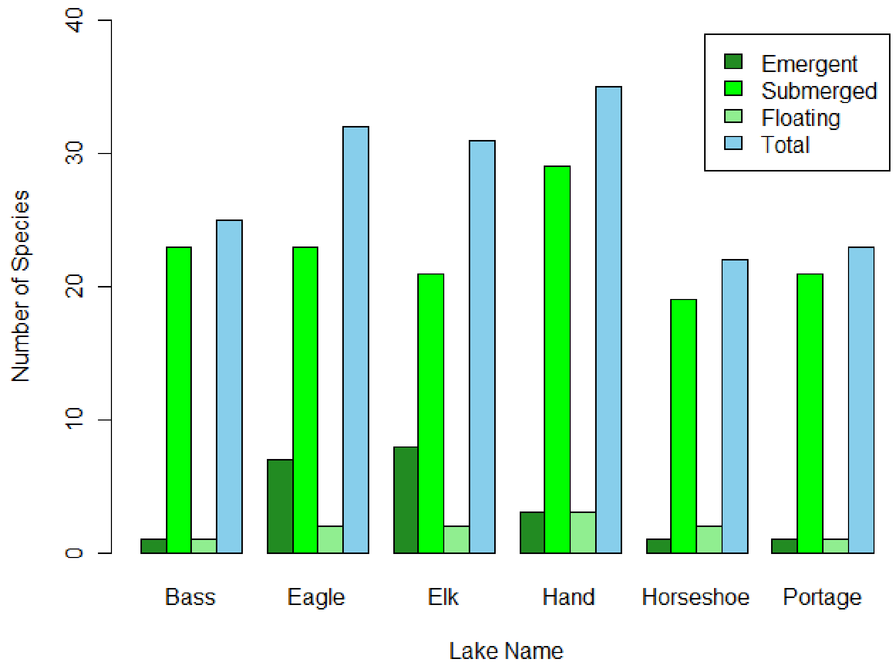


Figure 2. Number of emergent, submergent, floating, and total macrophyte species in the six 'extensive' lakes in point-intercept surveys.

Coarse woody structure density ranged from 22 to 621 pieces per shoreline kilometer along surveys of the perimeter of the six 'extensive' lakes. CWS abundance was assessed in relation to site-specific land use within the 13 'site' lakes. Sampling sites were classified as "developed" or "natural" based on the presence or absence of a cabin at the site. Sites designated as "other" were either near or between "developed" sites. We found a significantly higher mean abundance of CWS at natural sites relative to developed sites, and other sites were intermediate to developed and natural sites (Figure 3).

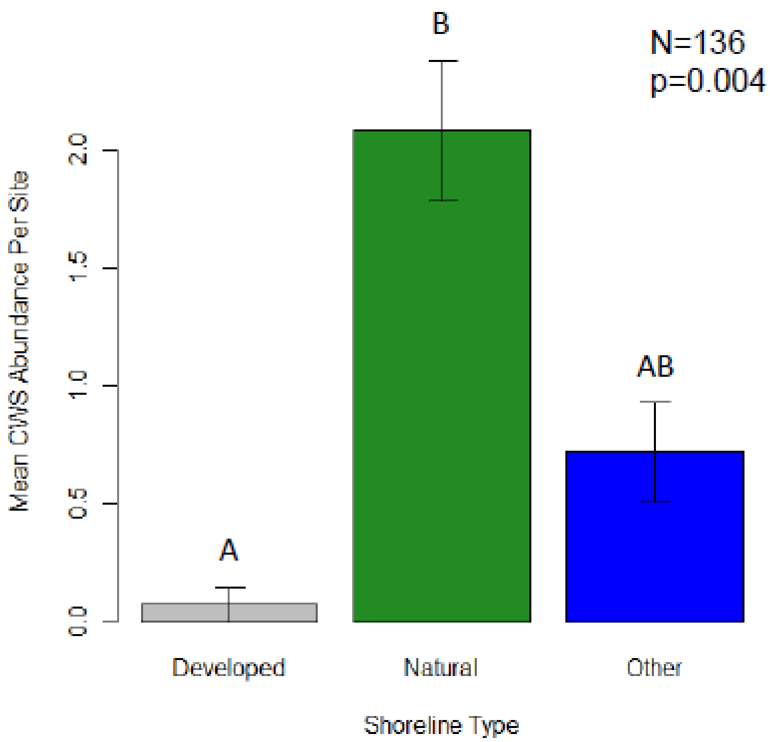


Figure 3. Mean abundance of CWS at sites classified as developed, natural, and other at 13 lakes. Different letters above a histogram indicate a significant difference.

Biovolume surveys indicated variation within lakes. Although we have visual depictions of biovolume for the six extensive lakes we include Portage Lake as an example (Figure 4).

We have evaluated a number of simple correlations to evaluate the relationship between a number of variables, e.g., CWS density vs the number of docks per kilometer; however, most are not significant, likely because of the limited number of lakes in our current database. We will continue to evaluate the data until the next field season begins in May.

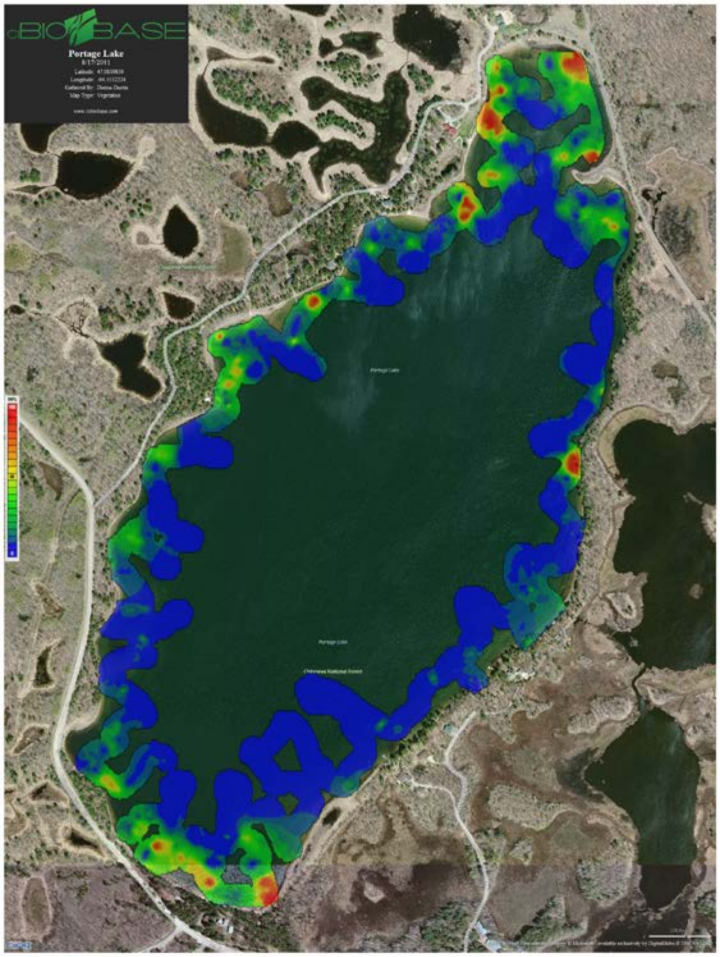


Figure 4. Biovolume of aquatic macrophytes in Portage Lake. Blue indicates low biovolume whereas red indicates high biovolume.

Result Status as of:
September 2011
Description: We completed extensive habitat surveys on six of the subset of 12 lakes. We documented each piece or group of coarse woody structure (CWS) encountered at water depths from one to three feet and recorded the diameter, length, branching complexity, and maximum depth. We also noted the shaded area provided by overhanging trees and shrubs. Docks, boatlifts and other in-water structures were described and marked with GPS waypoints. We recorded macrophyte species and biovolume at depths of one, two and three feet along transects located approximately every 50 to 120 feet of shoreline, depending on the size of the lake.

We completed point-intercept surveys on the six lakes with extensive habitat surveys. The point-intercept surveys are used to evaluate species composition of macrophytes in the remainder of the littoral zone.

We used acoustic surveys to quantify macrophyte biovolume incidental to the point-intercept surveys.

We completed fish and Score Your Shore surveys on the six lakes where extensive habitat surveys were conducted plus nine additional lakes (fish and Score Your Shore surveys). Thus, 15 of the subset of 30 lakes have been surveyed. The number of sites per lake ranged from 10 to 17, with ten lakes having 10 sites per lake, one lake having 12 sites, and two lakes having 17 sites per lake. The number of fish sampled per lake ranged from 164 to 5,551. Although fish species abundance varied among lakes, overall, bluntnose minnow, bluegill, and yellow perch were the most abundant fish sampled. In addition, macrophytes varied considerably among lakes, with some lakes having dense emergent, floating-leaved, and submerged vegetation, and some lakes having very little vegetation of any kind. Common emergent vegetation included bulrush, bur-reed(s), and cattail. Common floating-leaved vegetation included spadderdock and white water lily. Common submerged vegetation included muskgrass, coontail, and pondweeds. Purple-flowered bladderwort (*Utricularia purpurea*), a species of special concern in Minnesota, was sampled in one lake. As with the aquatic vegetation, course woody structure was also highly variable among lakes. Lakes without outlets experienced above-normal water levels, and tended to have more course woody structure present.

Result Status as of:
January 2011
Description: This past summer, the research team spent two weeks becoming familiar with several of the study lakes, as well as the field methods to be used during the next two field seasons. First, we refined a littoral habitat sampling protocol to be conducted on the 30 lakes where impacts of shoreline development on near-shore habitat will be assessed. We collected data on both developed and undeveloped lakes and estimated the time required to complete a site. We also devised a procedure for quantifying and describing the presence of docks and coarse woody structure along the shoreline. We worked with a DNR Fisheries team, who helped us learn fish identification and sampling protocol and completed three Fish-IBIs on three lakes. As well, we learned how to identify aquatic plants common to the region and point-intercept vegetation survey techniques on one lake.

RESULT/ACTIVITY 3: Assess impacts of shoreline development on near-shore habitat

Description: We will develop a model to evaluate human development on lakes by creating a framework to link our fine-scale data on near-shore habitat at 30 lakes (Result 2) to the whole-lake data for 100 lakes (Result 1) to evaluate cumulative impacts.

Summary Budget Information for Result/Activity 3: ENRTF Budget: $55,791
Amount Spent: $11,525
Balance: $44,266

Deliverable/Outcome	**Completion Date**	**Budget**
1. Develop a framework for assessing the cumulative impact of development that will allow lake managers to model consequences of different development scenarios.	June 2013	**$55,791**

Result Completion Date: Model development completed by June 2013

RESULT 3: Assess impacts of shoreline development on near-shore habitat

Final Status as of: (August 2013***)*:**

Description: Several of the statistical models reported in Result/Activity provided a framework for evaluating the complex interactions related to shoreline development, macrophyte species composition, depth of samples, substrate, dock density, and % disturbance in watersheds.

Result Status as of: (January 2013***)*:**

Description: No work was devoted to developing a framework to assessing the cumulative impact of development. However, this task will begin between now and the completion of the study.

Result Status as of:
September 2012**:**

Description: No work was devoted to developing a framework to assessing the cumulative impact of development. However, this task will begin between now and the completion of the study.

Result Status as of:
January 2012**:**

Description: No work was devoted to developing a framework to assessing the cumulative impact of development, as this task cannot begin until after the summer field season in 2011.

Result Status as of:
September 2011

Description: No work was devoted to developing a framework to assessing the cumulative impact of development, as this task cannot begin until after the summer field season in 2011.

Result Status as of:
January 2011
Description: No work was devoted to developing a framework to assessing the cumulative impact of development, as this task cannot begin until after the summer field season in 2011.

V. TOTAL ENRTF PROJECT BUDGET: $300,000
Personnel: $276,096 *(There will be four University personnel for this project: 1. A PhD student 0.5 FTE for three years $105,788, 2. a MS student 0.5 FTE for two years $70,337, 3. A Research Fellow 1.0 FTE for two years $76,251, and 4. An undergraduate student 1.0 FTE during two summers and 0.25 TE during the academic year $23,721)*
Contracts: $ $81,438 A temporary DNR employee will be contracted for about 22 months beginning 1 July 2011.
Equipment/Tools/Supplies: $7,204 *($500 for alcohol to preserve fish, and plants for identification; $2,717 for Nalgene sample jars; and $400 for nets to collect fish)*
Acquisition (Fee Title or Permanent Easements): $0
Travel: $12,200 *(in-state travel; $11,600 for mileage @$0.50/mile and $3,500 for food and lodging during data collection trips)*

Additional Budget Items: $0

VI. PROJECT STRATEGY:

A. Project Partners:

We will work directly with several employees with the Minnesota Department of Natural Resources, who will provide in-kind services (see VI. C. below).

B. Project Impact and Long-term Strategy: Our research will provide shoreline owners and lake managers with information about the impacts of development on aquatic ecosystems. Lakeshore managers may use this information to guide shoreland management practices and to focus protection or restoration strategies on sensitive areas. Research has been conducted on one or more of the aspects we will assess, but no single project has addressed all aspects we propose in a single study. A DNR employee will be hired to assist with data collection and analysis. No non-state money will be spent on the project during the funding period.

C. Other Funds Proposed to be Spent during the Project Period: The Project Manager is an employee of the U.S. Geological Survey and will provide in-kind support.

Donna Dustin, Senior Biologist and Cynthia Tomcko, Senior Biologist with the Minnesota Department of Natural Resources will provide in-kind support for data collection and model development. Paul Radonski, Senior Project Consultant with the Minnesota Department of Natural Resources will provide in-kind support for model development.

Laboratory space, assigned to the Project Manager, will be provided in Hodson Hall at the University of Minnesota.

D. Spending History: No previous funding

VII. DISSEMINATION: We will collaborate several people, such as Paul Radomski, Natural Resources Program Coordinator, with the Minnesota Department of Natural Resources who works on a project "Score Your Shore", to disseminate the information to agency managers and lakeshore owners. We will also collaborate with the appropriate Sheriff departments, who have jurisdiction over structures that are anchored in the study lakes.

VIII. REPORTING REQUIREMENTS: Periodic Work Program progress reports will be submitted not later than January 2011, September 2011, January 2012, September 2012, January 2013.

Final Report – August 2013.

IX. RESEARCH PROJECTS: Initial proposal draft sent to Sponsored Projects Administration, University of Minnesota 23 November 2009. A final proposal will be sent to Sponsored Projects Administration, University of Minnesota following revisions related to peer review.

Two masters theses were completed during the course of this project:
Keville, J. Effects of residential shoreline development on near shore aquatic habitat in Minnesota lakes
Lepore, J. Local and cumulative influences of docks on littoral habitat structure

Several presentations related to the project were given in a variety of venues:

Lepore, J., J. Keville, D. Dustin, C. Tomckko, and B. Vondracek . 2011. Cumulative impacts of residential lakeshore development on littoral habitat. 44th Annual meeting of the Minnesota Chapter of the American Fisheries Society, 8-9 February, Sandstone, Minnesota. (Poster)

Lepore, J., J. Keville, D. Dustin, C. Tomko, B. Vondracek. 2011. Cumulative Impacts of Residential Lakeshore Development on Littoral Habitat. Minnesota Water Resources Conference, 18-19 October, St. Paul, Minnesota. (Poster)

Lepore, J. and J. Keville. 2011. Cumulative effects of shoreline development on nearshore habitat. DNR Fisheries Research Meeting, 16-18 November, Cloquet Forestry Center

Keville, J., J. Lepore, D. Dustin, C. Tomko, B. Vondracek. 2012. Cumulative Impacts of Residential Lakeshore Development on Littoral Habitat. 142nd Annual meeting of the American Fisheries Society, 19-23 August, St. Paul, Minnesota. (POSTER)

Lepore, J. and J. Keville. 2012. Cumulative effects of shoreline development on nearshore habitat. Department of Natural Resources, Fisheries Research Winter 2012 meeting, Lake Itasca Biological Station, 25-26 October

Lepore, J, J. Keville, D. Dustin, C. Tomcko, and B. Vondracek. 2012. Cumulative impacts of lakeshore residential development on littoral habitat. Minnesota Water Resources Conference, 16-17 October 2012, St. Paul, Minnesota. (Poster)

Lepore, J. A., J. R. Keville, and B. Vondracek. 2013. Localized and cumulative impacts of lakeshore residential development on littoral habitat. Annual meeting of the Minnesota Chapter of the American Fisheries Society, 12-13 March, St. Cloud, Minnesota.

Attachment A: Budget Detail for 2010 Projects - Summary and a Budget page for each partner (if applicable)

Project Title: *Assessing Cumulative Impacts of Shoreline Development*

Project Manager Name: *Bruce Vondracek*

Trust Fund Appropriation: $ *300,000*

1) See list of non-eligible expenses, do not include any of these items in your budget sheet

2) Remove any budget item lines not applicable

2010 Trust Fund Budget	**Result 1 Budget:**	**Amount Spent** *(6/30/13)*	**Balance** *(6/30/13)*	**Revised Result 2 Budget 01/13/2011**	**Amount Spent** *(6/30/13)*	**Balance** *(6/30/13)*	**Revised Result 3 Budget 09/15/20111**	**Amount Spent** *(6/30/13)*	**Balance** *(6/30/13)*	**TOTAL BUDGET**	**TOTAL BALANCE**
	Assess near-shore, in-water habitat on lake ecosystems			Assess impacts of shoreline development on near-shore habitat			Assess impacts of shoreline development on near-shore habitat				
BUDGET ITEM											
PERSONNEL: wages and benefits *(List individual names, amount budgeted and %FTE; add rows as needed)*											
Research Assistant (MS) Keville	8,816	8,816	0	79,343	79,343	0	17,632	4,547	13,085	105,791	13,085
Research Assistant (MS) Lepore				54,752	54,752	0	17,584	5,788	11,796	72,336	11,796
Civil Service hourly - Alex Gee								5,983	-5,983	0	-5,983
Undergraduate Research Assistant				11,880	6,882	4,998				11,880	4,998
Research Fellow Vinje				60,863	60,863	0	20,575	4,935	15,640	81,438	15,640
~~**Contracts**~~											
~~**Professional/technical** *(MN DNR NR Speialist (6L) assist in data collection, data analysis, and model development)*~~				~~60,863~~			~~20,575~~			~~81,438~~	~~81,438~~
Supplies *(list specific categories)*											
Dip nets				400		400				400	400
Thermo Scientific* Nalgene* Transparent Polymethylpentene Jars ~$18.00/jar				2,717	2,329	388				2,717	388
Alcohol to preserve fish and macroinvertebrates				500		500				500	500
Travel expenses in Minnesota											
Mileage for University of Minnesota vehicle in car pool of the Minnesota Cooperative Fish and Wildlife Research Unit @$0.50/mile				21,438	15,210	6,228				21,438	6,228
Per diem @ $50/day reimbursed for actual cost per University policy				3,500	3,500	0				3,500	0
COLUMN TOTAL	**$8,816**	**$8,816**	**$0**	**$235,393**	**$222,879**	**$12,514**	**$55,791**	**$21,253**	**$34,538**	**$300,000**	**$47,052**

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

To be completed…

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 Resources'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.

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Introduction

Littoral habitat is a critical component of lake ecosystems. Defined by the extent 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 related to 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. 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 supplement 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.

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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 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.

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

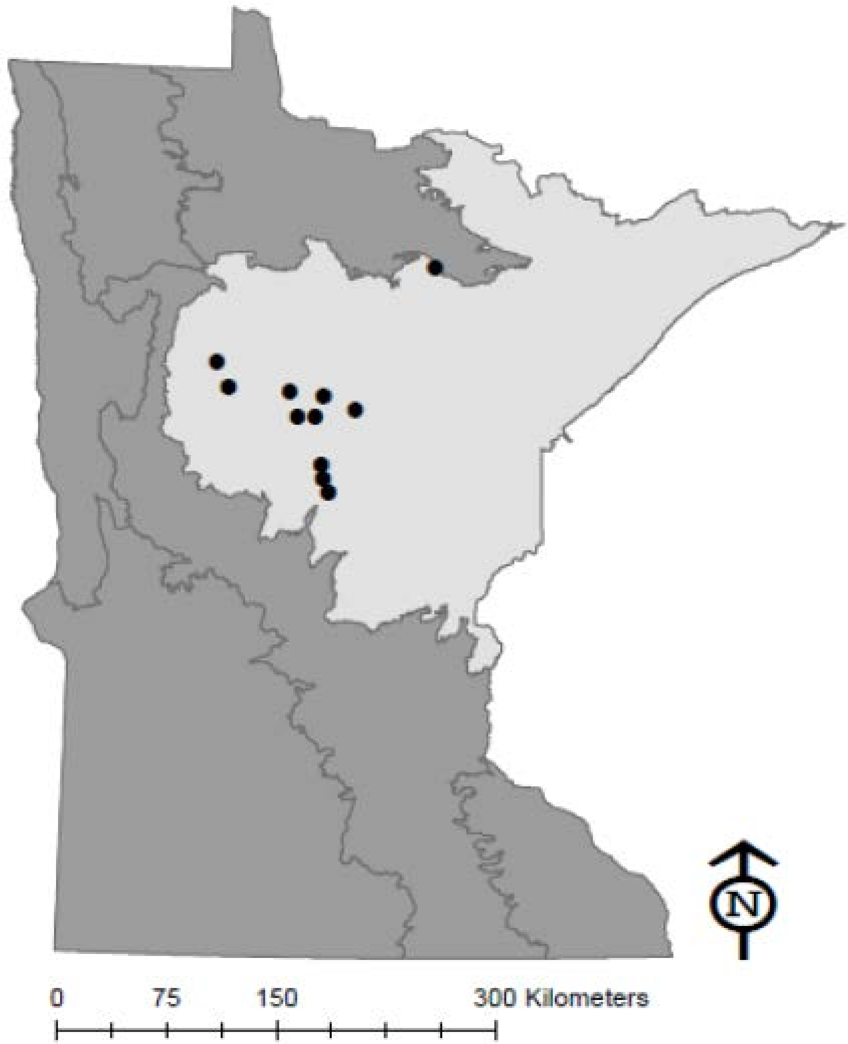

Figure 1. Locations of 10 study lakes within the Northern Lakes and Forests Ecoregion of Minnesota (modified from Lepore 2013).

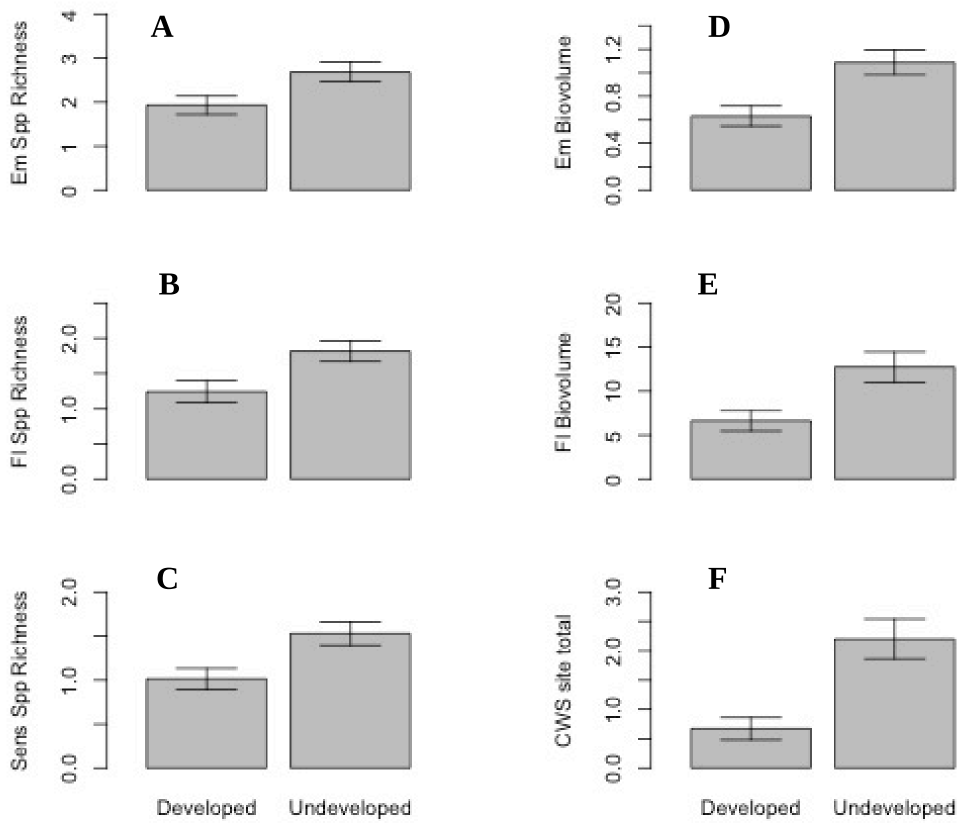

Figure 2. Mean values for littoral habitat response variables that were significantly different between developed and undeveloped site types (Mann-Whitney-Wilcoxon, alpha=0.05). Whiskers represent 95% confidence intervals. **A**. Mean emergent species richness. **B.** Mean floating-leaf species **C.**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

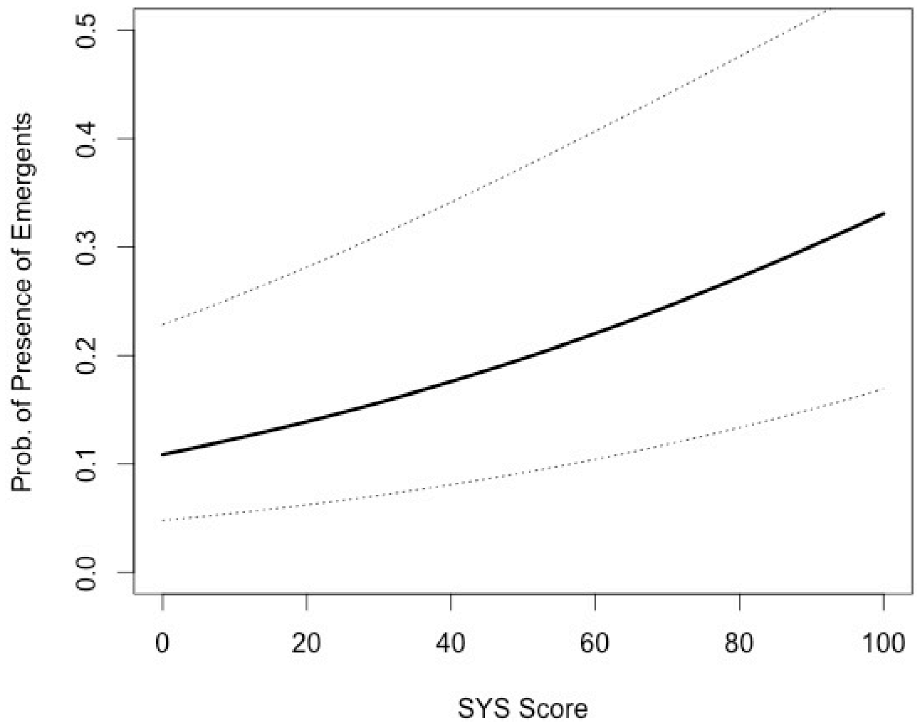

Figure 3. Probability of presence of emergent macrophytes with SYS from best-supported model estimates. Dotted lines represent 95 % confidence intervals. Substrate was set to fine and the mean value for site floating–leaf biovolume was used to obtain the estimates.

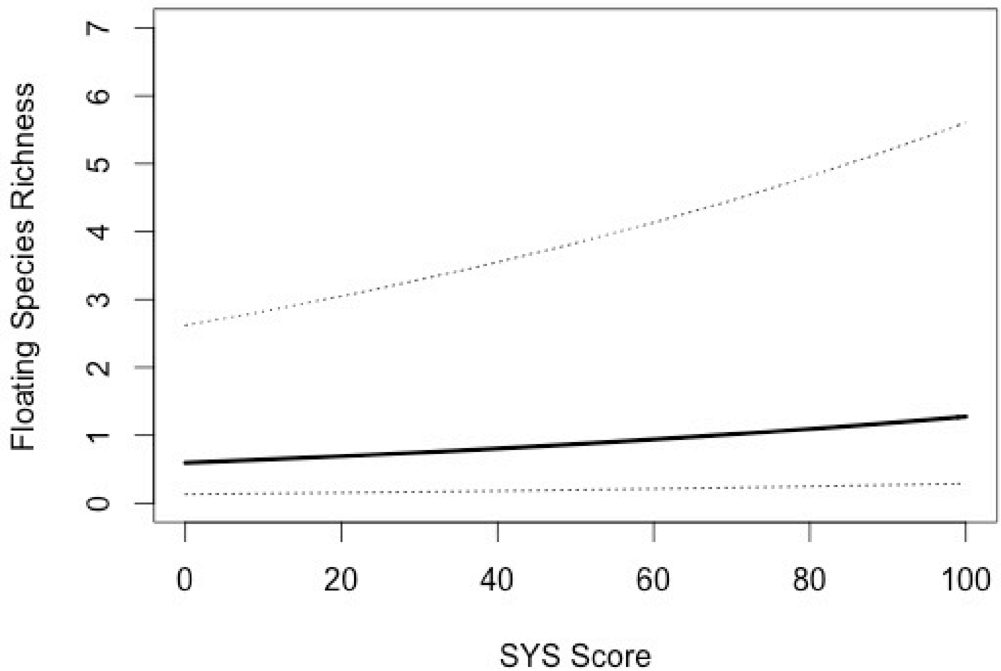

Figure 4. Model predictions for floating leaf species richness. Substrate type was set at fine. The solid line represents estimates from the best-supported model for floating-leaf species richness with SYS score. Dotted lines represent 95% confidence intervals.

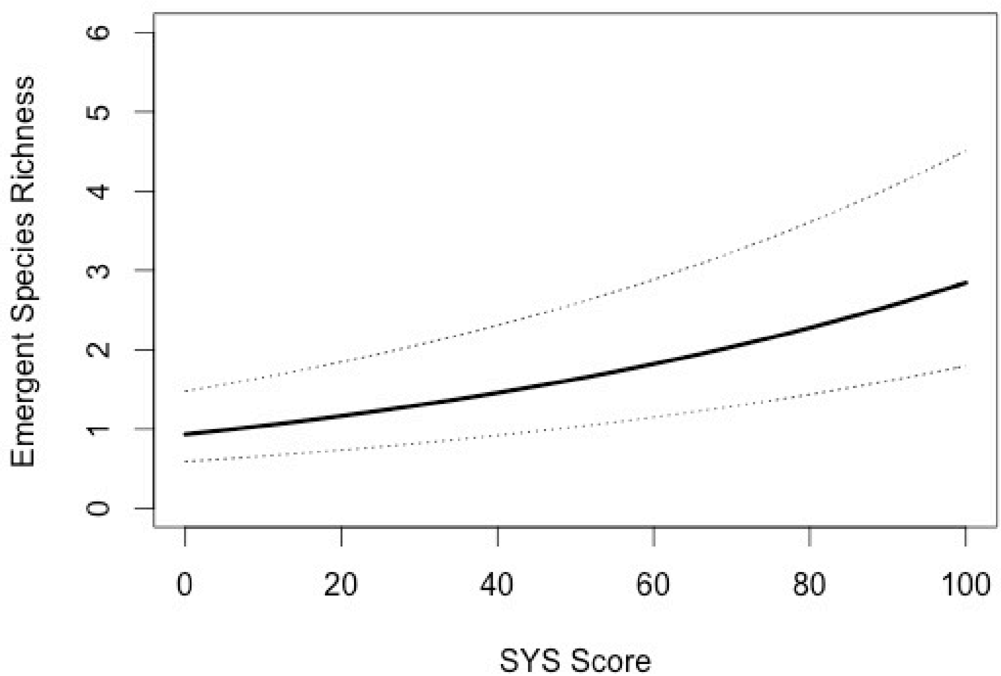

Figure 5. Model estimates from the best-supported model for emergent species richness with SYS score. Substrate was set to fine. Dotted lines represent 95% confidence intervals.

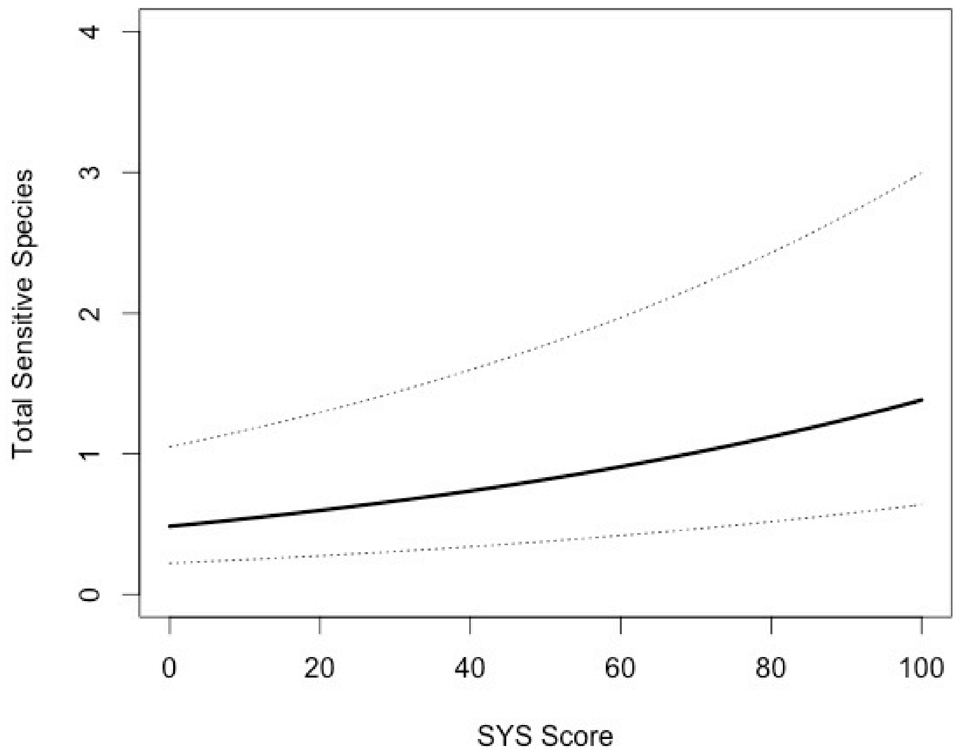

Figure 6. Model estimates from the best-supported model of sensitive species richness with SYS score. Substrate was set to fine. Dotted lines represent 95% confidence intervals.

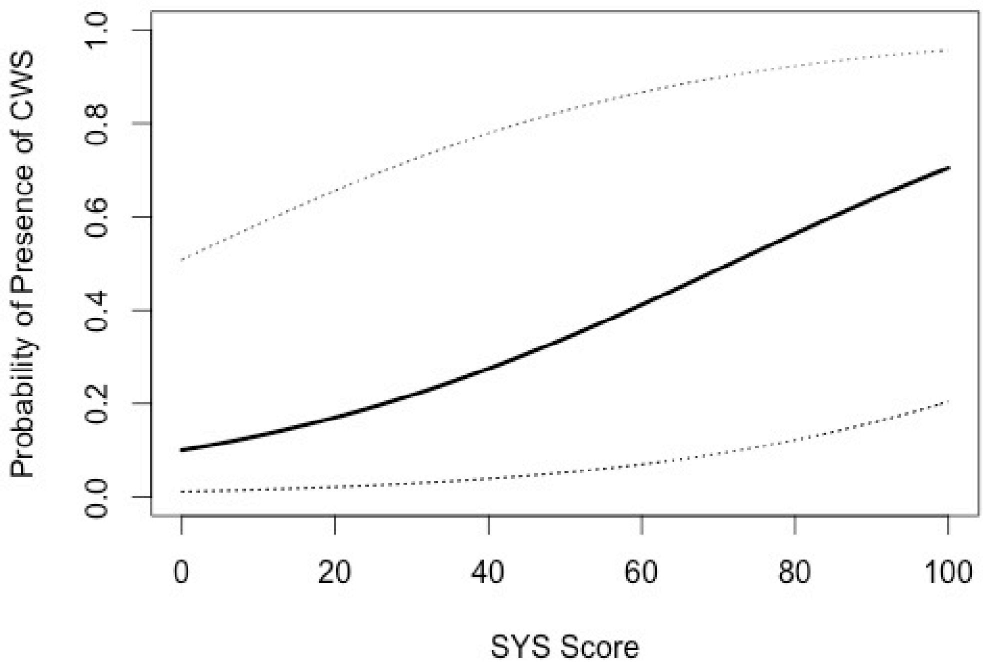

Figure 7. Model estimates for the probability of presence of CWS at a site as SYS score increases. Dotted lines represent 95 % confidence intervals.

Local and Cumulative Influences of Docks on Littoral Habitat Structure

A Thesis
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

Jessie Lepore

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Bruce Vondracek

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Abstract

Littoral habitat is a critical component of lake ecosystems. Aquatic macrophytes and coarse woody structure provide refuge, foraging area, and spawning substrate for many fish species. The expansion of residential development along Minnesota lakeshores has led to substantial habitat modification, and is considered a threat to lake fish communities. Previous studies have linked lakeshore development to reductions in abundance of aquatic vegetation and coarse woody structure; however, few studies have quantified the specific influence of docks on aquatic habitat structure. We assessed coarse woody structure and three measures of macrophyte abundance across three scales of development in 11 Minnesota lakes, using docks as an index of development. All four structural habitat components were significantly influenced by distance to the nearest dock structure. Coarse woody structure and emergent and floating-leaf vegetation were reduced at sites where docks were present. Site-level abundance of coarse woody structure and presence of emergent species were significantly and negatively related to lake-wide dock density, indicating that these habitat components are particularly vulnerable to development. These findings suggest that management of lake fish habitat should address both local and lake-wide scales of development. In addition, dock size restrictions could minimize impacts to critical habitat structure.

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Introduction

Littoral habitat complexity supports lake fish communities by providing critical structure for fish assemblages and their prey. More complex, structurally heterogeneous habitats generally support higher species diversity across lakes (Eadie and Keast 1984) and within lakes (Weaver et al. 1997, Jennings et al. 1999, Pratt and Smokorowski 2003). Large substrate particles and coarse woody structure (CWS; Newbrey et al. 2005) increase surface area for colonization by bacteria, periphyton, and macroinvertebrates (Schmude et al. 1998), and serve as spawning substrate for many northern freshwater fishes (Smokorowski and Pratt 2007). CWS with complex branching patterns offers refuge for small and juvenile fishes (Newbrey et al. 2005). High densities of submerged wood support fish species richness and centrarchid abundance (Barwick 2004). Similarly, the diverse array of growth forms exhibited by emergent, submerged, and floating-leaf macrophytes enhances spawning, refuge, and foraging opportunities for littoral fishes. Young-of-the-year fish, in particular, rely on densely vegetated areas for protection (Weaver et al. 1997). By influencing prey densities (Crowder and Cooper 1982) and predator-prey interactions (Savino and Stein 1982), macrophyte abundance plays an important role in fish growth.

Reductions in littoral habitat structure have been associated with negative impacts to fish communities. A number of studies have examined the effects of littoral CWS depletion on fish community structure (Sass et al. 2006, Roth et al. 2007), lake food web interactions (Helmus and Sass 2008, Ahrenstorff et al. 2009), and black bass *Micropterus spp.* nest site selection (Hunt and Annett 2002; Lawson et al. 2011). The removal of littoral CWS exerts complex effects on lake food webs by affecting prey availability, mortality rates, and reproductive success across multiple trophic levels. Several studies proposed that reductions in littoral CWS due to increased lakeshore development drove observed changes in fish productivity and spatial distribution. CWS loss was attributed to decreased growth of bluegill *Lepomis macrochirus* (Schindler et al. 2000) and largemouth bass *Micropterus salmoides* (Gaeta et al. 2011), reduced nest success among largemouth bass (Wagner et al. 2006), and increased dispersion of littoral fishes (Scheuerell and Schindler 2004). Recent evidence suggests that changes to fish communities associated with littoral CWS removal are not easily reversed by CWS addition (Sass et al. 2012).

Studies documenting the effects of large-scale macrophyte removal on fish communities have largely focused on lakes dominated by invasive plant species, such as Eurasian watermilfoil *Myriophyllum spicatum* (Olson et al. 1998; Valley and Bremigan 2002, Kovalenko et al. 2009); thus, it is less clear how widespread macrophyte removal affects fish populations among lakes with diverse native plant communities. Two studies in Minnesota observed minimal changes in fish abundance and growth in response to widespread chemical removal of submerged aquatic vegetation (Radomski et al. 1995, Pothoven et al. 1999). Nevertheless, aquatic macrophytes contribute to habitat heterogeneity within lakes, and are particularly important in areas lacking other forms of habitat structure.

Previous studies have established that lakeshore residential development modifies littoral habitat through direct and indirect mechanisms. CWS is highly vulnerable to lakeshore residential development because natural recruitment from riparian forest succession is a slow process (Christensen et al. 1996). The clearing of upland trees, as well as direct removal of CWS from the near-shore area rapidly deplete littoral CWS along developed shorelines (Christensen et al. 1996, Jennings et al. 2003, Francis and Schindler 2006, Marburg et al. 2006), and ultimately limit the potential for natural CWS input in the future.

Macrophyte communities are also affected by lakeshore development. Reduced coverage of emergent and floating-leaf macrophytes has been attributed to lakeshore development in Wisconsin (Jennings et al. 2003), Minnesota (Radomski and Goeman 2001, Radomski 2006), Iowa (Bryan and Scarnecchia 1992), and Ontario, Canada (Hicks and Frost 2011). Although submerged macrophyte abundance is generally not affected by lakeshore development (Jennings et al. 2003; Hicks and Frost 2011), overall macrophyte species richness has been shown to decline as lakeshores become more developed (Hatzenbeler et al. 2004, Hicks and Frost 2011).

Past research in this area has typically relied on the presence of a residential cabin, or cabin density, as indices of lakeshore development, whereas other studies defined ‘developed’ shoreline more loosely, as shoreline that has been altered from its natural condition (e.g. Bryan and Scarnecchia 1992). Although cabins provide a clear indication of human presence on the shore, they can be difficult to monitor remotely and are often disconnected from the aquatic zone. In contrast, docks physically occupy the littoral zone and are readily identified from aerial imagery. Due to their association with in-water recreational activities, docks likely represent ‘loci’ of lakeshore development, or areas of highly concentrated disturbance (Radomski et al. 2010). Landowners may intentionally remove littoral CWS and aquatic vegetation to improve swimming and boating conditions near the dock. Unintentional vegetation removal may result from dock shading (Garrison et al. 2005, Campbell and Baird 2009) and motorized water sports (Asplund and Cook 1997). Motorboats, in particular, can limit vegetation by reducing water clarity and physically damaging plants (Liddle and Scorgie 1980, Asplund and Cook 1997).

Few studies have specifically investigated the influence of docks or other in-water recreational structures on littoral habitat. Although previous research has confirmed that docks effectively block sunlight and directly limit aquatic plant growth in Wisconsin (Garrison et al. 2005) and Florida (Campbell and Baird 2009), these studies did not investigate impacts extending beyond the footprint of the dock structure. The only study to quantify dock-related impacts to littoral habitat on Minnesota lakes derived vegetation data from aerial photographs (Radomski and Goeman 2001). To date, no field investigations have defined the influence of residential dock structures on surrounding aquatic habitat.

We assessed four components of littoral habitat structure (CWS and three measures of macrophyte abundance) in relation to lakeshore development, which was defined by the presence of an in-water dock. Relationships were examined across three spatial scales (*proximity, site-level,* and *lake-wide*) to meet the following objectives:

1) *Proximity*: Define the relationship between aquatic habitat structures and distance to the nearest dock. 2) *Site-level:* Compare littoral habitat structure between developed and undeveloped sites. 3) *Lake-wide:* Investigate relationships between lake-wide development density and littoral habitat structure.

This research is part of a larger project investigating the cumulative impacts of lakeshore residential development on macrophyte and fish communities across a larger group of Minnesota lakes. Thus, I will relate my findings to the broader context of the project, as well as other relevant studies.

Methods

Lake selection

Lakes with similar limnological and watershed characteristics were chosen to isolate the effects of lakeshore development on littoral habitat structure. We selected lakes managed by the Minnesota Department of Natural Resources (MN DNR) which had fish and aquatic plant survey data collected within the past five years. Candidate lakes were located within the Northern Lakes and Forests (NLF) Ecoregion of Minnesota (Figure 1), a lake-rich area with widespread lakeshore development. We selected relatively small (40-200 ha) and mesotrophic lakes with at least 80 percent forested watersheds; these criteria are characteristic of recreational development lakes within the NLF Ecoregion (Heiskary and Wilson 2005). We used geo-referenced aerial imagery from the U. S. Department of Agriculture Farm Service Agency to estimate dock densities across all candidate lakes in the region. Dock density was calculated by dividing lake-wide dock counts by shoreline length. The lakes were ordered from undeveloped (< 1 dock/km shoreline) to highly developed (70 docks/km) and binned by quintiles. Six lakes were drawn from each grouping to obtain a set of 30 lakes spanning a range of development densities. These 30 lakes were involved in the larger research project assessing fish and plant communities. A representative subset of 12 lakes was selected for this study (Table 1). The study lakes belong to similar ecological lake classes with fish communities dominated by northern pike *Esox lucius* and bluegill (Schupp 1992). Two of the study lakes were undeveloped; therefore, dock-related habitat sampling was conducted on only 10 lakes. After the completion of lake selection and the commencement of the field season, we determined that one of the 12 study lakes did not meet all of the selection criteria. Located in a different region of the state and belonging to a dissimilar lake class, South Twin was inadequate for comparison with the other study lakes; hence, we eliminated it from the study. Sample sizes reported in the remainder of the manuscript were adjusted to reflect this change.

Field site selection

We used ArcGIS to divide the shoreline of each study lake into 20m segments, or "sites." Recent aerial photographs were used to classify shoreline sites as "developed" or "undeveloped". Candidate developed sites contained docks which were simple in shape and relatively isolated (at least 20m from a neighboring dock) to avoid sampling in areas influenced by an adjacent dock. Candidate undeveloped sites were also located at least 20m from neighboring dock structures. From these candidate sampling sites, we randomly selected five developed sites from each of the 9 developed study lakes. Five additional dock sites were sampled within the two largest developed lakes (Gilbert and Girl). In total, 55 developed sites were chosen for habitat sampling. Because undeveloped sites were expected to exhibit more variation than developed sites, we randomly selected a minimum of 10 undeveloped sites within each of the 11 study lakes. Fourteen undeveloped sites were selected from Gilbert and Girl. Thus, we selected a total of 118 undeveloped sites for sampling.

Field methods

Habitat sampling: Developed sites

Habitat data were collected during July and August of 2012. We navigated to each pre-determined site location using a handheld GPS unit and documented habitat structure along transects spaced at fixed distances from the dock (Figure 2). Transects were oriented parallel to the dock and extended from the shoreline to the end of the dock; thus, transect length was equivalent to the length of the dock over the water. Sampling transects began at the edge of the dock (distance = 0m) with subsequent transects spaced every meter until a distance of eight meters was reached. If a boat lift, boat, or other structure extended from the edge of the dock proper, sampling began at the edge of the ancillary structure. As a result, transects were not always linear, but conformed to the unique shape of the recreational structure. Nine transects were surveyed on each side of the dock, for a total of 18 transects per developed site.

Coarse woody structure (CWS) was defined as any piece of wood ≥ 10cm in diameter anywhere along the trunk and ≥ 60cm in length. We counted every piece of CWS intersecting each transect and assigned each piece a qualitative complexity score from 1 to 5. A “1” indicates the simplest structural type, typically a simple log with no branches. A “5” indicates a highly complex, branchy tree exhibiting fourth-order branching patterns (e.g. Newbrey et al. 2005) along the majority of the trunk. If a single piece of CWS crossed more than one transect line, it was documented each time; however, we also obtained CWS counts within the entire site.

We recorded water depth, substrate type (i.e. sand, cobble, etc.), and visual macrophyte biovolume estimates at points along each sampling transect using a buoyant circular sampling ring (50cm diameter) constructed from foam pipe insulation. The sampling points began at the shoreline and were spaced every 3m from shore until the end of the dock was reached. Therefore, docks over 6m long received sampling along more than three points per transect. Most docks were sampled at three or four depths, with the deepest sampling points aligned with the end of the dock. Macrophyte biovolume was estimated for each of three structural categories: emergent, submerged, and floating-leaf. Emergent biovolume was assigned integer values from 0 to 5 based on the following stem counts: 0: absent (0), 1: sparse (< 4 stems), 2: 4-9 stems, 3: 10-19 stems, 4: 20-30 stems, 5: dense (>30 stems). Submerged biovolume was recorded as a percentage from 0 to 100 in increments of 5 percent, based on the density of vegetation within the water column. In areas where vegetation was sparse, 1 percent biovolume was reported. Coverage of floating-leaf vegetation was recorded as the percentage of the sampling ring covered by floating leaves. Estimates of floating-leaf cover could range from 0 to 100 percent in increments of 5 percent, although 1 percent was noted for areas with minimal cover.

Habitat sampling: Undeveloped sites

The sampling approach at undeveloped sites was similar to that used at developed sites, in which macrophyte sampling was conducted along transects oriented perpendicular to the shoreline. To reduce bias, the first sampling transect was placed at the GPS location and subsequent transects were located to the right of the first transect. Three macrophyte sampling transects were spaced approximately 6.7m apart and extended from 0.3 to 0.9m water depth. Macrophyte sampling points were placed along each transect at depths of 0.3, 0.6, and 0.9m. Macrophyte biovolume was visually estimated in each of the three structural categories following the methods described for developed sites. We counted each piece of CWS within the sampling area defined by the macrophyte transects, which covered approximately 20m of shoreline.

Near-shore Fish Sampling

As part of the larger research project, near-shore fish assemblages were sampled in 29 lakes during the summers of 2011 and 2012. Thirteen lakes were sampled in 2011, and the remaining 16 lakes were sampled in 2012. Fish were collected following the sampling protocol as per the fish-based index of biotic integrity for Minnesota lakes (Fish IBI; Drake and Pereira 2002, Drake and Valley 2005). Each lake was sampled at 10 or more random sites spaced equal distances around the shoreline. At each site, fish were collected along 30m of shoreline using a combination of electroshocking and shoreline seining. We made two passes with a backpack electroshocker parallel to shore, each covering a width of about 1.5m. One pass was made in shallow water, close to the shoreline; the second pass was made in deeper water (approximately 75-100 cm), adjacent to the first sampling pass. Where possible, a 15ft or 50ft bag seine was hauled along 30m of shoreline and out to the length of the seine from shore or maximum wadeable depth (approximately 1.3m). Sites with soft bottoms or steep drop-offs were sampled by electroshocking from the boat. The abundance of each fish species was recorded for each site.

Near-shore fish abundance data were compiled with the most recent fish biomass data from standardized gillnet and trapnet surveys collected by the MN DNR. These data were used to calculate a Fish IBI score for each study lake.

Statistical Analyses

Overview

A number of statistical models were used to examine the influences of development and other non-anthropogenic factors on near-shore habitat structure at the local scales (Table 2). Each structural habitat component (CWS, emergent, submerged, floating-leaf biovolume) was included as a response variable in at least one model. All mixed models included random effects, which were used to account for variation between the sampling units; these random effects are associated with the model's error term (Zuur et al. 2009). Generalized linear mixed models (GLMMs) and generalized linear models (GLMs) were used for response variables with specific distributions, such as presence/absence data (binomial) and count data (Poisson). Generalized models use link functions to relate the explanatory variables to the response variable. Other data transformations, square-root and ln(+1), were applied to linear mixed model (LMM) responses to satisfy the analytical assumptions, which were verified by graphical inspection of residual plots.

Models were generated for five different response variables relating to aquatic habitat structure: presence/absence of coarse woody structure (pCWS), abundance of coarse woody structure (CWS_Total), presence/absence of emergent biovolume (pEm), submerged biovolume (Sub) and floating-leaf biovolume (Float). The two binary response variables, pCWS and pEm, were examined because both CWS and emergent vegetation were infrequently observed near docks; only 6 percent of the dock sampling transects contained CWS, and emergent species were present in 31 percent of the transects. The second CWS response variable, “CWS_Total,” corresponded to site-level CWS abundance. CWS structural complexity was not examined because the majority of documented CWS consisted of simple logs (complexity=1). Submerged and floating-leaf biovolume were treated as numeric variables.

The three explanatory variables used in CWS models were related to development: distance to the nearest dock (Dist), site type (Type), and lake-wide dock density (Docks_km). Dist and Docks_km were treated as continuous, numeric variables. Type was a two-level factor consistent with the shoreline site classification in which sites were “developed” or “undeveloped”. Macrophyte models incorporated development characteristics, as well as several other covariates, to explain variation in the responses. Measures of macrophyte presence or abundance, pEm, Sub, and Float, were included as predictors to examine potential competitive or mutualistic interactions between macrophyte structural types. Water depth (Depth) and substrate texture (Substrate) were included as other potential sources of variation. Depth, recorded in meters, was treated as a numeric variable. Substrate was analyzed as a four-level factor based on gross particle size differences (coarse, mix, sand, fine) among substrate types; for example, boulder, gravel, and cobble substrates were considered “coarse”, whereas substrates such as silt, clay, and muck were classified as “fine.” Combinations of coarse and fine substrates (e.g., cobble and silt) were designated as “mix.” Sand was distinguished from other fine substrates not only because it is associated with a distinct macrophyte community, but also because it is a highly desirable substrate for lakefront property.

Aquatic Habitat Structure and Proximity to Docks

A binomial GLMM was used to investigate the relationship between presence of coarse woody structure (pCWS) and distance to the nearest dock. A nested random effect was used to account for variation between sampling sites within study lakes.

Mixed models were used to examine relationships between aquatic macrophyte responses (pEm, Sub, Float) and distance to the nearest dock (Dist). A binomial GLMM was used to model pEm, and LMMs were used to model Sub and Float, which were square-root transformed. All three models included a nested random effect.

We also applied mixed models to identify key drivers of local macrophyte abundance. Each of the three macrophyte responses were modeled in response to a suite of physical, biological, and development characteristics. For example, the full model for pEm response included the following five explanatory variables: Dist, Sub, Float, Substrate, and Depth. Each model was refined via backward elimination, which uses Akaike's Information Criterion (AIC) and *P*-values to arrive at the best model.

Site-Level Comparisons of Habitat Structure

We used nonparametric statistics and mixed models to compare aquatic habitat structure between developed and undeveloped sites. Developed sites were standardized for comparison to undeveloped sites by eliminating samples from water depths less than 0.3m or greater than 0.9m. Mean submerged and floating-leaf biovolume was calculated for each site. We compared CWS_Total, Sub, and Float responses across Type using the Mann-Whitney *U*-test. Two high outliers (CWS_Total > 90) from Portage lake were removed from the CWS analysis to facilitate site-level comparisons. LMMs were used to examine Sub and Float in relation to Type and Substrate; these models included a random lake effect. Both macrophyte responses were transformed by ln(+1). Sub and Float were compared across substrate categories using the Kruskal-Wallis test.

Presence of emergent vegetation (pEm) was analyzed using Chi-square contingency tables. We constructed a 2x2 contingency table to examine pEm across Type. A 2x8 contingency table was used to examine pEm across unique combinations of Substrate and Type (e.g. coarse/undeveloped, fine/developed).

Cumulative Effects of Lake-wide Development on Habitat Structure

We used analysis of covariance (ANCOVA) to investigate cumulative effects of lake-wide development on site-level aquatic habitat structure (Table 3). Data from all 11 study lakes were used to examine trends across dock densities ranging from 0.3 to 46 docks per shoreline kilometer. Models were constructed for each of four response variables: abundance of coarse woody structure (CWS_Total), presence of emergent vegetation (pEm), mean submerged biovolume (Sub), and mean floating-leaf cover (Float). Each initial model included an interaction between site type (Type) and dock density (Docks_km). If the interaction term was not statistically significant ($\alpha = 0.05$), we eliminated the interaction term and fitted a model with both individual explanatory variables.

Results

Aquatic Habitat Structure and Proximity to Docks

Presence of CWS was positively related to distance to the nearest dock (Z= 3.32, P= 0.001; Figure 3), indicating that the probability of CWS presence increased with separation from docks. The model intercept was also statistically significant (Z= -9.46, P <0.001), suggesting that at the edge of a dock (Dist = 0m), the probability of CWS was significantly different from zero.

Presence of emergent species exhibited a positive and significant relationship with distance to the nearest dock (Z= 11.76, P <0.001; Figure 4A). The model intercept was significantly different from zero (Z= -7.43, P <0.001), indicating a 9 percent likelihood of emergent species occurrence at the edge of a dock.

Submerged and floating-leaf biovolume were significantly related with distance to the nearest dock. Submerged biovolume had a slight, positive relationship with distance (t= 8.01, df=3177, P <0.001; Figure 4B). The model intercept was significantly different from zero (t= 11.41, df=3177, P <0.001), and estimated to equal 2.3 percent biovolume. Floating-leaf biovolume was also positively associated with distance to the nearest dock (t= 13.00, df=3177, P <0.001; Figure 4C). The model intercept was not significantly different from zero (P= 0.16).

Macrophyte responses were not only affected by proximity to docks, but other local physical and biological factors as well. We used AIC to compare the simple proximity models to the more complex local models and found that for each macrophyte response, the complex models, which included Substrate and Depth, accounted for more variation in the response. However, Dist remained a significant explanatory variable in each of the models. Presence of emergent vegetation was significantly related to distance to the nearest dock, floating-leaf cover, substrate texture, and water depth (Table 6). Presence of emergent species was positively related to distance to the dock (Z= 13.35, P <0.001) and negatively associated with floating-leaf cover (Z= -3.03, P= 0.002) and water depth (Z= -17.37, P <0.001). Presence of emergent species was also affected by substrate particle size; emergent species were most common in fine substrates and least common in coarse substrates.

Submerged biovolume was significantly and positively related to distance to the nearest dock (t= 8.92, df=3171, P <0.001; Table 7), presence of emergent species (t= 2.46, df=3171, P <0.001), floating-leaf cover (t= 2.15, df=3171, P= 0.01), and water depth (t= 27.08, df=3171, P <0.001). Submerged vegetation was most abundant in fine substrates and least abundant in coarse substrates.

Floating-leaf biovolume was positively and significantly related to distance to the nearest dock (t= 12.79, df=3171, P <0.001; Table 7), submerged biovolume (t= 7.73, df=3174, P <0.001) and water depth (t= 7.68, df=3171, P <0.001). Floating-leaf cover was negatively related to presence of emergent vegetation (t= -2.98, df=3171, P= 0.003). Floating-leaf biovolume was highest in fine substrates; interestingly, the model coefficients relating to the other three substrate categories (coarse, mix, and sand) were not significantly different from zero ($P \geq 0.05$; Table 7).

Site-level Comparisons of Aquatic Habitat Structure

Site-level CWS abundance was quite variable among study lakes (Table 4). Portage Lake had particularly high CWS densities, with a mean of 14 pieces per site and a maximum of 91 pieces observed at one site. However, the grand mean CWS abundance across all 11 study lakes was 3.2 pieces per site. CWS abundance was significantly related to site-level development, with undeveloped sites exhibiting higher CWS abundance than developed sites (Mann-Whitney *U*-test, W=2137, P=0.04). Mean CWS abundance was 0.73 (SE, 0.15) at developed sites and 1.72 (SE, 0.27) at undeveloped sites (Figure 5).

The presence of emergent species varied significantly with site type (X^2= 8.47, df= 1, P= 0.004). Whereas emergent species were present at only 53% of developed sites, they were present at 74% of undeveloped sites (Figure 6). Presence of emergent vegetation was also significantly related to a combination of substrate texture and site type (X^2= 64.05, df =7, P <0.001; Figure 7). Emergent species were most commonly observed at undeveloped sites with fine substrates (1.0), and absent from developed sites with coarse substrates. Among developed sites, the highest frequency of emergent species was observed at those with fine substrates (0.82). Although presence of emergent species varied greatly with substrate texture, emergent species were more frequently observed at undeveloped sites than developed sites.

Abundance of submerged and floating-leaf macrophytes also varied with site-level development (Figure 8). Mean submerged biovolume was 4.84 (SE, 0.35) at developed sites and 5.96 (SE, 0.40) at undeveloped sites; however, this difference was not statistically significant (Mann-Whitney *U*-test; U= 2201, P= 0.10). Floating-leaf cover varied significantly with site type (Mann-Whitney *U*-test; U= 1791, P= 0.001) with developed sites averaging 5.47 (SE, 1.53) percent cover and undeveloped sites averaging 13.50 (SE, 1.72) percent cover. Substrate texture was an important source of variation in macrophyte abundance (Figure 9). Both macrophyte forms were most abundant at undeveloped sites with fine substrates and least abundant at developed sites with coarse substrates. The highest mean submerged biovolume was 6.76 (SE, 0.45); the lowest mean biovolume was 2.45 (SE, 0.45), which was observed at developed sites with coarse substrate. Submerged biovolume was significantly different across the four substrate categories (Kruskal-Wallis test; H= 52.77, df= 3, $P < 0.001$). The highest floating-leaf cover was 12.20 (SE, 0.91) at sites with fine substrates, which was higher than the mean coverage for the other three substrate categories, even among undeveloped sites (range 1.07 to 2.90). The estimate of mean floating-leaf cover at developed sites with coarse substrates was effectively zero (P= 0.72). Floating-leaf cover varied significantly across all four substrate groupings (Kruskal-Wallis test; H= 76.21, df= 3, $P < 0.001$).

Cumulative Effects of Lake-wide Development on Habitat Structure

Site-wide abundance of coarse woody structure (CWS) was significantly related to the interaction of site type (developed/undeveloped) and lake-wide dock density (Figure 10); CWS abundance within undeveloped sites decreased as lake-wide development increased. The model indicated that at moderately high development densities, approximately 25 docks per kilometer, CWS abundance within undeveloped sites equaled that within developed sites.

Probability of presence of emergent vegetation was affected by a combination of site type and lake-wide dock density (Figure 11). Both site types were negatively related to dock density (Z= -2.14, P= 0.03); however, probability of emergent presence was approximately 0.07 higher at undeveloped sites than developed sites regardless of lake-wide development density.

Submerged and floating-leaf biovolume were not related to either the interaction term, Type*Docks_km, or dock density (*P* >0.05), suggesting that these growth forms may be less sensitive to development than emergent macrophyte species.

Discussion

Local Effects of Docks on Habitat Structure

Human activities associated with residential docks significantly influence natural aquatic habitat structure. Reductions in the presence and abundance of critical habitat components were documented as far as eight meters from docks in this study. Presence of CWS and emergent vegetation, as well as abundance of submerged and floating-leaf macrophytes, were reduced within this 8m zone. These findings are consistent with the 7.6m 'habitat impact zone' suggested by Radomski et al. (2010), which was based on vegetation removal guidelines for recreational development lakes in Minnesota. Dock impacts to habitat could extend beyond eight meters; however, our sampling efforts did not allow us to determine the full extent of the influence. Nevertheless, our findings suggest that habitat impacts may increase with dock size; assuming natural structure is limited beneath the dock footprint, our localized habitat models imply that increasing dock width would expand the total area of influence. This inference is supported by Radomski and Goeman (2001), who documented reduced coverage of emergent and floating-leaf vegetation in plots with larger docks; however, we did not explicitly test this hypothesis.

Other local factors, such as substrate texture and water depth, were also key drivers of macrophyte biovolume. Presence of emergent species and coverage of submerged and floating-leaf vegetation was consistently highest in areas with fine substrates. Dock-related impacts to aquatic vegetation are likely to be highest at sites with fine substrates simply because aquatic plants are naturally more abundant in such areas. Floating-leaf vegetation was particularly abundant in sites with fine substrates. Substrate is an important feature of lakefront properties; whereas muck is a highly undesirable substrate type, sand is very appealing to potential landowners. Landowners may even augment natural substrates with sand to create artificial beaches (Engel and Pederson 1998). We found that a majority (61%) of the developed sites sampled had sandy substrates; however, a large proportion of undeveloped sites (42%) also contained sand. Although sand was not associated with the highest macrophyte abundance, sandy substrates typically supported higher macrophyte coverage than coarse and mixed substrates. If landowners preferentially develop sandy sites, naturally vegetated areas will be limited, particularly in highly developed lakes. Widespread reductions in macrophyte cover could negatively affect the survival of juvenile fishes, as well as intolerant north temperate fish species, such as the blackchin shiner *Notropis heterodon*, blacknose shiner *Notropis heterolepsis*, and banded killifish *Fundulus diaphanus*, which are strongly associated with dense beds of vegetation (Valley et al. 2010). Although the preferential development of sandy sites could spare impacts to densely-vegetated boggy sites, macrophyte species favoring sandy substrates, such as emergent hardstem bulrush *Scirpus acutus*, would remain at risk. Reductions in the coverage of hardstem bulrush could limit nesting habitat for fishes such as black crappie *Pomoxis nigromaculatus* which are closely associated with the species (Reed and Pereira 2009).

Our findings also suggested that macrophyte structural types are somewhat partitioned by depth zones. Emergent species tend to occupy shallower areas and become less frequent as water depth increases. Conversely, abundance of floating-leaf species increased with water depth. The negative associations between presence of emergent species and floating-leaf biovolume suggest that these growth forms may compete for sunlight. Low-growing, shade-tolerant submerged macrophytes were positively associated with the presence of emergent species and abundance of floating-leaf cover, and became more abundant as water depth increased. This partitioning of macrophyte structural types by depth could influence the sensitivity of macrophyte growth forms to shoreline disturbance. Because emergent species tend to colonize areas nearest the shoreline, they are likely the most vulnerable to development impacts.

Cumulative Effects of Lake-wide Development on Habitat Structure

Our analyses indicated that lake-wide development had a cumulative impact on some forms of aquatic habitat structure. Abundance of CWS, in particular, was significantly related to the interaction between site type and lake-wide dock density such that CWS abundance at undeveloped sites declined with as dock densities increased. CWS abundance at developed sites increased with dock density, although at a slightly lower rate. The reduction in CWS abundance at undeveloped sites could be attributed to land use changes around the lake. For instance, the clearing of shoreline trees for access roads may have limited the natural recruitment process. Additionally, riparian CWS could be depleted by lakeshore residents collecting firewood (Marburg et al. 2006). The increase in CWS abundance in relation to site-level and lake-wide development is puzzling; however, this result may reflect our ability to detect CWS, rather than an accurate pattern of abundance. Whereas detection was particularly difficult in densely-vegetated sites, which were generally undeveloped, CWS was easily observed at developed sites that were cleared of vegetation. Nevertheless, increases in lake-wide development are likely to cause reductions in the overall availability of CWS throughout the littoral zone. Estimates of CWS density, projected from mean abundances for each site type (Table 4), suggested lake-wide CWS density declined rapidly with small increases in lakeshore development. CWS density dropped dramatically between zero and five docks per shoreline kilometer, then remained fairly constant as development increased (Figure 12). Our estimates of lake-wide CWS density were consistent with previous estimates for lakes of similar development densities in Wisconsin (Christensen et al. 1996, Marburg et al. 2006), and upper Michigan (Francis and Schindler 2008). Large-scale reductions to littoral CWS have been attributed to declines in yellow perch *Perca flavescens* (Sass et al. 2006), as well as dietary shifts and reduced growth among largemouth bass (Ahrenstorff et al. 2009). Reduced yellow perch abundance was attributed to limited recruitment and high mortality rates associated with loss of spawning substrate and refuge (Sass et al. 2006, Roth et al. 2007, Helmus and Sass 2008). It is possible that docks offer surrogate habitat structure in the absence of natural CWS; however, a recent study by Lawson et al. (2011) found that largemouth bass nests were consistently located nearer to CWS than they were to docks, even in highly developed lakes with low CWS densities. Reed and Pereira (2009) observed that nest site selection by largemouth bass and black crappie were influenced by development practices along the shore; although nests were rarely found near developed shores, they were located in deeper water than nests adjacent to undeveloped sites. These results, together with our findings, suggest the influences of docks on fish communities are largely negative.

As part of the larger research project, we calculated Fish IBIs for 29 lakes, including the 11 lakes from this study. Macrophyte-based IBIs (Beck et al. 2010) were also calculated for the 11 lakes. IBIs provide a standardized approach for assessing the biological integrity of ecosystems. IBI metrics were selected to be for their sensitivity to anthropogenic disturbance; thus, we expected IBI scores to decrease with dock density. Fish IBI was significantly and negatively related to dock density within the 11 study lakes (Figure 13); for every 1-unit increase in dock density, Fish IBI was predicted to decline by 0.6. Although the larger set of lakes followed a similar trend, the relationship was not statistically significant (P= 0.82). The decline of the Fish IBI across the 11 study lakes was due to an increase in the relative biomass of omnivorous fishes, most commonly bullheads *Ameiurus spp*. Omnivore biomass from trap-net catches was a significant predictor of Fish IBI (R^2= 0.65, P= 0.002); Fish IBI declined with increased omnivore biomass. Omnivore biomass was positively correlated with dock density (Spearman's rho=0.80, P= 0.003). CWS density was not correlated with omnivore biomass, which suggests that other factors associated with development, such as loss of vegetation, reduced water clarity, or fishing pressure could be driving the increase in omnivore productivity. Macrophyte IBI scores were not significantly related to lake-wide dock density; however, we documented significant reductions in the presence of emergent macrophyte species.

The presence of emergent macrophyte species declined with dock density, regardless of whether the site was developed or undeveloped. Abundance of submerged and floating-leaf macrophytes was not significantly related to dock density, suggesting that local factors exert a stronger influence over the coverage of these growth forms. Interestingly, substrate characteristics may account for the lack of response in floating-leaf vegetation. Floating-leaf species dominated sites with fine substrates, which are undesirable for lakefront property; therefore, impacts to floating-leaf cover may have been minimized by development preferences. Submerged macrophytes were least affected by development; site-level development did not significantly affect the abundance of submerged vegetation. This could indicate that submerged growth forms are more tolerant of disturbance than other macrophyte types. Alternatively, submerged species may be overlooked by landowners because they are less conspicuous than highly-visible emergent and floating-leaf species. Similar shifts in macrophyte communities have been reported in Canadian Shield lakes (Hicks and Frost 2011), where declines in emergent and floating-leaf macrophyte coverage were accompanied by increased coverage of submerged vegetation. The loss of emergent vegetation across highly developed lakes could have negative implications for species such as black crappie and other species which nest near emergent macrophyte species.

Conclusion

We documented reduced aquatic habitat complexity across three scales of lakeshore residential development. Our findings illustrate the importance of managing fish habitat across multiple scales. The site-level and lake-wide relationships between docks and habitat structure are consistent with the results of previous studies, which used cabins, rather than docks, as indicators of lakeshore development. This study was the first to quantify relationships between habitat structure and proximity to a dock. Coarse woody structure, presence of emergent species, and floating-leaf cover were significantly related to both local scales of analysis (*proximity* and *site-level*). CWS and emergent species appear to be particularly vulnerable to development; both were negatively related to lake-wide dock density. Reduced natural habitat structure associated with docks may limit the reproductive potential of fishes requiring CWS and/or emergent vegetation, such as black crappie, largemouth bass, and yellow perch. Finally, the distribution and size of docks may play a role in determining fish habitat availability in near-shore areas. Because the same measure of dock density can be achieved through multiple configurations, future research should explore impacts relating to the spatial arrangement of docks. Additional research linking shoreline management practices (e.g. vegetation removal, dock size) to biological outcomes is needed to inform lake management policies.

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Appendix: Tables and Figures

Table 1. Limnological and development characteristics of 11 study lakes. "% WS Disturbed" includes urban, agricultural, and mining land cover types (2001 National Land Cover Dataset).

Lake Name	Lake Class[a]	Surface Area (ha)	% Littoral	Max. Depth (m)	Mean TP (ppb)	Secchi Depth (m)	% WS Disturbed	Devel. Density (Docks/km)
Elk[b]	23	122	23.9	28.4	21	4.0	0.7	0.4
Thistledew[b]	23	130	22.4	13.7	19	5.0	2.8	0.8
Upper Cullen	29	174	69.0	12.2	26	3.0	13.1	7.3
Portage	23	111	34.3	25.6	14	8.0	7.4	13.4
Eagle	25	169	38.7	23.5	19	3.0	10.1	20.3
Gilbert	25	159	56.9	13.7	32	4.5	10.9	20.7
Horseshoe	23	104	30.7	15.5	38	5.0	7.8	24.8
Hand	25	116	48.4	17.4	23	4.0	4.3	24.9
Gladstone	29	175	55.8	11	18	4.0	3.7	34.4
Bass	23	77	22.3	16.8	15	5.0	3.6	39.1
Girl	25	171	63.5	24.7	18	4.0	4.8	46.0

[a] Schupp (1992)
[b] Undeveloped lake included as a reference condition.

Table 2. Summary of mixed models used in local-scale analyses. Presence/absence of coarse woody structure (pCWS), CWS abundance (CWS_Total) and presence/absence of emergent macrophytes (pEm) were examined using generalized linear mixed models (GLMMs) from the lme4 package (Bates et al. 2012). Submerged macrophyte biovolume (Sub), and cover of floating-leaf macrophytes (Float) were examined using linear mixed models (LMMs) in the nlme package (Pinheiro et al. 2012). Explanatory variables included distance to the nearest dock (Dist), site type (Type), categorical substrate texture (Substrate), and water depth (Depth). All models were created in R version 2.15.2.

Response	Explanatory Variables	Model	R Package	Family	Link	Random Effect	# Lakes
pCWS	Dist	GLMM	lme4	Binomial	logit	Lake/Site	9
CWS_Total	Type	GLMM	lme4	Poisson	ln	Lake	9
pEm	Dist	GLMM	lme4	Binomial	logit	Lake/Site	9
	Dist, Float, Substrate, Depth	GLMM	lme4	Binomial	logit	Lake/Site	9
Sub	Dist	LMM	nlme	Gaussian	ln(+1)	Lake/Site	9
	Dist, pEm, Float, Substrate, Depth	LMM	nlme	Gaussian	ln(+1)	Lake/Site	9
	Type, Substrate	LMM	nlme	Gaussian	ln(+1)	Lake	9
Float	Dist	LMM	nlme	Gaussian	sqrt	Lake/Site	9
	Dist, pEm, Sub, Substrate,Depth	LMM	nlme	Gaussian	sqrt	Lake/Site	9
	Type, Substrate	LMM	nlme	Gaussian	sqrt	Lake	9

Table 3. Summary of ANCOVA models used to investigate lake-wide impacts of docks on habitat structure. Response variables examined were: coarse woody structure abundance (CWS_Total), presence/absence of emergent species (pEm), submerged biovolume (Sub), and floating-leaf biovolume (Float). All responses were measured at the site scale. Explanatory variables were both development indices: site type (Type), and dock density, measured in docks per kilometer of shoreline (Docks_km). The asterisk (*) denotes an interaction between two variables. All models were created in R version 2.15.2.

Response	Explanatory Variables	Model	R Package	Family	Link	# Lakes
CWS_Total	Type*Docks_km	GLM	lme4	Poisson	ln	11
pEm	Type*Docks_km	GLM	lme4	Binomial	logit	11
pEm	Type, Docks_km	GLM	lme4	Binomial	logit	11
Sub	Type*Docks_km	LM	nlme	Gaussian	sqrt	11
Sub	Type, Docks_km	LM	nlme	Gaussian	sqrt	11
Float	Type*Docks_km	LM	nlme	Gaussian	sqrt	11
Float	Type, Docks_km	LM	nlme	Gaussian	sqrt	11

Table 4. Site-level and estimated lake-wide density of coarse woody structure (CWS; mean ± SE) for each study lake. Undeveloped (U) sites (n= 10-14 per lake) were located at least 20m from a dock. Each developed (D) site (n= 5 per lake) was centered around a residential dock.

Lake Name	Dock Density (docks/km)	CWS (U) (pcs/site)	CWS (D) (pcs/site)	CWS density (pcs/km)
Elk	0.4	5.70 ± 1.26	NA	284
Thistledew	0.8	8.40 ± 1.24	NA	411
Upper Cullen	7.3	0.30 ± 0.21	0.00 ± 0.00	13
Portage	13.4	21.90 ± 11.58	0.20 ± 0.20	948
Eagle	20.3	1.22 ± 0.62	0.40 ± 0.24	51
Gilbert	20.7	1.79 ± 0.49	0.60 ± 0.22	71
Horseshoe	24.8	1.00 ± 0.37	1.40 ± 0.60	55
Hand	24.9	1.60 ± 0.76	0.80 ± 0.58	73
Gladstone	34.4	0.80 ± 0.49	0.00 ± 0.00	23
Bass	39.1	2.40 ± 0.86	0.20 ± 0.20	74
Girl	46.0	2.07 ± 1.00	1.90 ± 0.48	99

Table 5. Macrophyte biovolume characteristics summarized for each of the 11 study lakes. Emergent biovolume (Em) was measured on a scale of 0-5 in increments of 1. Submerged biovolume (Sub) and floating-leaf cover (Float) were reported to range from 0 to 100 in increments of 5. Undeveloped (U) sites (n=10-14 per lake) were located at least 20m from a residential dock. Each developed (D) site (n=5 per lake) was centered around a residential dock.

Lake Name	Docks/km	Em (U)	Em (D)	Sub (U)	Sub (D)	Float (U)	Float (D)
Elk	0.4	1.96 ± 0.34	NA	4.61 ± 0.28	NA	4.24 ± 2.38	NA
Thistledew	0.8	1.32 ± 0.29	NA	5.56 ± 0.99	NA	3.17 ± 1.11	NA
Upper Cullen	7.3	2.30 ± 0.14	0.96 ± 0.22	5.91 ± 1.00	5.05 ± 0.25	21.79 ± 5.09	2.68 ± 0.46
Portage	13.4	0.57 ± 0.22	0.17 ± 0.11	3.57 ± 0.56	3.33 ± 0.38	0.17 ± 0.12	0.19 ± 0.19
Eagle	20.3	2.13 ± 0.31	0.65 ± 0.46	11.73 ± 1.51	6.20 ± 0.83	23.63 ± 6.15	7.65 ± 1.32
Gilbert	20.7	2.18 ± 0.47	0.29 ± 0.12	5.91 ± 0.59	4.60 ± 0.97	9.09 ± 2.25	5.88 ± 4.54
Horseshoe	24.8	0.77 ± 0.26	0.50 ± 0.45	4.31 ± 0.43	3.44 ± 0.49	4.63 ± 3.20	4.59 ± 4.59
Hand	24.9	0.94 ± 0.18	0.80 ± 0.33	6.26 ± 0.60	5.41 ± 0.37	34.47 ± 7.89	21.25 ± 10.30
Gladstone	34.4	2.81 ± 0.38	0.91 ± 0.67	5.36 ± 0.82	5.82 ± 1.95	13.72 ± 5.19	1.36 ± 0.74
Bass	39.1	0.08 ± 0.04	0.00 ± 0.00	2.76 ± 0.43	2.77 ± 0.72	1.07 ± 0.48	0.00 ± 0.00
Girl	46.0	1.10 ± 0.24	0.68 ± 0.31	7.74 ± 1.63	6.00 ± 0.99	15.10 ± 3.04	5.36 ± 2.91

Table 6. Parameter estimates from the binomial generalized linear mixed model examining presence of emergent species (logit-transformed) in relation to distance to the nearest dock in meters (Dist), floating-leaf macrophyte cover (Float), substrate texture (Substrate: coarse, mix, sand, fine), and water depth in meters (Depth).

	Estimate	SE	*Z*	*P*
Intercept	-2.63	0.44	-5.88	<0.001
Dist	0.32	0.02	13.35	<0.001
Float	-0.02	0.01	-3.03	0.002
Substrate:fine	3.13	0.54	5.80	<0.001
Substrate:mix	1.71	0.34	4.98	<0.001
Substrate:sand	1.64	0.33	5.00	<0.001
Depth	-4.05	0.23	-17.37	<0.001

Table 7. Parameter estimates from linear mixed models examining responses of submerged biovolume (Sub) and floating-leaf macrophyte cover (Float) in relation to a suite of local factors, including distance to the nearest dock in meters (Dist), presence/absence of emergent species (pEm), substrate texture (Substrate: coarse, mix, sand, fine), and water depth in meters (Depth). Submerged biovolume responses were transformed using ln(+1), and floating-leaf cover responses were square-root transformed.

Response	Predictor	Estimate	SE	df	*T*	*P*
Sub	Intercept	0.24	0.113	3171	2.09	0.04
	Dist	0.03	0.004	3171	8.92	<0.001
	pEm	0.07	0.028	3171	2.46	<0.001
	Float	0.002	0.001	3171	2.15	0.014
	Substrate:fine	0.59	0.088	3171	6.73	0.031
	Substrate:mix	0.36	0.055	3171	6.58	<0.001
	Substrate:sand	0.50	0.041	3171	10.1	<0.001
	Depth	0.84	0.031	3171	27.08	<0.001
Float	Intercept	-0.58	0.20	3171	-2.82	0.005
	Dist	0.13	0.01	3171	12.79	<0.001
	pEm	-0.23	0.08	3171	-2.98	0.003
	Sub	0.08	0.01	3171	7.73	<0.001
	Substrate:fine	1.48	0.24	3171	6.03	<0.001
	Substrate:mix	0.30	0.15	3171	1.97	0.049
	Substrate:sand	0.02	0.14	3171	0.13	0.894
	Depth	0.68	0.09	3171	7.68	<0.001

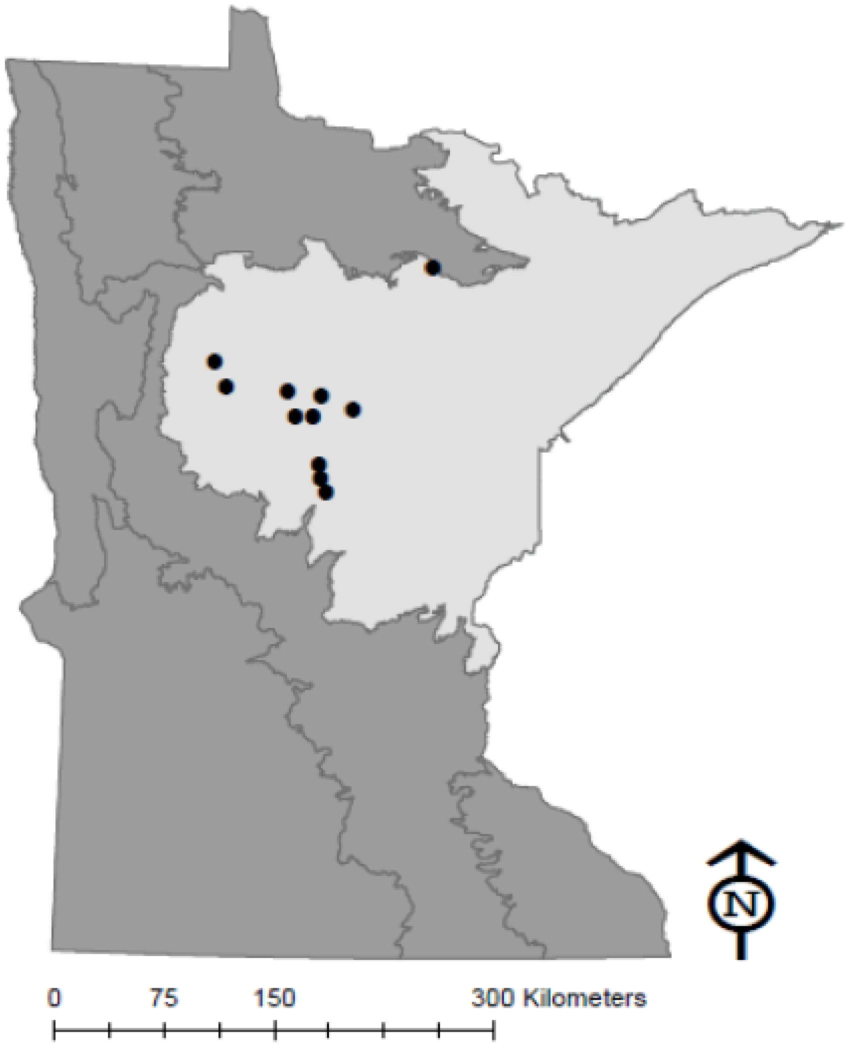

Figure 1. Locations of the 11 study lakes (black circles) within the Northern Lakes and Forests Ecoregion of Minnesota (light gray area).

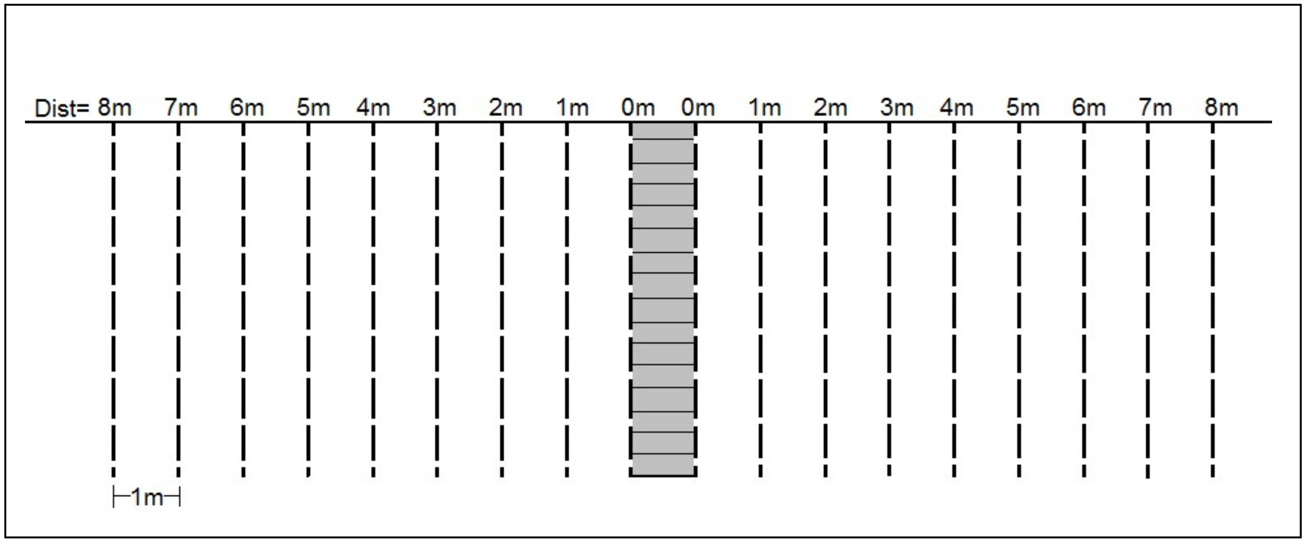

Figure 2. Example habitat sampling scheme with the shoreline located at the top of the figure. Nine sampling transects (dashed lines) were sampled on each side of the residential dock (gray rectangle). Transects began along the edges of the dock (Distance= 0m) and were spaced at 1m intervals until a distance of 8m was reached on either side.

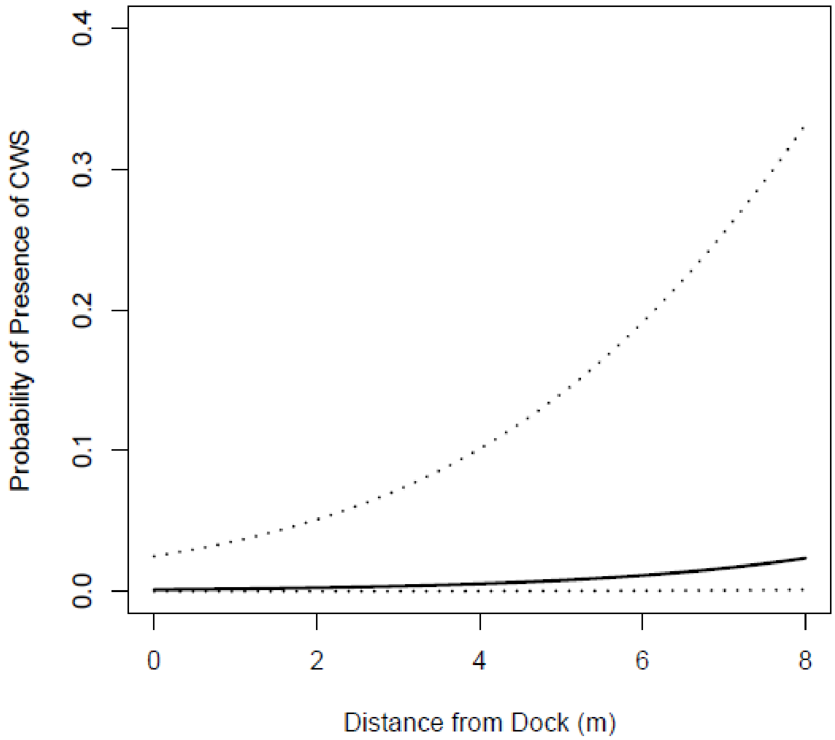

Figure 3. Predicted probability of CWS presence, pCWS, increases with distance to the nearest dock. The mean response is shown by the solid line, and dotted lines indicate 95% confidence intervals.

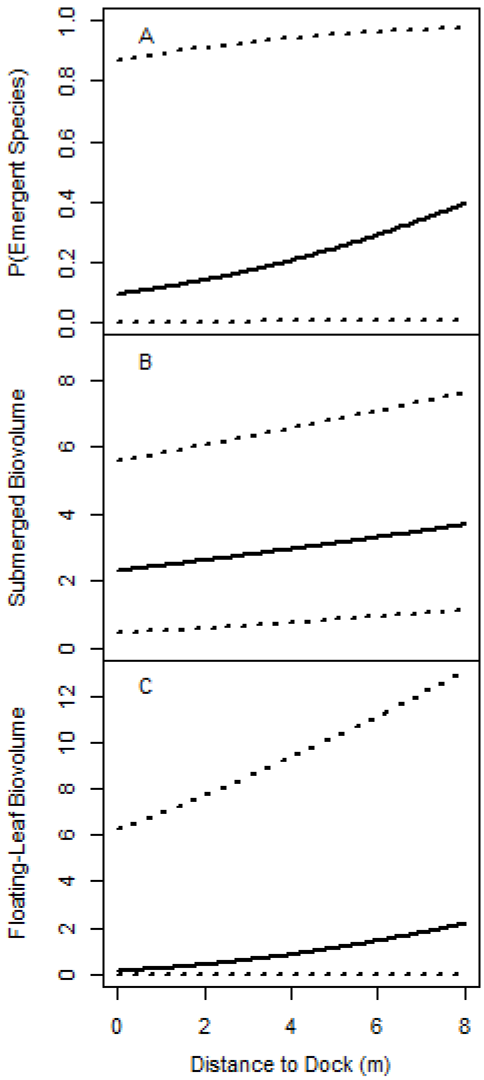

Figure 4. Presence of emergent species (A), submerged biovolume (B), and floating-leaf cover (C) in relation to distance to the nearest dock structure. The solid black lines indicate the model estimates and the dotted lines represent 95% confidence intervals.

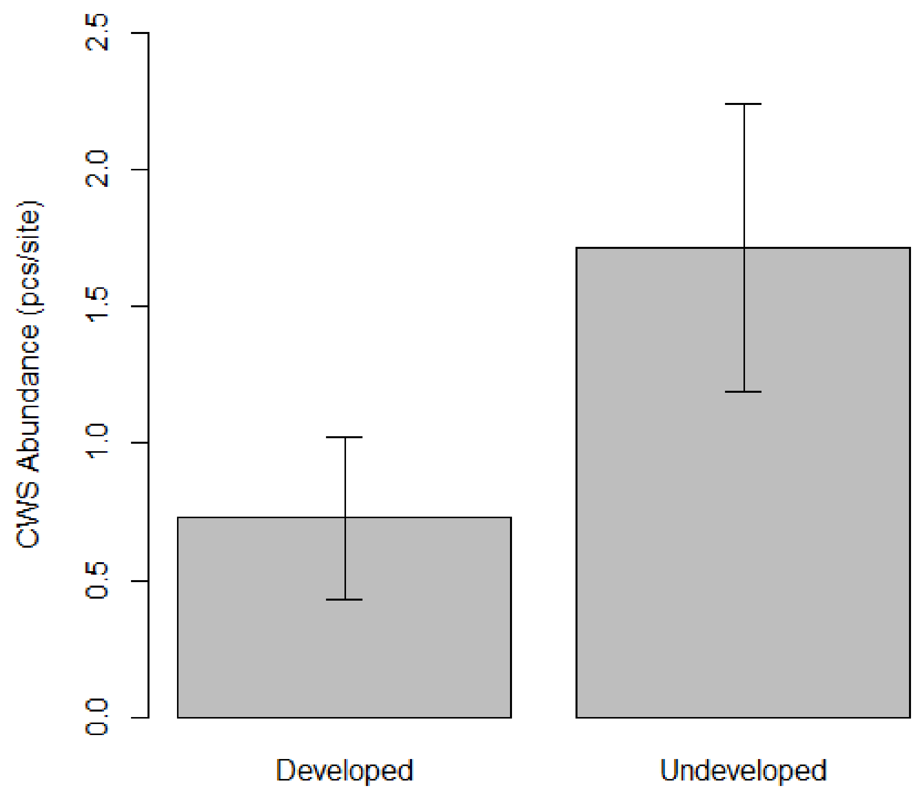

Figure 5. Mean abundance of coarse woody structure (CWS) varied significantly between site types. The mean abundance at developed sites was 0.73 (SE, 0.15) and 1.72 (SE, 0.27) at undeveloped sites. Whiskers indicate 95% confidence intervals.

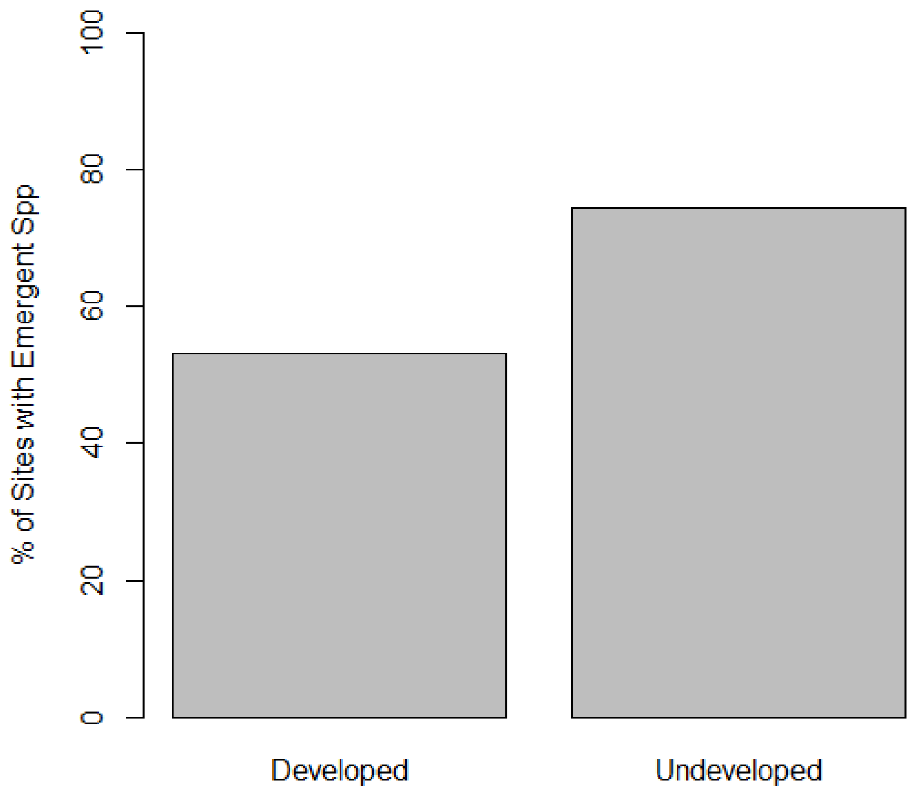

Figure 6. The presence of emergent species varied significantly with site type. Whereas emergent species were present at only 53% of the developed sites sampled, they were present at 74% of undeveloped sites.

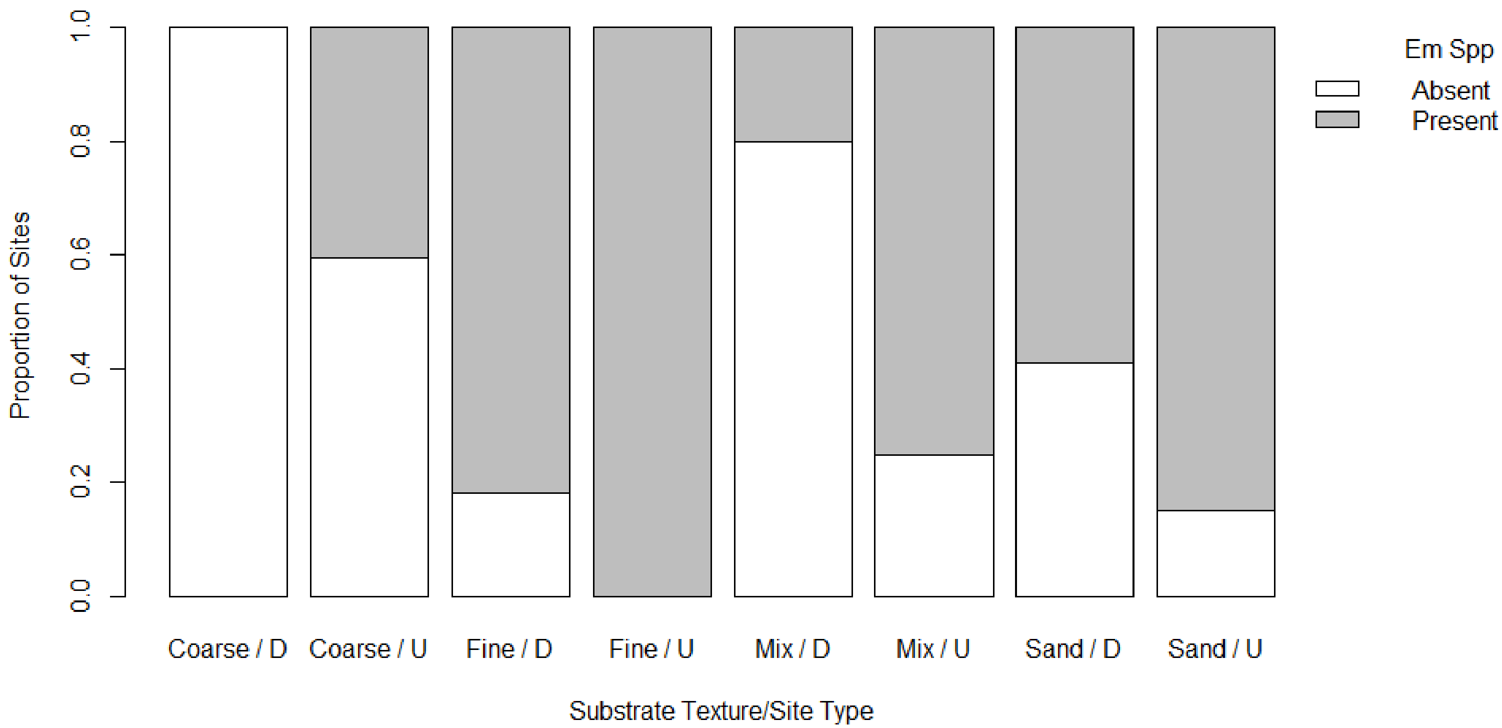

Figure 7. Presence of emergent species varied greatly with substrate texture and site type. Emergent species were present (gray) at all sites with fine substrates, and absent (white) from all sites with coarse substrates. Although presence of emergent species varied with substrate texture, emergent species were more frequently observed at undeveloped (U) sites than developed (D) sites.

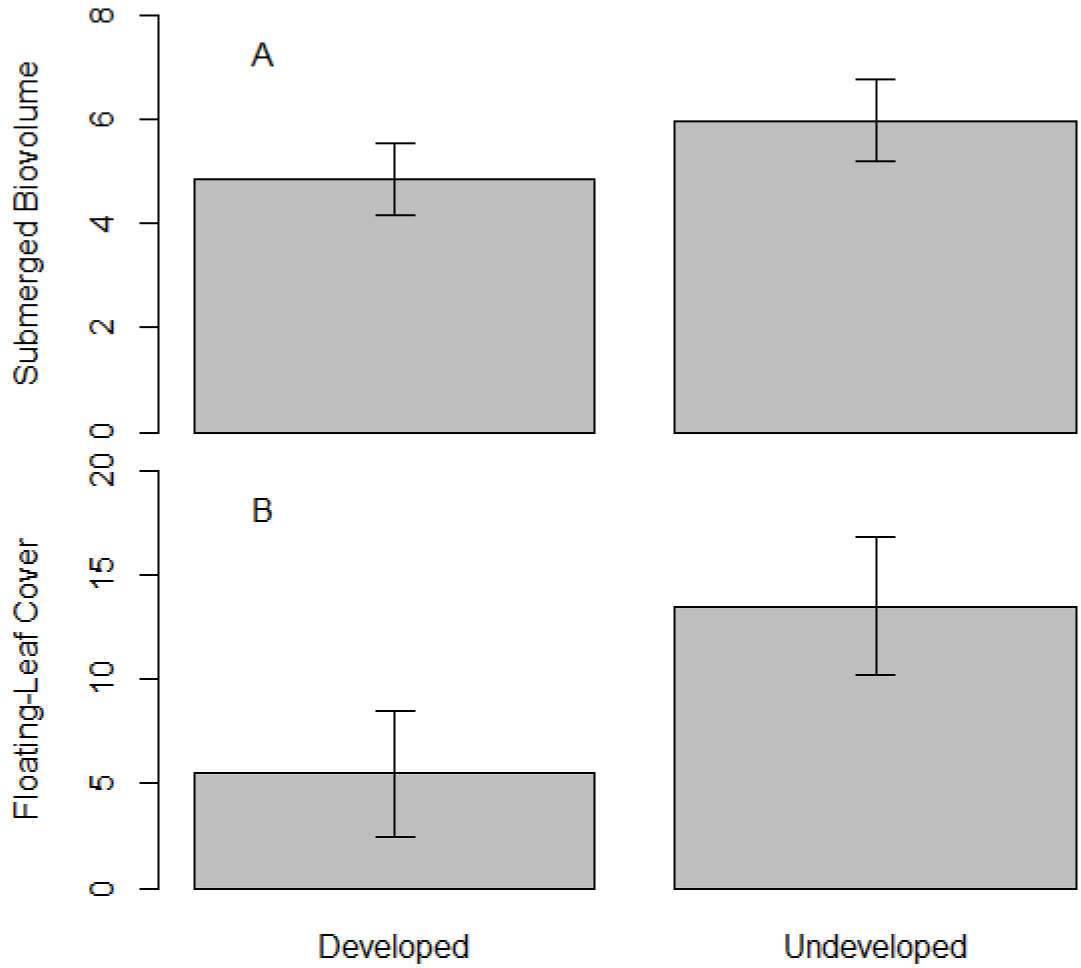

Figure 8. Mean abundance of submerged biovolume (A) did not differ across site type (*P*= 0.10). Floating-leaf cover (B) was more variable across site type, with undeveloped sites exhibiting significantly higher mean biovolume than developed sites. Whiskers represent 95% confidence intervals.

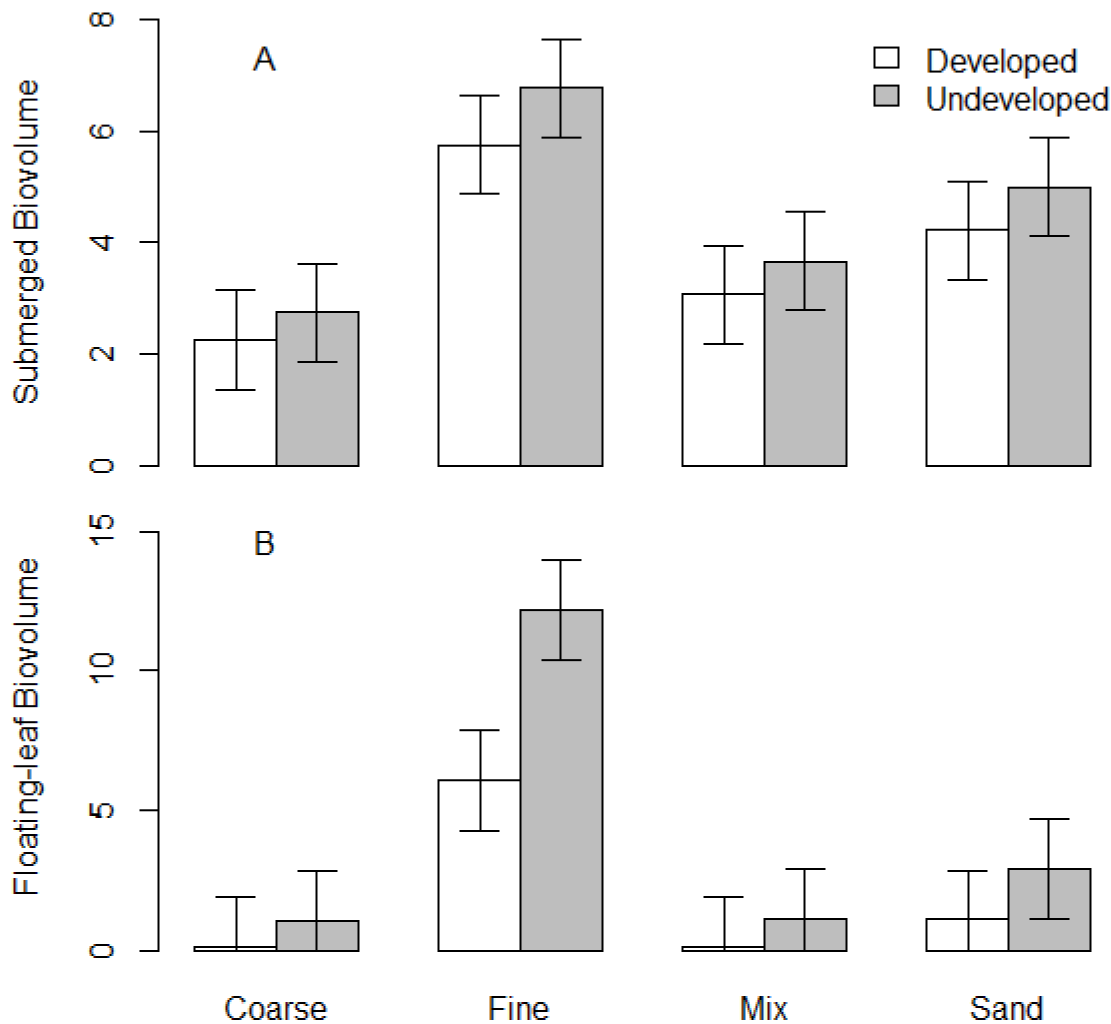

Figure 9. Submerged (A) and floating-leaf (B) biovolume varied as a function of both site type and substrate texture. Undeveloped sites (gray) consistently exhibited higher mean biovolume than developed sites (white). Whereas fine substrates supported the greatest abundance of submerged and floating-leaf vegetation, coarse substrates were associated with the lowest macrophyte abundances. Whiskers indicate 95% confidence intervals. Submerged and floating-leaf biovolume varied significantly across the four substrate categories.

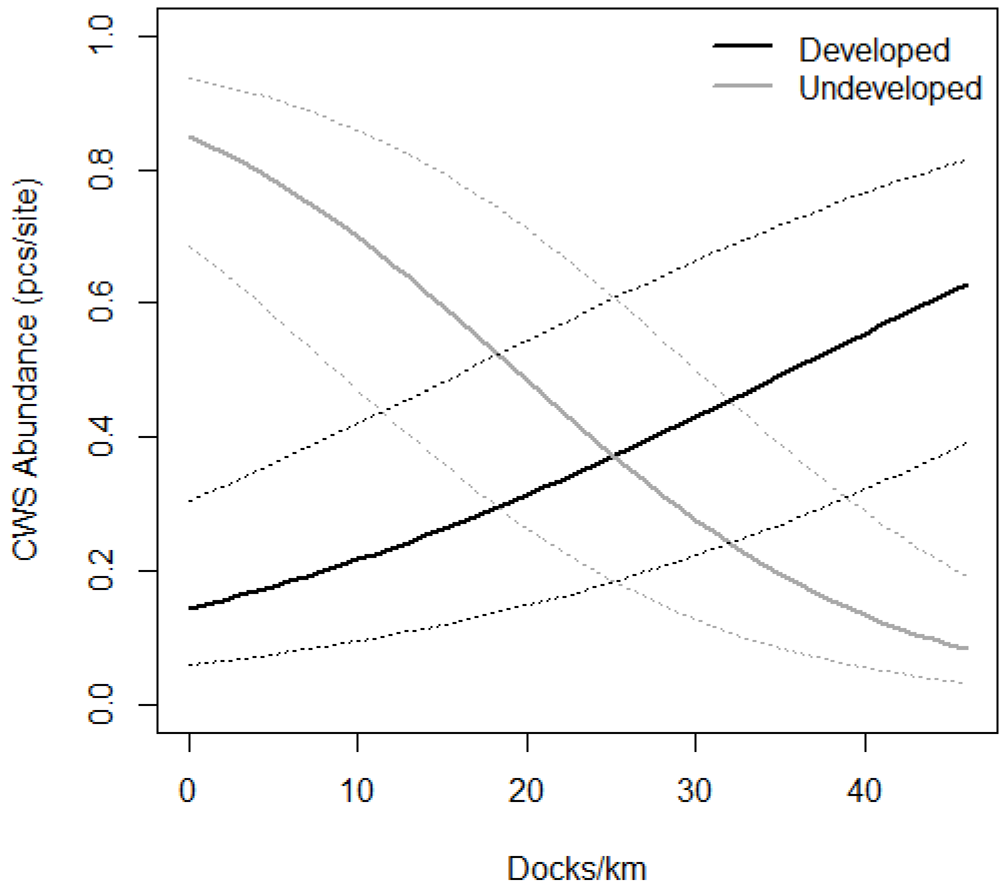

Figure 10. Site-wide abundance of coarse woody structure (CWS) was related to the interaction between site type (developed/undeveloped) and lake-wide dock density, in which expected CWS abundance within undeveloped sites (gray line) decreased as lake-wide development increased. The model indicated that at moderately high development densities, approximately 25 docks per kilometer, CWS abundance within undeveloped sites equaled that within developed sites (black line). Dotted lines represent 95% confidence intervals.

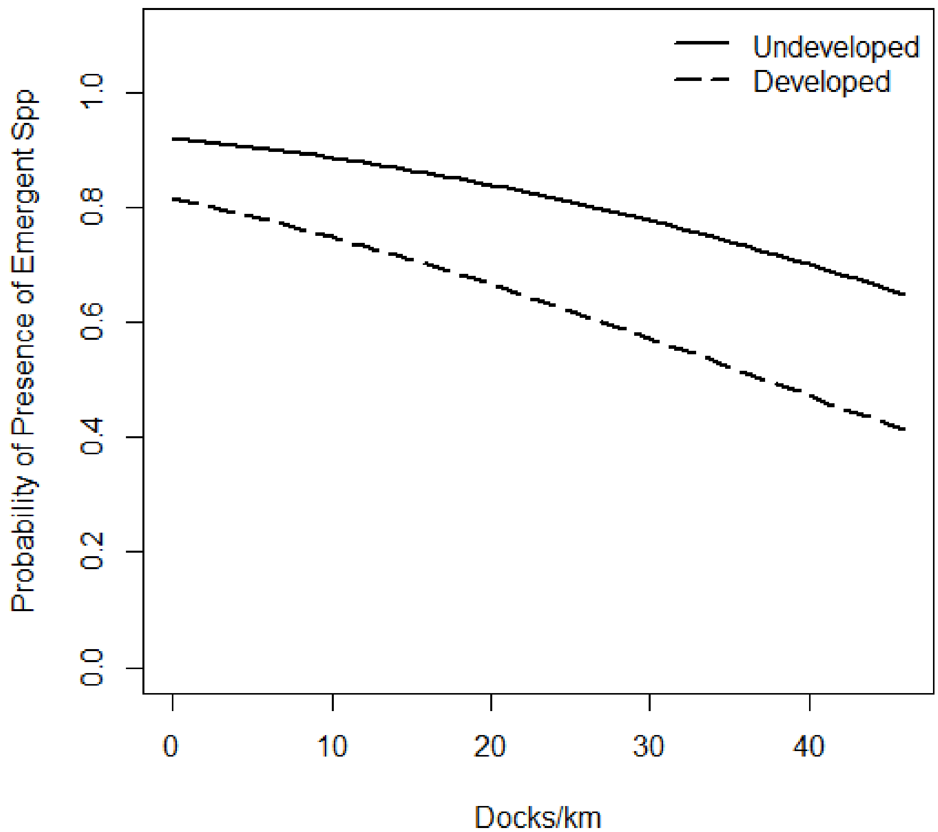

Figure 11. Probability of presence of emergent vegetation was affected by a combination of site type (developed/undeveloped) and lake-wide dock density. Both site types were negatively related to dock density; however, emergent species were more likely to occur at undeveloped sites (solid line) than developed sites (dashed line).

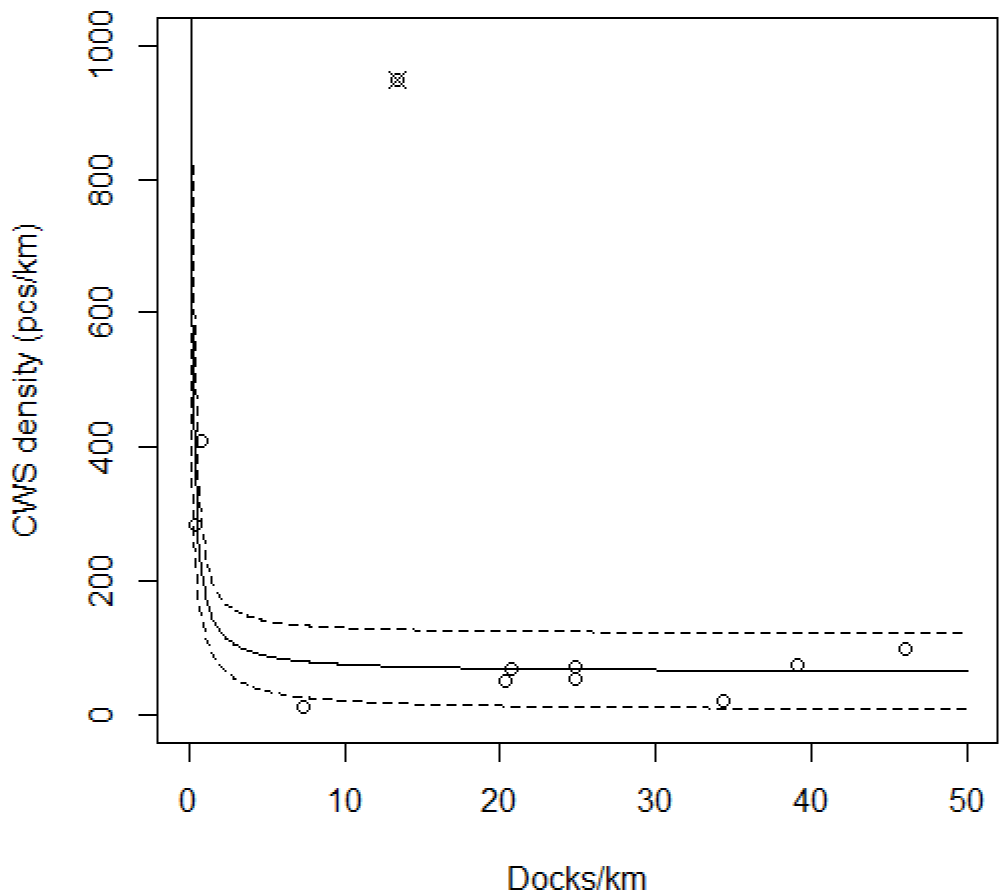

Figure 12. Estimated lake-wide density of coarse woody structure (CWS) declines dramatically as lake-wide dock density increases from 0 to 5 docks per kilometer. Beyond development densities of 5 docks per kilometer, CWS density was relatively constant at approximately 100 pieces per kilometer. The high outlying point with the "x" through the middle corresponds to Portage lake, which was excluded from the model. The model (solid line) explains approximately 60% of the variation in CWS density. Dashed lines represent 95% confidence intervals.

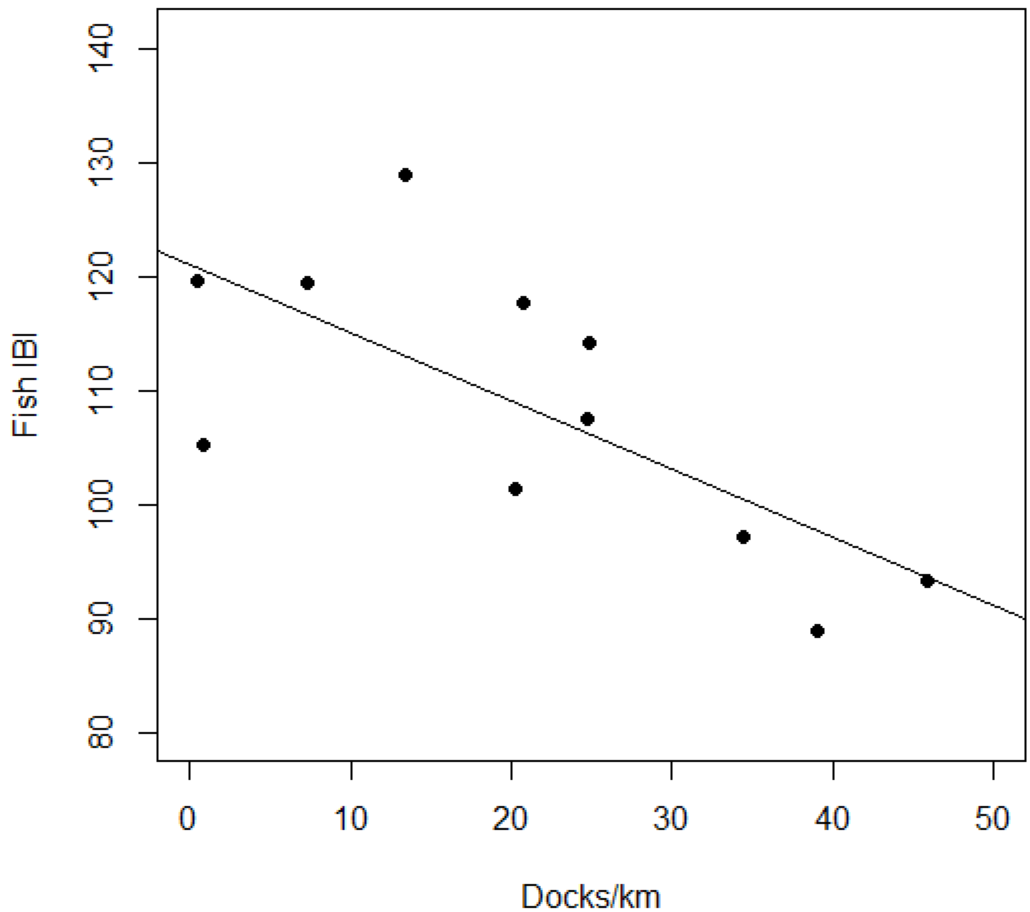

Figure 13. The fish-based Index of Biological Integrity (Fish IBI) was significantly and negatively related to lake-wide dock density within the 11 study lakes. The linear model explains approximately 45% of the variation in Fish IBI scores.