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Is Littoral Habitat Affected by Residential Development and Land Use in Watersheds of Wisconsin Lakes?

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ABSTRACT

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We measured differences in nearshore littoral zone habitat among lakes with different amounts of residential development and different patterns of watershed land use. Sampling stations were located at randomly selected sites within the nearshore littoral zone of limnologically similar lakes. An index of development density (based on counts of residential structures) and watershed cover types detected by satellite imagery summarized human influence in the riparian zone and watershed. To compare effects of development at local sites to effects of cumulative development density (structures/km shoreline), we used analysis of covariance. Quantity of woody debris, emergent vegetation and floating vegetation decreased at developed sites and in lakes with greater cumulative lakeshore development density. Littoral sediments contained more fine particles at developed sites and in lakes with greater development density. Sediment composition, quantity of vegetation, and woody debris were weakly associated with differences in watershed land use. Cumulative changes to watersheds and riparian zones are associated with measurable differences in littoral habitat that may not be detectable at smaller scales. For effective conservation, regulatory programs should consider the cumulative effects of development and land use on aquatic systems.

Key Words: aquatic habitat, lakes, land use, development, spatial scale, macrophytes, substrate, woody debris.

Residential and recreational development can induce profound changes in natural landscapes. Understanding the nature of these changes is critical for managing, mitigating, or preventing deleterious consequences of development. Lakes are vulnerable to changes that occur not only within the aquatic

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environment, but also to changes in the watershed. Lakes and their watersheds have been extensively studied with regard to some potential consequences of development pressure, such as inputs of nutrients and contaminants through non-point sources (Downing and McCauley 1992). Inputs of phosphorus have predictable effects, decreasing water clarity and increasing primary production (Schindler et al. 1971), and in severe cases leading to oxygen depletion and fish kills. Human activity also affects biological communities of lakes by altering rates of fish species colonization through deliberate or unintentional introductions (Radomski and Goeman 1995, Rahel 2000). People may also indirectly change food webs through harvest of resident organisms and subsequent cascading trophic effects (Carpenter and Hodgson, 1985). Finally, human activity can change the physical structure of the environment, altering the habitat within lakes.

In comparison to the well-studied effects of land use on water quality, consequences of land use change or development pressure for structural, in-lake habitat have received little attention. Bryan and Scarnecchia (1992) compared fish distributions along developed and undeveloped stretches of lakeshore within a lake, noting that some structural habitat differences were associated with local fish assemblages. Christensen et al. (1996) found that development along Wisconsin lakeshores reduced the quantity of littoral coarse woody debris. Beauchamp et al. (1994) studied fish distributions in relation to artificial shoreline structures in Lake Tahoe and found that complex structures were associated with increased fish densities. In Great Lakes wetlands, Crosbie and Chow-Fraser (1999) detected a reduction in submergent macrophyte species richness associated with a decrease in forest and increase in agricultural land use. Trial et al. (2001) found localized differences in fish species composition associated with urbanization of shorelines and vegetation within a Texas reservoir. In a seventeen-lake study, Jennings et al. (1999) investigated fish distribution in relation to both habitat complexity and anthropogenic stress at the scale of whole lakes. Whereas localized habitat complexity was associated with greater species richness, basin-scale effects as indicated by water quality were associated with reductions in intolerant fish species.

Structural elements of lentic systems are clearly important to a range of taxa, although responses of aquatic communities to alteration of lentic habitat structure are poorly understood. Responses of lake biota, such as fishes, to anthropogenic stressors have been described only in terms of general trends (Jennings et al. 1998, Whittier and Hughes 1998), and basic questions remain regarding mechanisms for these changes. Thus, hypotheses regarding mechanisms for aquatic community responses to human disturbances remain somewhat speculative and centered on the better-studied phenomena of water quality change and species introductions. A notable exception is the recent work of Radomski and Goeman (2001), who documented a link between vegetation and both biomass and size of three fish species in Minnesota lakes. Most studies of lake habitat have focused on a narrow range of habitat features. To improve our understanding of how development and shifting patterns of land use change the physical structure of lakes requires perspectives that incorporate a wider range of habitat attributes and evaluate human activity at multiple spatial scales. In this study, we used a comparative approach with northern Wisconsin lakes that are limnologically similar but subject to different amounts of development. Our objective was to evaluate relations between several habitat attributes and development at three spatial scales: that of residential properties, the entire lakeshore, and the watershed.

Methods

Lake Selection

Study lakes were selected to minimize ecoregional and limnological differences that might lead to large differences in habitat structure. To reduce the extent of natural differences among lakes that might confound interpretations of development and land use associations with habitat, we used a classification system developed by Emmons et al. (1999). The 34 lakes were all located in northern Wisconsin, and conformed to a single lake class characterized by relatively small surface area (18 to 80 ha), high landscape position (small watershed area), and similar depth (Table 1). Most of the study lakes also had low alkalinity (<55 mg $\cdot$ mL^{-1}), although 3 exceeded the values recommended by Emmons et al. (1999) for classifying lakes in this region. Some lakes within this class remain undeveloped; therefore, use of this class has potential for practical application to future land use decisions. A subset of 16 lakes was first used to evaluate effects of site-level riparian development and development density on habitat. Candidate lakes for this analysis were randomly selected from a pool of lakes meeting the classification criteria.

To evaluate relations between littoral zone habitat and watershed land-use patterns, we combined data from the 16 lakes with data from 18 additional lakes. Whereas lakeshores of 14 of the original 16 lakes contained at least moderate development, the watershed-level analysis required inclusion of more lakes with low development density to adequately represent the existing range of conditions. To accomplish this, we used a stratified-random approach, selecting the additional lakes from the Nicolet-Chequamegon National Forest (NCNF), which contains many undeveloped or lightly developed lakes. Thus, the 18 lakes were randomly selected from candidate lakes that met the classification criteria and were located on the NCNF.

Habitat Measurements

Within the 16-lake data set, habitat characteristics of the nearshore littoral zone were measured at each of 20 randomly selected sites within each lake (N=320 sites). Measurements within the subsequent 18 lakes were taken at 6 randomly selected sites within each lake (N=108 sites). Differences in sample effort reflected slightly different objectives of the two primary analyses. In the first group of 16 lakes, we evaluated

Table 1.-Limnology and morphometry data of 34 northern Wisconsin lakes used in this study. Two sets of analyses were conducted; the first sixteen lakes (marked with asterisk) were part of the analysis addressing development at local sites. All 34 lakes were used in subsequent analyses.

Lake	Surface Area (ha)	Maximum Depth (m)	Alkalinity (mg·L^{-1})	Watershed Area (ha)
Cedar*	79.5	6.1	34	7751
Upper Clam*	69.1	6.1	32	4435
Big Dardis*	60.0	7.0	20	431
Granite*	64.0	9.1	54	2794
Bass*	54.1	9.4	9	257
Cisco*	39.6	32.0	5	34
Bass-Patterson*	78.3	10.6	19	445
Tahkodah*	63.3	5.5	6	243
Crystal*	46.3	8.8	9	97
Poquette*	40.4	7.0	17	261
Black*	52.1	5.2	25	1203
Little Bear*	53.3	16.8	19	38
Pallette*	72.1	18.2	6	80
Atkins*	73.3	24.4	10	227
Leisure*	31.2	10.7	18	186
Taylor*	32.2	5.0	10	917
Spring	37.5	4.5	20	293
Otter	29.2	6.1	140	2102
Anodanta	21.7	9.1	140	7651
Arrowhead	27.5	11.8	100	101
Langley	20.0	2.7	21	56
Bass	30.4	10.7	9	103
Woodbury	30.0	6.1	42	133
Ed's	21.2	5.5	2	273
Imogene	27.5	12.5	2	72
Van Zile	32.5	5.2	1	15
McLaren	27.5	5.2	2	178
Little Star	21.3	5.5	1	99
Dewey	32.3	5.5	<1	89
Ludington	20.4	9.5	1	371
Wolf	18.5	4.8	<1	68
Bastile	23.8	7.0	<1	92
Flynn	26.7	12.8	34	214
Bailey	36.7	5.5	<1	372

differences at the whole-lake and site levels, whereas the second group of lakes was used only for evaluation of differences at the watershed scale.

To quantify littoral zone habitat at each site, four systematic transects were placed at 3-m intervals (starting 3 m from edge of 15-m wide site); transects were oriented perpendicular to shore and extended from shore a distance of 5m. The degree to which interstitial spaces of coarse substrates were embedded with fine particles (embeddedness) was estimated visually at intervals (0.5 m intervals to 3.0 m, and then at 4.0 and 5.0 m) along each transect. The term "embeddedness" (Platts et al. 1983) is established in the stream habitat literature, where the issue of sedimentation and impacts on fish has received considerable attention, and is measured on a scale from 0 to 5 with higher numbers indicating greater embeddedness. Visual counts and quadrat sampling were used to quantify woody debris and vegetation at each site. A 1 m^2 quadrat was placed along each of the four transects at distances of 0.5, 2.5 and 4.5 m from shore. Within each quadrat we individually estimated percent coverage of emergent vegetation, submergent vegetation, floating vegetation, and small woody debris (<4 cm in diameter). We counted each piece of medium woody debris (>4 cm but <10 cm in diameter) that intersected or was contained within any quadrat, and obtained a total count of coarse woody debris (>10 cm in diameter) occurring within the 15m x 5m site. Development at the level of individual sites was a binary variable representing the presence or absence of a residential structure within 100 m of the shore.

Lakeshore Development Density

In the first 16 lakes, development density (number of structures/km shoreline) was calculated by counting residential structures from aerial photographs of the shoreline taken during 1998-99. For the remaining 18 lakes, residential structures were counted by an observer cruising the shoreline in a boat. In both cases, residences were considered to be part of the riparian zone if they were located within 100 m of the shore.

Land Use

Land use within lake watersheds was quantified with LANDSAT satellite imagery. The predominant cover types within 30 m^2 blocks were defined as forest, wetland, open water, grass, agriculture, shrub, and barrens. Based on direct observation on the ground, grass and agriculture were not well differentiated in the GIS data set, as much of the grass was likely pasture. Therefore, these two cover types were combined. None of the lakes contained concentrated urban land use.

Statistical Analyses

In the first 16 study lakes, we evaluated the effect of development on structural habitat attributes of the site at two scales. In this analysis of covariance (ANCOVA), site-level development was a class variable (presence or absence of a structure on the shoreline adjacent to the sampling site) and lake-wide development density (structures/km) was the covariate. Since the ANCOVA analyses were performed at the whole-lake scale, we considered lake as a random effect in a mixed effects model. All analyses were performed using the SAS Mixed Procedure. All dependent variables were properly transformed using either a log (+1) transformation or an arcsin-square root transformation for proportion data.

To evaluate the effects of watershed land use and density of shoreline development on littoral zone habitat, land-use variables were derived from satellite imagery and were expressed as percentage of the watershed containing each land-use type. The land-use data were summarized with principal components analysis (PCA). In this analysis, all components with eigenvalues greater than one were retained for further investigation. Each littoral zone habitat variable (mean value for each lake) was then correlated with each component using a Pearson product moment correlation to examine the associations of watershed landuse with littoral zone habitat characteristics. All data for all analyses were transformed as appropriate using a Box-Cox optimal power procedure (Yandell 1997). All analyses were conducted in SAS 6.12.

Results

Site- and Lake-Level Analyses

Within the 16 lakes in which undeveloped and developed sites were compared, both the local effect of a residential structure and cumulative effects of total density of structures on the lakeshore were evident on nearshore habitat. Both site development and lakeshore development density were significantly related to substrate embeddedness ($P = 0.0003$ and $P = 0.004$ respectively). Comparisons of least square means indicated that if a house was present, significantly greater embeddedness was observed than when a house was absent (4.12 versus 3.54 respectively, $P< 0.001$). Additionally, measures of embeddedness were positively related to the number of structures/km. The interaction between site level development (presence or absence of residential structure) and lakeshore development density was not significant. The highest levels of embeddedness were observed at developed sites in lakes with high structure density.

Large woody debris had a significant, negative relation to both site level development and lakeshore development density (P = 0.026 and P = 0.004 respectively). The interaction of site level development and lakeshore development density was also significant (P = 0.030) with significantly less large woody debris found at sites in highly developed lakes with adjacent riparian development.

The amount of medium woody debris was more strongly associated with the cumulative development of the lakeshore with less medium wood found in lakes with more development (structure density P = 0.003) regardless of the development status of the adjacent lakeshore (P = 0.125). Small woody debris however, had no significant relationship with either development at the site level or the whole lake level.

Littoral zone vegetation also was associated with development both at the site and whole lake level. Emergent vegetation was reduced at high levels of development density and if the adjacent riparian area was developed (P = 0.006 and P = 0.002 respectively). The interaction between site level development (presence or absence of residential structure) and lakeshore development density was not significant (P = 0.078). Comparisons of least square means indicated that if a house was present in the adjacent riparian area, about 20% less emergent vegetation was observed than when a house was absent (P = 0.013). The lowest levels of emergent vegetation were observed at developed sites in lakes with high structure density.

Abundance of floating vegetation was reduced in lakes with higher development density and at developed sites (both P<0.0001). The interaction of development density and house presence was significant (P<0.0001) with the least amount of floating vegetation observed at developed sites in lakes with higher levels of lakeshore development. The amount of submergent vegetation was significantly affected by neither the cumulative density of development nor by the presence or absence of a house at the sampling site.

Watershed and Lake Level Effects

Principal components analysis of land use data for 34 lakes resulted in two axes that explained 92.7% of the variance in the data (Table 2). The first principal component (PC1) had heavy positive loading on percent forest cover and negative loadings on other landuse types. The second principal component (PC2) had positive loading on wetland and negative loading on agriculture. We used these two principal components as summary variables of watershed landuse because they described most of the variation in the data set (Table 2).

Correlations of littoral zone habitat measures and watershed landuse as summarized by PCA indicated several significant associations. The degree of substrate embeddedness increased as forested lands decreased and agriculture increased within the watershed (Table 3). Both large and small woody debris were correlated with watershed land use. Significantly less large and small woody debris were observed in lakes with low forest cover within the watershed (Table 3). Medium woody debris was inversely correlated with the amount of agriculture within the watershed.

The three structural categories of vegetation, emergent, submergent, and floating were all correlated with watershed land-use variables. Emergent and

Table 2.–Correlations of the first two principal components with the original land-use variables along with proportion variance explained by each component with eigenvalues greater than one. Principal Component Analysis (PCA) conducted on watershed land-use of each lake in the 34-lake dataset.

Watershed Land-Use	Component 1	Component 2
Percent Forested	0.883	-0.049
Percent Wetland	-0.283	0.727
Percent Agriculture/Grassland	-0.366	-0.684
Percent Barren	-0.041	0.004
Percent Shrubs	-0.024	-0.004
Percent Open Water	-0.046	0.035
Percent Variance Explained	0.665	0.262
Cumulative Variance Explained	0.665	0.927

floating vegetation were both less abundant in lakes with low forest cover within the watershed, and floating vegetation was also related to amount of agriculture and wetland (Table 3). Submergent vegetation was also associated with watershed land use with less submergent vegetation observed in lakes with less forested watersheds (Table 3).

Discussion

Human influence at each scale was related to a variety of structural habitat characteristics in the littoral zone of north temperate lakes. Habitat variables were significantly correlated with: 1) development at individual sites; 2) density of riparian development at the whole-lake scale; and 3) watershed land use. Development was associated with a wide range of habitat variables including attributes of substrates, macrophytes, and wood.

Coarse substrates have interstitial spaces that provide living space for a variety of organisms (Hynes 1970). In streams, a common form of habitat degradation is the filling of these spaces with fine sediment from erosion, leading to poor survival of incubating fish eggs or displacement of intolerant aquatic organisms (Cordone and Kelley 1961, Scrivener and Brownlee 1989). The extent to which this form of habitat modification occurs in lakes has received little attention. Our results indicate a greater degree of substrate embeddedness associated with the presence of development at the level of individual sites, and with greater density of development around the lake. Concurrently, the land use analysis suggests that conversion of watershed land use to agriculture also contributes to substrate embeddedness. Although we did not assess mechanisms, the results are likely attributable to effects of land use on sediment transport. Soils disturbed by construction and removal of vegetation allow more erosion and transport of fine sediment particles, directly affecting substrates. Land-use changes from forest to agriculture likely contribute to changes in rates of sediment transport to the lake. Although we did not measure water quality, increased sediment transport would likely lead to greater amounts of other materials such as nutrients and contaminants entering the lake.

The structural habitat element that has probably received the most widespread attention in aquatic systems is woody debris. Although most of the literature concerning distribution of wood concentrates on streams, relatively few studies address lakes. In north-temperate lakes, the reduction in woody debris as a consequence of riparian development was first demonstrated in a set of 16 Wisconsin lakes by Christensen et al. (1996). Our analyses of woody debris distribution in 34 additional lakes is consistent with their findings for coarse woody debris and provide additional information regarding interactions at different spatial scales, and data on distribution of smaller wood. In this study, the quantity of large wood was reduced at developed sites, as well as in lakes with higher levels of lakeshore development density. Large woody debris was also less abundant in lakes with low forest cover in the watershed. Reduced abundance of woody debris in smaller size categories was associated with development density (medium woody debris). Overall, the results are consistent with the hypotheses that development reduces local abundance of woody debris, and that both the cumulative effects of development and watershed land use changes affect the overall distribution of this habitat type in lakes. Christensen et al. (1996) discussed the relation between development and wood removal from littoral and riparian areas. Removing forest cover and removing trees to develop riparian property eliminates sources of wood, while

Table 3.-Correlations of measured habitat variables from 34-lake data set with principal component score of watershed land-use variables. PC-1 was associated with forests while PC-2 was associated with wetlands (positive) and agriculture (negative). All correlations significant at P≤ 0.01, N.S. indicates non-significant correlation.

Habitat Measure	Correlation PC-1	Correlation PC-2
Substrate Embeddedness	-0.358	-0.236
Percent Emergent Vegetation	0.244	NS
Percent Floating Vegetation	0.199	0.185
Percent Submergent Vegetation	0.197	0.244
Large Woody Debris	0.315	NS
Medium Woody Debris	NS	0.222
Small Woody Debris	0.287	NS

riparian landowners often remove additional wood from the littoral area to reflect personal aesthetic preferences. Similar results were also observed by Jennings et al. (1999), who found a relation between placement of shoreline structures and habitat simplification, including loss of woody debris.

In this study, we evaluated general categories of macrophytes that differ in the form of structural habitat that they may provide for other aquatic organisms. For the purposes of describing gross differences in distribution of habitat across many lakes, this approach is more practical than a species-based approach. We found that emergent macrophytes had reduced abundance at developed sites, in lakes with high development density, and in lakes with less forest and wetland cover in the watershed. Floating vegetation was also reduced in relation to site-level development, development density and reduction of forest and wetland cover. In a recent study of Minnesota lakes, Radomski and Goeman (2001) also found reduced abundance of floating leaf and emergent vegetation in relation to human development of lakeshores at local sites. However, the results of Radomski and Goeman (2001) differ from ours in the weaker relations they detected between vegetation and development at the whole-lake scale. Both studies selected lakes within an objectively defined limnological class; however, the Minnesota study included only lakes with a minimum of 12 residences; perhaps sufficient loss of vegetation occurs at lower development densities to obscure the relation when undeveloped lakes are absent from the analysis.

Although this study was designed to detect robust patterns of association rather than mechanisms, we can speculate about the observed relations. Macrophytes are often perceived to be a nuisance to riparian landowners and can be directly removed physically or by chemical treatment, a mechanism that tends to be site-specific. In addition, physical disturbance from increased boating activity has been shown to reduce macrophyte abundance (Asplund and Cook 1997) – this is a more general type of disturbance associated with greater development but not necessarily confined to developed sites. Other general impacts might stem from nonpoint inputs of nutrients or sediments.

Submergent vegetation did not appear to be affected by site level or lake level development, and although correlations with land use were significant, they were also fairly weak. The correlations showed that in lakes with less forest cover and more agriculture, submergent macrophytes were less abundant. Perhaps sensitive submerged macrophytes could be affected by non-point source runoff that changes water quality or substrate, as observed in the relation between land use and substrate embeddedness. However, this would likely lead toward favorable conditions for different macrophyte species, thus changing species composition but not necessarily abundance in this broadly defined group. Follow-up studies focusing on species composition would be required to better understand interactions between changes in watershed landuse and macrophyte assemblage.

Implications for Lake Management and Conservation

Lakes are hierarchically structured with attributes at landscape, watershed, lake basin, and local habitat scales each contributing to ecosystem function (Kolasa and Pickett 1992). Lake habitat generally has been managed at smaller scales, and much of our regulatory framework remains focused on the level of individual properties, for example, restricting cutting of riparian vegetation and regulating construction activity at the shoreline of individual residential lots. However, processes at larger scales also contribute to the shaping of habitat; therefore, habitat conservation is dependent upon maintaining functional attributes at these larger scales. Although conservation approaches designed to manage habitat at smaller scales clearly have application and benefit, the results suggest that protecting small pieces of habitat within lakes is probably insufficient to maintain ecological integrity because many impacts are transported from elsewhere in the lake or watershed. A comprehensive approach to lake management should include not only in-water and riparian zone management, but should also put appropriate emphasis on activities aimed toward maintaining watershed scale processes. Examples include maintaining intact wetlands, agricultural and forestry best management practices to reduce non-point source runoff, maintenance of vegetative riparian buffers, and limiting the density of development in riparian zones through mechanisms such as zoning.

The general pattern of association between development and several lake habitat variables seems fairly robust, suggesting that habitat monitoring might be useful to a lake management program. However, any habitat monitoring program would need to be calibrated to account for natural ecoregional and limnological differences that affect expectations for littoral habitat. In addition, whole-lake and watershed effects are the cumulative result of many incremental changes accumulating and interacting over time (Jennings et al. 1999). By their nature, these incremental causative factors in habitat modification are likely to be in place for some time before their impacts are realized in the water. Because of time lags between impacts and detectable responses, lake management decisions cannot be based exclusively on reaction to habitat-based indicators, but should also emphasize proactive conservation measures at the scale of whole lakes and watersheds.

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