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ARTICLE

Nearshore Habitat and Fish Assemblages along a Gradient of Shoreline Development

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Abstract
Littoral habitat is a critical component of lake ecosystems. Expansion of residential development along lakeshores has led to habitat modification, which may alter lentic fish communities. Previous studies have linked lakeshore development to reductions in abundance of aquatic vegetation and coarse woody structure (CWS), and many have quantified the influence of the density of docks on aquatic habitat structure and individual fish species. However, few studies have quantified fish assemblages relative to the effect of density or pattern of development. Using docks as a proxy for development, we calculated dock density, cumulative dock area, and estimates of the proportion of shoreline that was developed, affected by development, or left in large undeveloped segments for 28 Minnesota lakes. We assessed nearshore structural habitat (aquatic vegetation, CWS, and riparian features), a lake-wide fish index of biotic integrity (IBI), and nearshore components of the fish IBI relative to the development measures derived from docks. The nearshore IBI metrics were community composition metrics based on the proportion of intolerant, small benthic-dwelling, and vegetation-dwelling species caught in nearshore sampling, which we also evaluated individually and summed as a nearshore IBI. All measures of development were correlated and performed similarly in our models. Emergent vegetation and CWS declined with increasing development. Nearshore fish IBI declined with increasing development, but the lake-wide IBI did not change significantly with development. The decline of the nearshore fish IBI appeared to have been driven by a decline in vegetation-dwelling species.

Lakeshore residential development is associated with reductions in littoral habitat structure, which may have negative impacts on fish communities. Macrophytes play an integral role in ecosystem processes in lake systems, mediating physical, chemical, and biotic interactions (Carpenter and Lodge 1986). Lakeshore residential development modifies littoral habitat through direct and indirect mechanisms, which may decrease nearshore emergent and floating-leaf macrophytes and coarse woody structure (CWS; sensu Bryan and Scarnecchia 1992; Christensen et al. 1996; Radomski and Goeman 2001; Elias and Meyer 2003; Jennings et al. 2003; Hatzenbeler et al. 2004; Newbrey et al. 2005; Francis and Schindler 2006; Marburg et al. 2006; Radomski 2006; Gaeta et al. 2011; Hicks and Frost 2011; Lawson et al. 2011).

Nearshore habitat supports fish communities by providing structure for fish assemblages and their prey. Structurally complex littoral habitats generally support higher species diversity among and within lakes (Eadie and Keast 1984; Randall et al. 1996; Weaver et al. 1997; Jennings et al. 1999; Pratt and Smokorowski 2003; Taillon and Fox 2004; Smokorowski and Pratt 2007) and can affect abundances, growth rates, mean lengths, and trophic interactions of young

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of year fish (Olson et al. 1998; Pothoven et al. 1999; Schindler et al. 2000; Gaeta et al. 2011; Middaugh et al. 2013). Aquatic macrophytes influence spawning, refuge, and feeding opportunities for nearshore fishes (Crowder and Cooper 1982; Savino and Stein 1982; Hunt and Annett 2002; Carey et al. 2010). Young of year fish, in particular, rely on vegetated areas to avoid predation (Savino and Stein 1982; Hayse and Wissing 1996; Weaver et al. 1997).

Similarly, CWS contributes to structural complexity, provides cover for spawning, and increases surface area for colonization by food items such as bacteria, periphyton, and macroinvertebrates (Everett and Ruiz 1993; Cochran and Cochran 2005; Roth et al. 2007; Lawson et al. 2011). Submerged CWS supports fish species richness and centrarchid abundance (Barwick 2004). Several studies have examined the effects of littoral CWS on fish community structure (Sass et al. 2006a; Roth et al. 2007) and lake food web interactions (Helmus and Sass 2008; Ahrenstorff et al. 2009). Removal of littoral CWS exerts complex effects on lentic food webs by affecting prey availability, mortality rates, and reproductive success across trophic levels (Sass et al. 2006b; Helmus and Sass 2008; Ahrenstorff et al. 2009). A loss of CWS was credited for decreased growth of Bluegill *Lepomis macrochirus* (Schindler et al. 2000) and Largemouth Bass *Micropterus salmoides* (Gaeta et al. 2011) and greater dispersion of littoral fishes (Scheuerell and Schindler 2004). Recent evidence suggests that changes to fish assemblages associated with littoral CWS removal are not easily reversed by CWS addition (Sass et al. 2012).

Shoreland development can impact nearshore structural habitat in lakes due to human activities in and near the water. Littoral CWS and aquatic vegetation may be removed to improve swimming and boating conditions. Species richness of emergent and floating macrophytes may be lower near docks but higher with increasing distance from docks (Beck et al. 2013a). Motorboats, in particular, can limit vegetation by reducing water clarity and physically damaging plants (Liddle and Scorgie 1980; Asplund and Cook 1997). In addition, docks and associated structures can effectively block sunlight and limit aquatic plant growth (Garrison et al. 2005; Campbell and Baird 2009). Docks represent “loci” of lakeshore development or areas of highly concentrated disturbance (Radomski et al. 2010) and have been used in the past to indicate lakeshore development (Bryan and Scarnecchia 1992). Although residential buildings provide evidence of development adjacent to a lakeshore, they are difficult to quantify remotely and may be disconnected from the aquatic zone. In contrast, docks occupy the littoral zone and are readily identified from aerial imagery.

Few studies have specifically investigated the influence of shoreline residential development or docks on abundance of multiple fish species or communities (but see Scheuerell and Schindler 2004). We evaluated five measures of shoreline development, based on the location and size of docks and assessed fish species abundance, fish index of biotic integrity (IBI), and nearshore fish IBI metrics relative to the amount of shoreline development in 28 lakes in Minnesota. Our hypothesis was that CWS, aquatic vegetation, fish IBI, and the nearshore community composition IBI metrics based on the proportion of intolerant, small benthic-dwelling, and vegetation-dwelling species would decrease relative to increased development as measured by the presence of docks. We also hypothesized that some fish species would decline with increasing development, particularly species classified as intolerant to human disturbance such as Blackchin Shiner *Notropis heterodon*, Blacknose Shiner *N. heterolepis*, and Banded Killifish *Fundulus diaphanous* (Drake and Valley 2005). This research was part of a larger project investigating the cumulative impacts of lakeshore residential development on aquatic macrophytes, nearshore terrestrial vegetation, and fish assemblages in Minnesota lakes.

METHODS

*Lake selection.—*Candidate lakes for our study were selected within the Laurentian Mixed Forest ecological province of the Ecological Classification System (Cleland et al. 1997), a lake-rich area with a range of lakeshore development (Beck et al. 2013a, 2013b). Lakes with similar limnological and watershed characteristics managed by the Minnesota Department of Natural Resources were chosen to isolate the effects of lakeshore development on nearshore habitat and fish species. We initially selected 114 relatively small (40–200 ha), mesotrophic lakes with 20–80% littoral area and at least 80% undisturbed watersheds characteristic of recreational development lakes in the region (Heiskary and Wilson 2005). The characteristics and locations for the 28 study lakes are presented in Table 1 and Figure 1, and data for each lake are provided in Table S.1 in the Supplement provided in the online version of this article.

We used ArcMap 10.1 (Environmental Systems Research Institute, Redlands, California) to draw digitized dock polygons

TABLE 1. Mean and range of physical, chemical, shoreline development, and watershed characteristics for the 28 study lakes in Minnesota.

Characteristic	Mean	Range
Lake characteristic		
Area (ha)	126	49–188
Maximum depth (m)	53	25–97
Littoral area (%)	43	21–69
Mean total phosphorus (μg/L)	16	7–26
Shoreline length (km)	7.7	3.7–14.9
Watershed size (ha)	13,022	270–81,143
Watershed land use (%)		
Undisturbed (forest, grassland, water)	93	80–99
Cultivated	5	0–17
Urban and mining	2	1–5

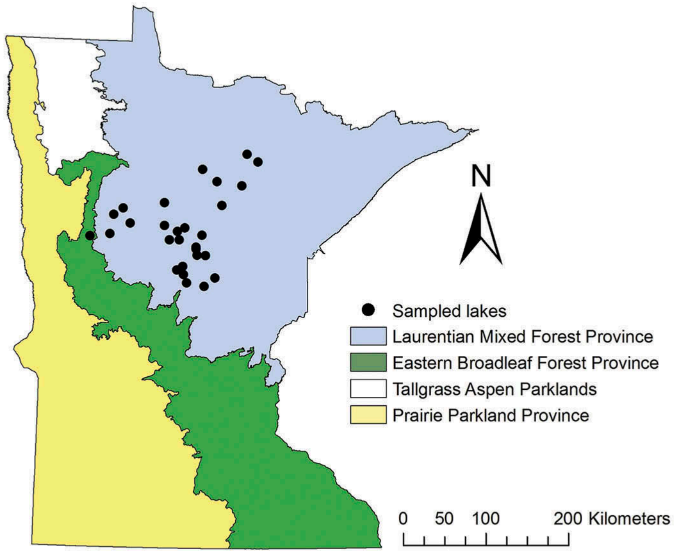

FIGURE 1. Location of the 28 lakes in the Laurentian Mixed Forest ecological province of Minnesota evaluated in 2011 and 2012.

for all candidate lakes using georeferenced National Agricultural Imagery Program aerial photos taken between 2008 and 2010 (Farm Service Agency 2010). We calculated dock density by dividing lake-wide dock counts by shoreline length. Lakes were ordered from undeveloped (no docks) to highly developed (24 docks/km) and binned by quintiles. Six lakes were randomly drawn from each grouping bin to obtain a set of 30 study lakes spanning a range of development densities. Our initial lake selection process did not explicitly consider the Minnesota lake classification system, which identifies four major lake groups in the state based on a multivariate analysis of limnological variables (Schupp 1992). Two of the 30 lakes that we selected as study lakes belonged to the northeast Minnesota lake group. However, the Minnesota fish IBI (Drake and Valley 2005) has not been validated for northeastern lakes; thus we excluded those two lakes from the analysis.

Five measures of shoreline development intensity were calculated. All five were based on docks, but each focused on a different aspect of development (Table 2). In addition to dock density, we summed the area of dock polygons for each lake and standardized by dividing total lake-wide dock area by shoreline length. Three other development metrics were calculated, taking into account disturbance from activities around docks and whether development was clustered or scattered. In Minnesota, the maximum shore frontage from which landowners are allowed to remove submersed aquatic vegetation is 15.2 m, so we added a 7.6-m buffer to each dock polygon (Figure 2). We divided the sum of shoreline overlapping with the buffered dock polygons by the total length of shoreline for each lake to obtain the proportion of each lake with developed shoreline. Since smaller fragments of undeveloped shoreline are associated with more clumped development and may be subject to more human disturbance than large expanses of undeveloped shore, we added the length of all fragments less than 25 m to the sum of developed shoreline to calculate the proportion of affected shoreline. Finally, we summed large undeveloped shoreline segments greater than 100 m to calculate the proportion of natural shoreline (Figure 2; Table 2). The affected and natural metrics were meant to capture different patterns of shoreline development (clustered versus scattered) and explore whether the degree of fragmentation of undeveloped shoreline had different effects from development alone.

Habitat assessment.—Sites were 30 m long, and we assessed each one from a boat using the “Score Your Shore” survey technique (Perleberg et al. 2010). This survey divides a site or lakeshore lot into “Upland,” “Shoreline,” and “Aquatic” zones. We used the “Upland” and “Shoreline” zone portions of the survey, which assigns points to a site based on various characteristics reflecting the extent of natural land cover such as tree canopy, brush, and tall grass. The points for each zone were summed to develop a shoreland habitat score, with a maximum score of 100.

At each site we established three equally spaced transects perpendicular to the shore. Transects were approximately 8 m apart. At developed sites, the locations of transects were sometimes moved so that the first transect was adjacent to the dock. We estimated macrophyte abundance within a 0.5-m^2–diameter, buoyant, sampling ring at three water depths (0.3, 0.6, and 0.9 m) along each transect. The distance from shore of these sample locations varied depending on the morphometry of each site. Aquatic plant abundance was estimated separately for each of three structural forms of macrophytes: emergent, submerged, and floating-leaf.

TABLE 2. Five measures of the extent and intensity of shoreline development in Minnesota study lakes. Metrics were calculated for each lake.

Development metric	Calculation	Mean	Range
Dock density (docks/km)	dock count / shore length	9	0–24
Dock area (m^2/km)	Σ dock area / shore length	359	2–1,339
Developed shoreline (%)	Σ developed shore / shore length	14	0–36
Affected shoreline (%)	Σ affected shore / shore length	18	0–45
Natural shoreline (%)	Σ natural shore / shore length	68	30–100

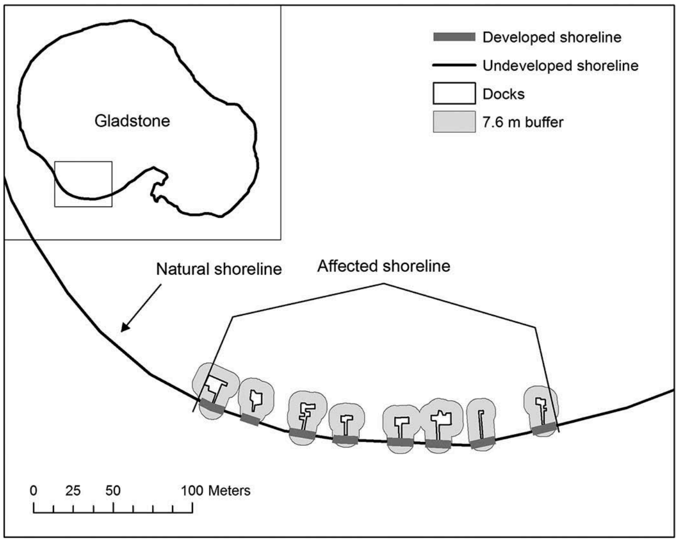

FIGURE 2. A portion of Gladstone Lake, Minnesota, showing dock outlines, 7.6-m dock buffers, developed shoreline segments, undeveloped shoreline (all shoreline not classified as developed), affected shoreline (developed segments plus undeveloped fragments < 25 m), and natural shoreline (undeveloped segments > 100 m).

Coverage 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 recorded in 5% increments between 0 and 100%. Where abundance of submerged or floating-leaf macrophytes was very low but greater than 0, a score of 1% was assigned. Emergent macrophytes such as bulrush *Scirpus* spp. have thin stems; thus estimating the percentage of the water column occupied is difficult. Therefore, we assessed abundance of emergent species based on stem counts within the sampling ring, assigning the following indices: 0: stems absent; 1: sparse (<4 stems); 2: 4–9 stems; 3: 10–19 stems; 4: 20–30 stems; 5: dense (>30 stems). We also counted all pieces of CWS > 10 cm in diameter and >60 cm in length within the site area delineated by the nine macrophyte sampling locations.

Near-shore fish sampling.—Fish were collected following the sampling protocol of the fish-based IBI for Minnesota lakes (Drake and Pereira 2002; Drake and Valley 2005) in June, July, or August of 2011 and 2012. Each lake was sampled at 10 or more sites depending on lake area. The first site at each lake was selected at random and the other sites were spaced at equal distances along the shoreline. At each site, fish were collected along 30 m of shoreline using a combination of backpack electroshocking and shoreline seining. We completed two passes with a backpack electrofisher parallel to shore, each covering a width of about 1.5 m. 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. Sites with soft bottoms or steep drop-offs were sampled by backpack electroshocking from a boat. Where possible, a 4.6-m or 15-m bag seine with 0.3-cm mesh was hauled along 30 m of shoreline and out to the length of the seine from shore or maximum wadeable depth (approximately 1.3 m).

The abundance of each fish species was recorded for each site and summed for each lake. For the eight lakes we sampled at more than 10 sites, we standardized our nearshore catch numbers to 10 sites per lake by dividing the total catch by the number of sample sites multiplied by 10 and rounding all fractions up to the next whole number. All references to catch numbers refer to these adjusted counts, unless otherwise specified.

We calculated a nearshore fish IBI, which was based on a subset of metrics from Drake and Pereira's (2002) fish IBI for small, central Minnesota lakes. Using data from fish caught with nearshore sampling gear (seines and backpack electroshocking), we calculated three community assemblage metrics. These metrics were based on the proportion of individuals belonging to (1) nearshore intolerant species, (2) small benthic-dwelling species, and (3) vegetation-dwelling species (Table 3; Drake and Pereira 2002). These three metrics were summed to produce a nearshore IBI. Since this IBI has not been studied in relation to shoreline development or littoral habitat disturbance, we evaluated each metric separately, as well as the summed nearshore IBI. Nearshore IBI metrics were not based on species richness, but we recorded the number of fish species, excluding hybrids, caught in nearshore sampling.

We combined our nearshore fish collection data with the most recent Minnesota Department of Natural Resources game fish surveys that used standardized gill nets and trap nets to calculate the lake-wide fish IBI score for each study lake (MNDNR 1993). This fish-based IBI, which has been validated for lakes similar to those in our study, uses eight species richness metrics, three trophic composition metrics based on trap-net relative biomass, and two trophic composition metrics based on gill-net relative biomass, in addition to the three nearshore community assemblage metrics (Drake and Pereira 2002; Drake and Valley 2005). The trap-net and gill-net surveys were completed between 2004 and 2013.

Analyses.—We evaluated the responses of mean shoreland habitat score, mean count of CWS, mean abundance of aquatic vegetation, lake-wide fish IBI, nearshore IBI, and the three component metrics of nearshore IBI relative to all five development metrics. All statistical analyses were performed with R (R Core Team 2015).

We calculated Pearson correlation coefficients between the five development metrics and used simple linear regression to compare them to the habitat and fish variables (Sokal and Rohlf 1981). Each set of variables was plotted, and adjusted R^2 and Akaike information criterion (AIC) values were used to compare models using different measures of development (Burnham and Anderson 1998). Regression diagnostic plots were examined for each model. We log transformed nearshore fish metrics due to patterns in the residuals indicating unequal variance. In some cases diagnostic plots indicated that a nonlinear relationship was

TABLE 3. Total adjusted catch (*N*) of each fish species, by decreasing abundance, from nearshore sampling, the number of lakes in which each species was collected, the environmental tolerance (I = intolerant, T = tolerant), and habitat (small benthic-dwelling [Smb] or vegetation-dwelling [Veg]). The odds ratio comes from the logistic regression for presence of each species caught in 5–23 lakes as dock density increases. An asterisk (*) indicates a *P*-value less than 0.05 and two asterisks (**) indicates a *P*-value of 0.05–0.1.

Species	*N*	Number of lakes	Tolerance	Habitat	Odds ratio
Bluegill *Lepomis macrochirus*	8,096	28			
Bluntnose Minnow *Pimephales notatus*	6,976	25			
Yellow Perch *Perca flavescens*	2,914	27			
Mimic Shiner *Notropis volucellus*	917	10	I	Veg	1.08
Largemouth Bass *Micropterus salmoides*	892	28			
Blackchin Shiner *Notropis heterodon*	835	23	I	Veg	0.82*
Blacknose Shiner *Notropis heterolepis*	721	17	I	Veg	1.19**
Pumpkinseed *Lepomis gibbosus*	434	26			
Banded Killifish *Fundulus diaphanous*	434	21	I		1.29*
Golden Shiner *Notemigonus crysoleucas*	414	16			0.97
Central Mudminnow *Umbra limi*	285	24		Veg	
Rock Bass *Ambloplites rupestris*	242	21	I		1.08
Johnny Darter *Etheostoma nigrum*	237	24		Smb	
Iowa Darter *Etheostoma exile*	205	24	I	Smb/Veg	
Green Sunfish *Lepomis cyanellus*	166	7			1.14
Spottail Shiner *Notropis hudsonius*	158	10			1.17**
Logperch *Percina caprodes*	152	5		Smb	1.05
White Sucker *Catostomus commersonii*	148	6	T		1.06
Black Crappie *Pomoxis nigromaculatus*	135	7			1.07
Hybrid sunfish *Lepomis* spp.	68	12			1.06
Tadpole Madtom *Noturus gyrinus*	54	13		Smb/Veg	0.98
Least Darter *Etheostoma microperca*	54	4	I	Smb/Veg	
Yellow Bullhead *Ameiurus natalis*	39	15			1.35*
Longear Sunfish *Lepomis megalotis*	16	2	I		
Northern Pike *Esox lucius*	35	9		Veg	0.98
Brook Silverside *Labidesthes sicculus*	20	4			
Common Shiner *Luxilus cornutus*	18	2			
Bowfin *Amia calva*	12	7		Veg	1.17**
Hornyhead Chub *Nocomis biguttatus*	12	5	I		1.14
Mottled Sculpin *Cottus bairdii*	12	3	I	Smb	
Walleye *Sander vitreus*	12	2			
Pugnose Shiner *Notropis anogenus*	11	6	I	Veg	1.07
Brook Stickleback *Culaea inconstans*	11	5			0.94
Smallmouth Bass *Micropterus dolomieu*	10	5	I		1.17**
Black Bullhead *Ameiurus melas*	7	1	T		
Creek Chub *Semotilus atromaculatus*	6	3	T		
Fathead Minnow *Pimephales promelas*	4	4	T		
Brown Bullhead *Ameiurus nebulosus*	3	3			
Burbot *Lota lota*	1	1			

present, and we assessed the fit of polynomial models, which were evaluated using AIC corrected for small sample size (AIC_c; Burnham and Anderson 1998). When the plot of residuals versus leverage indicated highly influential points (high Cook's distance scores), we examined the influence of those points on the results of the model.

We performed logistic regressions on the presence or absence of nearshore fish species that were collected in at least five lakes. We used scatterplots to assess the numbers of common fish species relative to the number and area of docks. Common species were defined as those that were collected in at least 15 of the 28 lakes or represented by at least 125 individuals (excluding young of year).

RESULTS

We collected 27,050 fish representing 38 species (plus hybrid sunfish) in nearshore areas across 333 sites in the 28 study lakes. After standardizing our counts to 10 sites per lake, 20 species were represented by at least 125 individuals or were found in at least 15 lakes (Table 3). Mean shoreland habitat scores across lakes ranged from 53 to 98, and mean count of CWS ranged from 0 to 8.5 pieces per site. Mean submersed vegetation abundance ranged from 2% to 36%, and mean floating vegetation coverage ranged from near zero to 29%. The mean index of emergent vegetation ranged from 0.4 to 2.6 per site (on a 0–5 scale; all development characteristics are summarized in Table S.2).

The five measures of shoreline development were highly correlated (Table 4; all response variables are summarized in Table S.3). Dock area had the lowest correlation to the other development variables, and Pearson correlation coefficients ranged from 0.82 to 0.92. Habitat response variables were related to the development metrics: dock density, dock area, percent developed, and percent affected were negatively related, whereas percent natural was positively correlated with habitat variables.

Shoreland scores were significantly related to all measures of development ($P < 0.05$), but dock area per kilometer explained less variance than the other development metrics; adjusted R^2 was 0.12–0.13 lower and ΔAIC values were between 4.5 and 5.0. The CWS count was related to all development metrics ($P < 0.05$), and all five metrics had similar performance as measured by adjusted (Adj) R^2 scores (0.16–0.17) and AIC values (maximum ΔAIC = 0.5). Dock area was not significantly related to emergent vegetation (P = 0.052), and although the other development variables were significantly related to emergent vegetation, less variance was explained (Adj R^2 = 0.11–0.13). The AIC scores did not show strong support for any of the remaining development metrics (maximum ΔAIC = 0.5). Floating and submersed vegetation were not significantly related to any development metric ($P > 0.05$).

Due to the high correlations between development variables and the simplicity of calculating dock density, most results and all subsequent figures use the dock density metric. Shoreland scores declined as dock density increased (P = 0.001), and CWS declined significantly and rapidly as dock density increased (P = 0.019; Figure 3). Emergent vegetation had a significant, negative relationship (P = 0.046) with dock density.

There was a significant positive relationship between the number of nearshore fish species captured and dock density (Figure 3). Unlike other response variables the number of nearshore fish species was better described by dock area per kilometer than by dock density (adjusted R^2 was 0.13 higher and ΔAIC value was 7.5). Subsequent modeling of number of nearshore fish species relative to lake area indicated that lake area, although not correlated to dock density (P = 0.148) explained more variance in the number of fish species than did dock density (adjusted R^2 of 0.60 using lake area versus 0.24 using dock area per kilometer). When both factors were included in the model neither dock area per kilometer nor the interaction term were significant ($P > 0.05$), and the variance explained by the more complex model was similar to the model with lake area alone (0.62 versus 0.60). The AIC_c scores differed by less than 0.5, indicating little support for the more complex model. Lake area was not related to other variables.

All fish IBI variables were log transformed to moderate the effect of higher variance at lower dock density. The scores for the nearshore IBI and the vegetation-dwelling fish metric declined significantly with increasing dock density (Figure 4). The lake-wide fish IBI and the nearshore intolerant and nearshore small benthic-dwelling metrics were not significantly lower at higher dock density. Since the vegetation-dwelling fish metric was the nearshore IBI metric with a significant relationship to dock density and was apparently driving the trend for the nearshore IBI, we chose to examine the vegetation-dwelling fish scores more closely. Diagnostic plots for the vegetation-dwelling linear model indicated that a nonlinear relationship might be present. We evaluated quadratic and cubic models with dock density as the predictor. The cubic polynomial fit was well supported as the best model of this relationship, with an adjusted R^2 of 0.48 and ΔAIC values from both other models of >9 (Figure 4). The cubic polynomial of dock density versus the vegetation-dwelling fish metric was influenced by the lake with the highest dock density (Cook's distance > 1). This lake is responsible for the upward slope at

TABLE 4. Pearson correlation coefficients between the five measures of lakeshore development.

Development measure	Dock density (number/km of shore)	Dock area (m^2/km of shore)	Percent of developed shore	Percent of affected shore	Percent of natural shore (>100 m)
Dock density (number/km of shore)	1.00	0.92	1.00	0.99	−0.95
Dock area (m^2/km of shore)	0.92	1.00	0.90	0.90	−0.83
Percent of developed shore	1.00	0.90	1.00	0.99	−0.97
Percent of affected shore	0.99	0.90	0.99	1.00	−0.97
Percent of natural shore (>100 m)	−0.95	−0.83	−0.97	−0.97	1.00

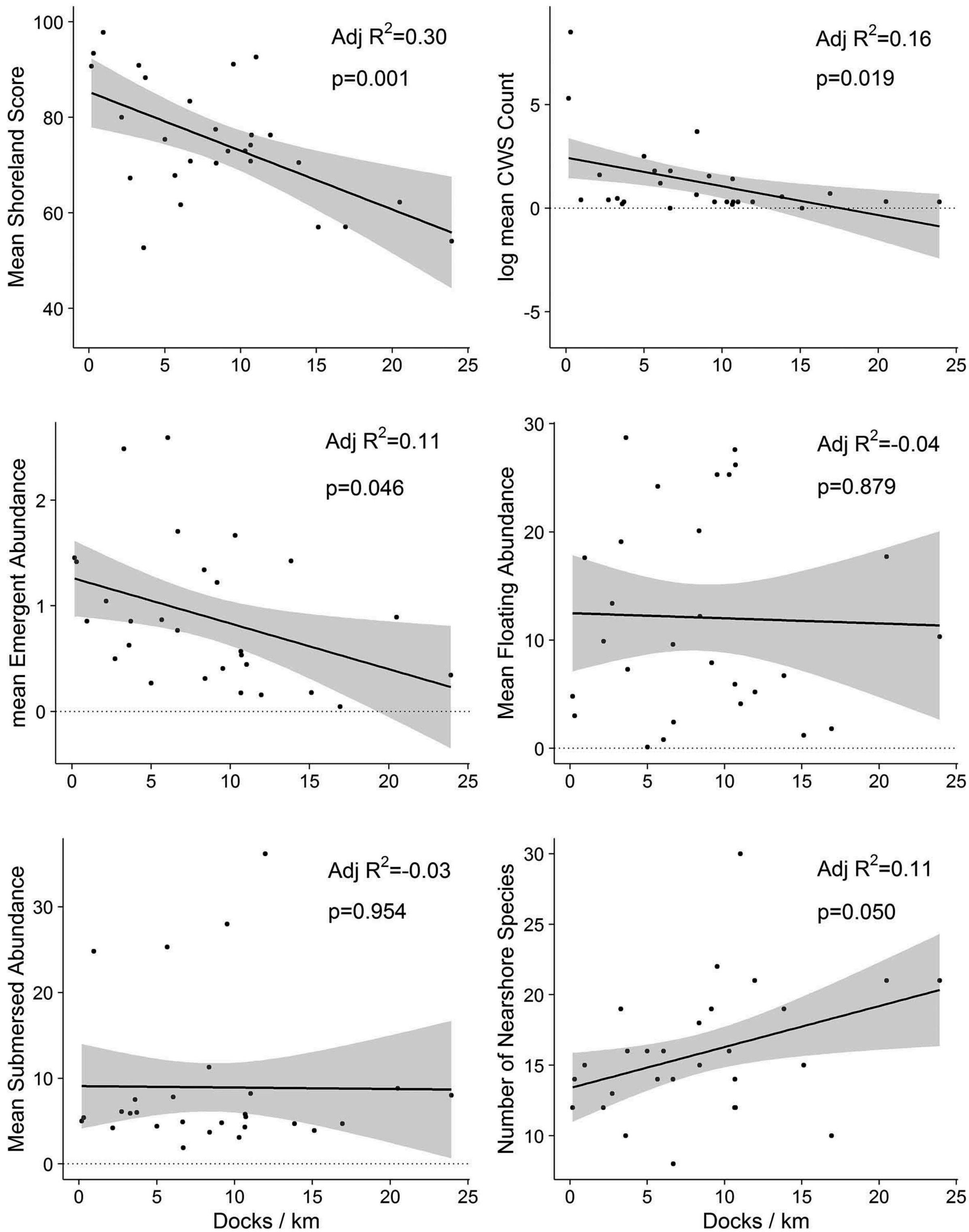

FIGURE 3. Linear models comparing shoreland scores, coarse woody structure (CWS), emergent vegetation, floating-leaf vegetation, submersed vegetation, and number of nearshore fish species captured with the number of docks per kilometer. The shaded area for each model is the 95% CI.

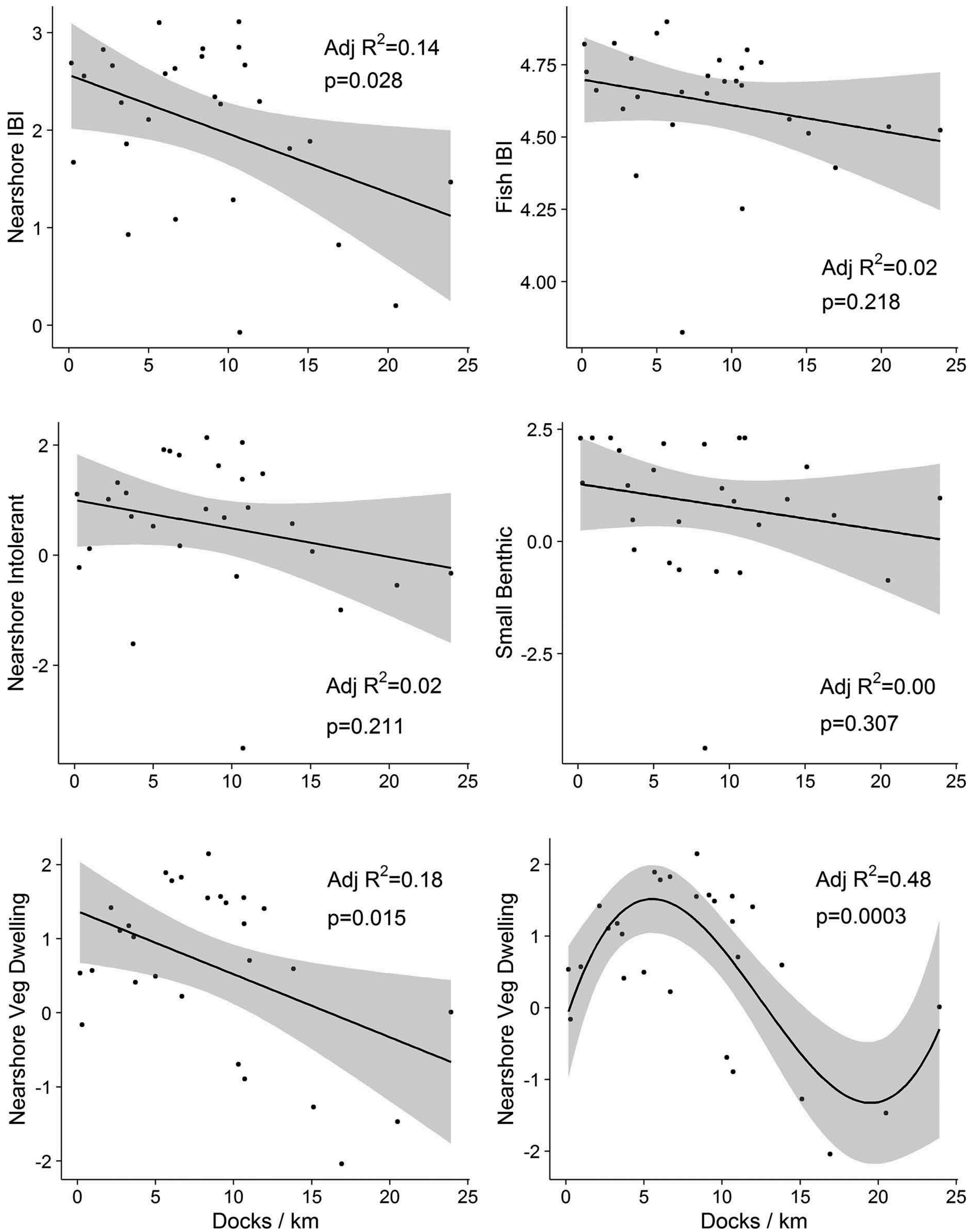

FIGURE 4. Regressions of the log-transformed nearshore fish index of biotic integrity (IBI) and its component metrics in relation to dock density. Both the linear and cubic polynomial models are shown for the vegetation-dwelling fish metric. The shaded area for each regression is the 95% CI.

the high dock-density end of the curve; however, the 95% CI at that end of the curve is quite wide, indicating little certainty about the shape at densities higher than 15 docks/km.

Presence or absence of most fish species was not related to dock density (Table 3). However, logistic regressions revealed a significant negative relationship ($P < 0.05$) between the presence of Blackchin Shiners and dock density, while Banded Killifish and Yellow Bullheads were more likely to be found as dock density increased. There were marginally significant ($0.05 < P < 0.10$) increases in the likelihood of occurrence with increasing dock density for Blacknose Shiners, Bowfin, Smallmouth Bass, and Spottail Shiners.

The catch of most fish species was not significantly related to dock density. However, often the maximum catch of a species was recorded near 10 docks/km, and at dock densities higher than 15 docks/km catch numbers were consistently low.

DISCUSSION

Our analysis adds to existing research linking reduced habitat quality and complexity to increases in lakeshore development, although it does not identify cause and effect for the relationships we evaluated. Although we evaluated a relatively small number of sites in each lake, shoreland score reflected the development status of the lake. The negative correlation between mean shoreland scores and dock density indicates a loss of structural coverage and complexity of upland vegetation as lakes became more developed. Emergent vegetation and CWS both declined with increasing development. The number of nearshore fish species was positively related to dock area per kilometer, likely because of a significant relationship between dock area per kilometer and lake area. The fish metrics that we evaluated had less consistent relationships with dock density; however, the metrics we used were not specifically developed to detect littoral habitat changes. Nearshore fish IBI was significantly, negatively related to lakeshore development. This relationship appears to be primarily due to the negative response of vegetation-dwelling species to increasing dock density.

Our initial hypothesis was that fish species abundance, nearshore fish IBI and its component metrics, and the lake-wide fish IBI would decline with an increase in the dock metrics we evaluated. Although the nearshore IBI, and particularly the vegetation-dwelling fish metric, decreased in lakes with high dock densities, many of the 20 fish species we evaluated were abundant across a range of dock densities, and the trend in lake-wide fish IBI scores was not significant. We suggest that the vegetation-dwelling fish metric is a more sensitive indicator of development impacts than that provided by catch of individual species. Although the linear trend for the intolerant fish metric was not significant, the most highly developed lakes had low scores (Figure 4). In the future, the list of intolerant species may be refined to distinguish species that are sensitive to loss of nearshore structural habitat from those intolerant of poor water quality, allowing a new community composition metric focused on nearshore habitat to be developed.

In a study conducted as part of the National Lakes Assessment Project in 50 lakes in Minnesota, Duval (2015) found that as dock density approached 10 docks/km, variability in a human disturbance index declined suggesting that dock density was a strong predictor of human disturbance in riparian areas. The littoral cover index in these lakes (a measure of nearshore habitat complexity) was consistently low when dock density exceeded 8 docks/km. Thus, for both habitat and fish catch, integrative metrics may be sensitive for detecting responses to shoreline disturbance.

In our study lakes, CWS declined substantially and rapidly with increasing dock density and was rare at development densities higher than 3.0 docks/km, which agrees with published studies. Christensen et al. (1996), Marburg et al. (2006), and Lawson et al. (2011) found similar declines in CWS, with a rapid loss at low levels of development and CWS virtually absent at more than 9–10 cabins/km. Low riparian tree density and reduced structural complexity of the littoral zone has been associated with residential development around lakes (Christensen et al. 1996; Marburg et al. 2006, 2009; Lawson et al. 2011). As part of our larger study, Keville (2013) found that development was associated with reduced nearshore terrestrial vegetation, which is consistent with low shoreland scores. Thus, direct removal of CWS from nearshore areas can rapidly deplete littoral CWS along developed shorelines, and loss of standing trees along the shore ultimately limits the potential for natural CWS input in the future (Christensen et al. 1996; Jennings et al. 2003; Francis and Schindler 2006; Marburg et al. 2006).

Woody structure provides important habitat for some fish species found in our study lakes, such as two important game species, Largemouth Bass (Reed and Pereira 2009; Lawson et al. 2011) and Black Crappie (Reed and Pereira 2009). Male Largemouth Bass nested near CWS, when available, and chose deeper water in lakes with low CWS (Lawson et al. 2011). In addition, bass never nested closer to docks than CWS, which suggests that docks do not act as surrogates for CWS. Nest success of Largemouth Bass was negatively related to increased development of lake shorelines (Wagner et al. (2006). In contrast, Weis and Sass (2011) did not find a significant effect of abundance of CWS on the density or nest site selection of Largemouth Bass nests. Black Crappies often nested close to undeveloped shoreline in stands of emergent vegetation, usually hardstem bulrush *Scirpus acutus* and avoided developed shorelines (Reed and Pereira 2009). When Largemouth Bass and Black Crappies built nests near developed shorelines the nests were in deeper water than when nests were adjacent to undeveloped shorelines (Reed and Pereira (2009). Thus, although there is some conflicting evidence, undeveloped shoreline and the presence of CWS may contribute to spawning success by Largemouth Bass and Black Crappies. We were unable to detect differences in these species in this study, but our nearshore sampling methods targeted highly variable age-0 fish of these game species.

Previous studies in Minnesota have found reductions in emergent and floating-leaf plant cover due to shoreline development ranging from 15% to 28% (Radomski and Goeman 2001; Radomski 2006). Lepore (2013) found a lower density of all three macrophyte growth forms adjacent to docks and higher plant density with distance from docks. In our study, the correlation between emergent plant abundance and dock area was negative but not significant, which could indicate that human impacts on emergent plant beds occur with any development and that larger docks do not necessarily lead to more vegetation removal. However, Radomski and Goeman (2001) found that larger dock structures were associated with more vegetation loss. The low number of lakes in our study with larger dock structures may have limited our ability to detect trends with this variable. We found that emergent macrophytes declined linearly with dock density, but we did not find significant cumulative effects of development on floating-leaf and submerged macrophytes at the lake scale. Although the historical extent of macrophyte beds is not known, development does not occur randomly. Our data do not indicate whether the decline in emergent plants was exclusively due to plant removal or partially due to preferential development of areas that already had fewer emergent plants.

The reduction in emergent aquatic macrophytes and CWS near docks, viewed cumulatively within lakes with high dock densities, may have reduced the distribution and abundance of intolerant and vegetation-dwelling fish, although we noted that the highest scores for both metrics occur between 5 and 11 docks/km. Faster growth of some age-classes of Largemouth Bass and Bluegills was noted after the removal of vegetation (Olson et al. 1998; Pothoven et al. 1999). Conversely, Largemouth Bass in lakes with extensive lakeshore development took 1.5 growing seasons longer to enter the fishery (Gaeta et al. 2011), and Bluegill growth was slower in lakes with higher lakeshore development than in lakes with less development (Schindler et al. (2000). However, Cheruvelil et al. (2005) found little evidence to support an optimal intermediate range of macrophyte cover for growth of Largemouth Bass and Bluegills. Valley and Bremigan (2002) did not find a positive effect on growth for Largemouth Bass after selective removal of Eurasian watermilfoil *Myriophyllum spicatum*. In our study, the higher scores associated with low to moderate levels of development may have been due to enhanced sampling efficiency at developed sites, where clear areas facilitated seining. But this pattern could also appear if disturbances in the littoral zone increased habitat diversity, providing edges and openings that were beneficial to some species.

Several of the most abundant or ubiquitous species in our surveys—Largemouth Bass, Yellow Perch, Rock Bass, Bluegill, Bluntnose Minnow, Pumpkinseed, Central Mudminnow, Iowa Darter, and Johnny Darter—were often found at similar numbers across the range of dock densities. Jacobus and Webb (2005) found widely distributed fish that were highly mobile and most abundant in their study appeared to be least affected by the size and distribution of macrophyte beds. Valley et al. (2010) found that Blacknose Shiners, Banded Killifish, and Blackchin Shiners moved extensively in a north-temperate mesotrophic lake. In our study, high catches of all three of these species were common at higher dock densities (10–15 docks/km). Only Blackchin Shiners were significantly less likely to be found in more highly developed lakes. Thus, our hypothesis that some fish species would decline or disappear with increasing development was not supported.

Although we found no interaction between lake size and development in our study lakes, the effect of lake size on the number of fish species captured was more important than dock density in linear models. Thus, even the limited range of lake sizes included in our study influenced the number of fish species caught. We also sampled more sites in larger lakes, which should have improved our chances of catching rare species. In Minnesota, larger lakes are more highly developed than small lakes (Jacobson et al. 2016). Jennings et al. (2009) concluded that a similar trend for fish species richness was probably due to game fish stocking in lakes with development. Since we sampled nearshore species, most of which are not stocked, this does not explain our results, but fish introductions via bait bucket could be responsible. Beck et al. (2013a) found a similar, unexpected, trend for the number of macrophytes species in Minnesota lakes, which they speculated may have been related to an interaction between lake size and development density.

The fish community composition metrics analyzed do not explicitly rely on species richness; rather they are computed using the proportion of fish belonging to various groups (Table 3). However, these metrics could be lower in species-poor communities if key species are absent. The confounding effect of lake size would make impacts of development more difficult to detect if larger lakes tended to have both a higher development density and more fish species present. Despite this potential confounding effect we detected negative changes in fish communities with higher development. Examination of dock data for the state of Minnesota revealed a much wider range of dock sizes than we found and that lakes with higher dock density tend to have greater variance in dock area (Beck et al. 2013b). Future studies that include a range of lake sizes will need to account for the effect of lake size on both response variables and development intensity.

Our study lakes contained a number of popular game species, including Largemouth Bass, Northern Pike, Walleye, Bluegill, Yellow Perch, and Black Crappie. Some of these species, such as Largemouth Bass and Bluegill, were sampled in the nearshore area of every study lake, while others were seldom caught in nearshore areas. The abundance and diversity of small-bodied species is important in that they are prey for many game species in our study lakes. Communities with high biological integrity indicate that lakes are under less anthropogenic stress and may be more resistant to new stressors (Carey and Wahl 2010; Chu et al. 2015). Our study supports the hypothesis that high levels of development have negative impacts on the fish community. Although we did not detect widespread negative impacts on popular game fish species, a loss of ecological integrity over time puts these species at risk of decline. The shape of the response curve for vegetation-dwelling species suggests that the relationship between fish community metrics and development is curvilinear, with a rapid drop in metric scores between 10 and 15 docks/km. If this relationship is confirmed it would provide land managers with much needed guidance for future decisions on lakeshore zoning.

Management Implications

Ours is the first study to indicate that parts of the fish IBI sampling protocol developed by Drake and Pereira (2002) may also have utility for assessing the impacts of shoreline development in addition to water quality and watershed development. The integration of the responses of various fish species by using nearshore community composition metrics appears to be more sensitive to changes in shoreline development than is the response of individual taxa. Our analysis also adds to existing research linking reduced habitat quality and complexity to increases in lakeshore development, although it does not identify cause and effect.

Many studies, including ours, reveal reductions in habitat quality and declining fish community integrity occur with increasing shoreline development. However, many of the habitat changes that we suspect are related to changes in fish communities are the result of choices made by lakeshore owners. Development itself may not have substantial impacts on littoral habitat if the shoreline is left relatively undisturbed. The link that we detected between dock density and lower habitat complexity and fish biotic integrity might be reduced if landowners embrace natural buffer zones and employ small recreational footprints in lakes. We found that both habitat and fish variables frequently maintained high values as development increased to at least 10 docks/km.

Fisheries managers often work closely with lakeshore owners and lake associations who want to be good stewards of their lakes. Studies like ours show links between nearshore habitat and fish populations that help illustrate the importance of landowner activities to each lake. The choice to remove CWS and vegetation from nearshore areas may become uncommon among people who understand that these activities may have cumulative negative impacts. As a primary resource for educating the public about healthy lake ecosystems, fisheries managers need to discuss the importance of healthy nearshore habitat for the larger system.

As lakeshore development continues to expand, we can expect policy debates regarding lakeshore zoning. We suggest that protection of nearshore structural habitat, such as CWS and emergent vegetation, benefits fish communities. Zoning officials might consider innovative rules that protect habitat, both on land and in water, thus mitigating the ecological impacts of new development on fish communities and reducing the cumulative impacts to lakes.

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