ABUNDANCE AND DIVERSITY OF FISH IN RELATION TO LITTORAL AND SHORELINE FEATURES

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ABSTRACT

ABUNDANCE AND DIVERSITY OF FISH IN RELATION TO LITTORAL AND SHORELINE FEATURES

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The effects of small-scale shoreline residential development on littoral fish abundance and species richness was examined at three different scales of observation (within 122, 244, and 488 meters) in Lake Simcoe (Ontario, Canada). A mixed model regression was used to test for effects of development after accounting for seasonal and spatial variation in environmental variables known to affect distribution and abundance of fish. Fish were aggregated near single development structures, such as permanent docks, and repelled from other single structures, such as bank stabilisation. Shoreline developed with multiple features, such as docks combined with break walls, tended to be positively correlated with fish abundance but negatively correlated with species richness. Features such as docks and break walls combined with boathouses were generally associated with a decrease in both abundance and richness. Cluster analysis detected no consistent pattern of association between specific fish assemblages and residential development across the three scales of observation. Increased density and diversity of shoreline residential development tended to be associated with reduced fish abundance and species richness. The specific development features associated with these patterns change with the scale of observation, indicating that fish responded to proximally and distantly located habitat alterations.

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Dedicated to all those fish that gave of themselves to tell us how it is, to my mother for always providing, particularly when no one else could, to my father for instilling a need to thrive through learnedness, and to my sister as an example to strive for.

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They will question thee concerning what they should
expend. Say: "The abundance."

The Koran

Introduction

Habitat alteration in land- and waterscapes is thought to be a leading cause of population and species extinction (Groombridge 1992; Myers 1997). In North American freshwater systems, it has been estimated that approximately half of the fish species extinctions are caused by habitat alteration (Groombridge 1992; Thomas 1994). Such findings have led governments in Canada and the U.S.A. to develop legislation that identifies the need to detect and mitigate the effects of human activity on species occurrence (e.g. Engangered Species Act, U.S.A.), ecosystem integrity (Westra 1994) and system productivity (Minns 1997).

Although the presence of suitable habitat is recognized as an important factor, the specific size, type, and configuration of habitat that must be present and particularly that which must be absent is not fully identified or understood. Facilitating such an understanding requires an examination of patterns between habitat, habitat alterations and occurrence of organisms, along with an understanding of how these patterns vary as a function of scale. Detecting patterns within and among systems and studying how these patterns vary with observational scale is central to the isolation of causative mechanisms operating within ecological phenomena (Levin 1992). In applied ecology, an understanding of scale of impact could shed light on the magnitude and location of repercussions expected from habitat alterations.

Detecting effects of habitat alteration on biota is challenging because, 1) logistical and time constraints allow for few large-scale ecological manipulative experiments, 2) statistical techniques used in observational studies often suffer from low adequacy (James and McCulloch 1990), low power (Peterman 1990), biased estimates (Koenig 1999), and 3) the strength of effects is often contingent on the scale of the observer and the extent of background variability (Levins 1992). These difficulties have not reduced the urgency with which ecologists are requested to study large-scale issues of human impact thus resulting in an increased use of data from a mixture of sources like observational and monitoring studies (Ex: Bethke and Nudds 1995).

Large-scale alterations to habitat induced by resource extraction, town expansions, and other industrial sectors such as power plants may be shown to affect organisms in aquatic systems (Osenberg and Schmitt 1996). Such alterations have attracted much research partly because their activities operate on large spatial scales and may cause impacts on similarly large scales. Yet, relatively little is known of the small-scale changes, and potentially additive effects on a large scale, of shoreline residential habitat alterations in lakes. Owners of waterfront properties typically build docks, boathouses, and various shoreline-retaining structures such as bank stabilisation and break walls to increase the value and enjoyment of their property and surroundings.

Increasing habitat complexity has been shown to be positively correlated with species diversity in aquatic systems (Eadie and Keast 1983; Benson and Magnuson 1992). Shoreline development structures may increase species richness or abundance of fish for similar reasons, as is the case for underwater reefs in marine systems (Turner et al. 1969; Prince and Maughan 1978), though evidence suggests the effect may not be noticeable in freshwater systems (Bohnsack 1991). Shoreline development may increase the complexity or heterogeneity of habitat at the land-water interface with potential influences on the distribution, feeding efficiency and growth of fish (Crowder and Cooper 1979), and docks and other floating structures may act as visual shelter from predators located in a sunlit environment (Helfman 1979; Bohnsack et al. 1991). Recent evidence suggests that interstitial space between materials used to build break walls may also attract fish by providing shelter (Walters et al. 1991; Jennings et al. 1999).

On the other hand, shoreline habitat alteration may have negative impacts on fish and other organisms. For example, development of shoreline properties and especially the removal of riparian trees reduce abundance and quality of coarse woody debris, a component of littoral fish habitat (Christensen et al. 1996). Shoreline development has also been associated with a lower abundance and richness of fish resulting from the removal of aquatic vegetation (Bryan and Scarnecchia 1992). Finally, in multi-lake studies across the northeastern U.S., increasing human activity in the watershed and along the shoreline of lakes was found to be related to decreased cyprinid species richness, presumably due to physical habitat alteration (Whittier 1997; Allen at al. 1999).

In addition to the specific effects of development, scale-dependent patterns can make it difficult to understand and manage habitat alterations. For example, the effects of shoreline development are more easily detectable at large spatial scales, such as watersheds, than at small scales, such as shoreline reach (Christensen et al. 1996; Whittier 1997; Allen at al. 1999; Jennings et al. 1999). Yet individual development features occur at a scale of several meters. Effects of these alterations at both local and system-wide scales are poorly understood, but of interest in applied (Lewis et al. 1996) and theoretical ecology (Levins 1992).

I examined the effects of littoral and shoreline residential development on fish abundance and richness in Lake Simcoe, Ontario, Canada. I tested whether fish abundance and species richness was lower at sites with greater development features in the vicinity, after accounting for seasonal and spatial variation in environmental variables known to be associated with fish occurrence, such as substrate as well as onshore and aquatic vegetation. Further, I examined patterns between fish occurrence and shoreline development at multiple scales of observation as a way to study cumulative effects and the spatial repercussions of habitat alteration. This approach focused on coarse indicators of fish occurrence rather than specific patterns in community composition in order to make general inferences about the effects of shoreline residential development regardless of local species assemblage. I used total species richness since species loss may be linked to decreased ecosystem performance (Naeem et al. 1994; Johnson et al. 1996). Descriptive statistics on community structure are presented to explore potential effects of habitat alteration and observational scale at the species level.

Materials and methods

Study site

Lake Simcoe (44°30´ N, 79°20´ W) is a mesotrophic dimictic lake located in southern Ontario (Figure 1). The lake has a surface area of 722 km^2 and shoreline length of 232 km. Total land area of the watershed occupies 2825 km^2 of which 45% is in agriculture

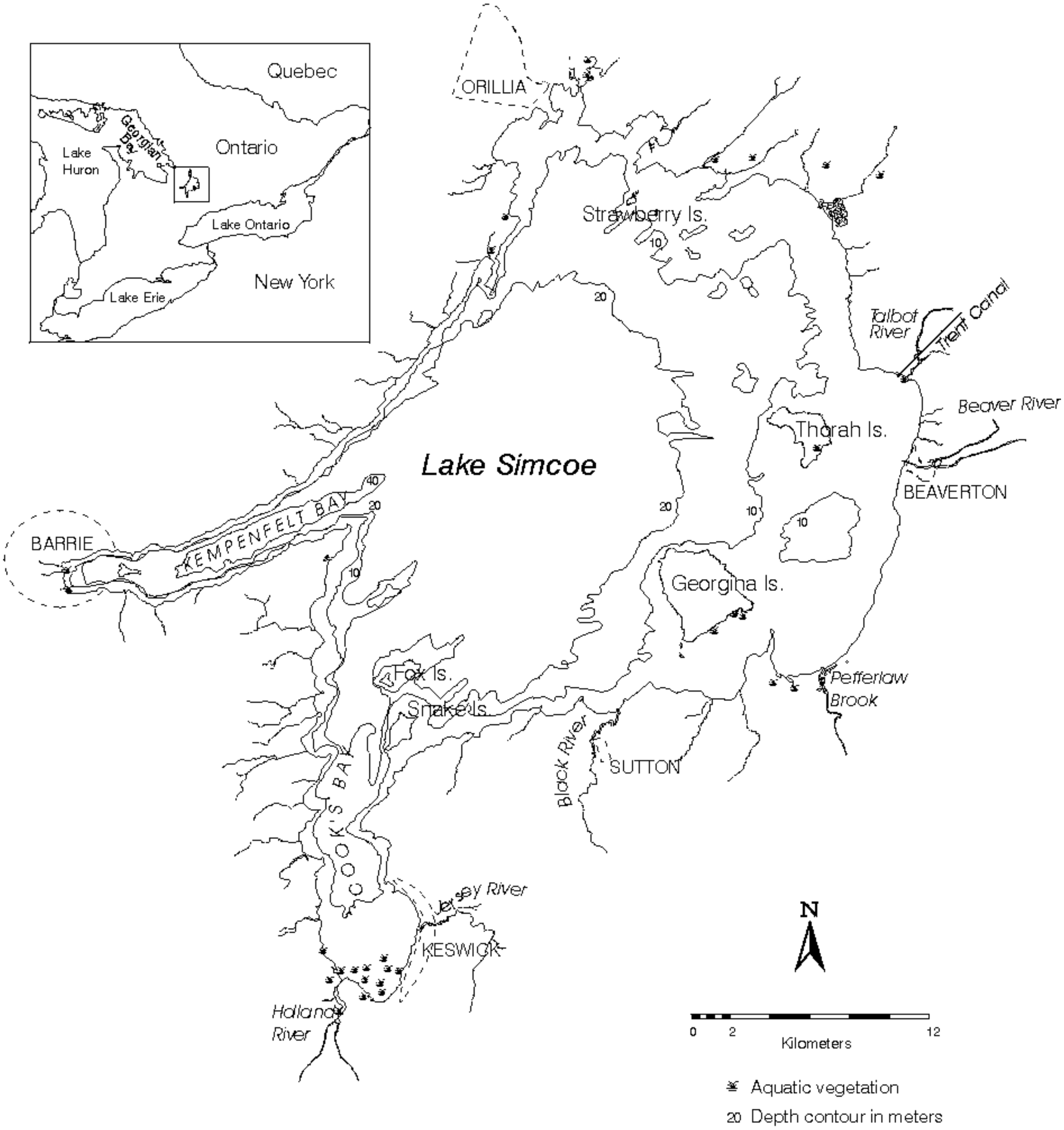

Figure 1 – Map of Lake Simcoe and surrounding human settlements.

and 52% in forest, wetland and scrubland. Urban development represents approximately 3% of the land use (Walker 1997).

Data set

The Lake Simcoe Fisheries Assessment Unit of the Ontario Ministry of Natural Resources collected data on fish, habitat, and shoreline development (see Appendix I for data references).

A protocol was developed to sample fish, habitat, and shoreline residential development for the entire coast of Lake Simcoe throughout the period May to September. The lake was divided into 9 sections and each section was sampled only once between 1982 and 1995. Approximately three sites were selected for each kilometer of coast. However, the amount of each section sampled was variable and depended on available resources. Data were collected along the shoreline of the lake at sites sampled only once (N=502) and at sites sampled weekly (N=114). Sites sampled weekly were selected as representative of the habitat in a specific section and were visited from 5 to 14 times each. Sites sampled only once were located randomly on a map of the lake shoreline overlaid with a numbered grid.

During each visit, fish were collected with a 15-m beach seine (1.7 m depth, 0.32 cm mesh) using one pass. The seine was extended to its full length (or until the water was too deep to wade in) at a 45 degree angle from shore and then circled back to the shore end. Fish were sorted by species and size-class, counted, and released. Field crew members were trained in fish identification by staff from the Royal Ontario Museum. When fish species could not be confidently identified in the field, samples were taken back to the laboratory for identification.

Habitat features measured at each site included in-water substrate, aquatic and terrestrial vegetation, water temperature (±0.5 °C), as well as minimum and maximum depth seined (±0.01 m). Both substrate and aquatic vegetation were visually assessed in the area sampled by the beach seine. Substrate was grouped into categories defined as rock, boulder, rubble, gravel, sand, clay, muck, marl, detritus and silt (Dodge et al. 1987) and described as present or absent. Similarly, presence or absence of floating, emergent and submergent aquatic vegetation was also recorded. Terrestrial vegetation with the potential of providing cover for fish and within one meter of the shoreline was recorded as either absent, low, medium or high.

The location and type of residential development features located on the shoreline were recorded on maps the same year a site was sampled. All structures visible from a boat cruising close to shore were recorded, however, logistical constraints prevented sampling of residential development for the western and southern shore of the lake. Development features were classified as seasonal docks, permanent docks, boathouses, break walls, and bank stabilisation structures. Seasonal docks are structures held above the water on pillars and removed before the lake freezes. Permanent docks are structures left in the water year round and anchored to the lake bottom with rock or concrete under-filling. The majority of docks are for residential use and range from 2 to 4 meters wide and 3 to 10 meters in length. Many docks, however, are for public use and are considerably larger (4 X 40 m for example). Break walls are structures built along the shoreline approximately 1 meter below the high water line and prevent erosion of the shoreline by wave and ice. Bank stabilisations are built above the high water line and prevent washout of topsoil into the lake. Both stabilisation and break walls are constructed of cement, steel, boulders, or gabion baskets.

In order to test for the effect of location of development on fish, features within circular ‘development zones’ of diameter 122, 244, and 488 m surrounding a site were counted. Within each development zones, docks and boathouses were counted, and the length of shoreline (±10 m) occupied by break wall and bank stabilisation measured using a curvimetre (map wheel). The nature of the analysis and of the data recorded on the maps did not allow distinction between building materials or estimation of structure dimension. Small and large structures and building materials are grouped together according to the functional categories seasonal dock, permanent dock, break wall, bank stabilisation, and boathouse. In this way, an attempt to identify the impacts of such structures through their functional roles was made.

In order to meet the assumption of normality relative abundance was log transformed and the square root of richness was used. The variables representing the substrates clay, marl and silt as well as floating aquatic vegetation appeared only a few times throughout the study period exhibiting a 95:5 ratio (95% of values are zero, 5% are one) in occurrence. Variables with a 95:5 ratio are considered outliers in regressions and were eliminated from the analysis to prevent bias (Tabachnick and Fidell 1997). No further univariate (z-scores > 3.29) or multivariate (Cooks distance) outliers were found. Descriptive statistics for all variables are in Table 1.

Table 1 – Descriptive statistics of variables measured in the Lake Simcoe Littoral Zone Study from 1982 to 1995. Shoreline development variables are for the 122 m development zone.

Variable	Minimum	Maximum	Mean	1 S.D.
Fetch (km)	0.02	10.42	3.91	2.54
Water temp. (°C)	8	29	20.56	3.90
Day of year	137	261	190.61	27.83
Rock	0	1	0.14	0.35
Boulder	0	1	0.39	0.49
Rubble	0	1	0.55	0.50
Gravel	0	1	0.59	0.49
Sand	0	1	0.59	0.49
Muck	0	1	0.13	0.34
Detritus	0	1	0.16	0.36
Submerge vegetation	0	1	0.40	0.49
Emergent vegetation	0	1	0.07	0.25
Shore vegetation cover	1	4	2.16	0.99
Dock temporary	0	11	1.42	1.82
Dock permanent	0	8	0.55	1.34
Stabilization (ft)	0	260	16.99	45.02
Break wall (ft)	0	400	32.61	64.87
Boat house (ft)	0	7	0.74	1.32
Abundance	0	19040	209.95	693.80
Richness	0	15	3.95	2.99

Patterns in habitat, development and fish catches

The relationships between abundance and richness of fish, season, development features, and occurrence of macrophyte and substrate type were estimated using the product-moment correlation coefficient *r* (Sokal and Rohlf, 1981). To provide a visual examination of patterns in habitat data, sites were grouped by vegetation and substrate types using K-means cluster analysis (Tabachnick and Fidell, 1997). Sites were plotted by cluster membership on a map of the lake. For shoreline residential development, the density of features immediately adjacent to a site (122 m development zone) was expressed as low, medium, or high (see Results for specific range values) and plotted on a map of the lake as three circles of increasing size.

In order to explore species-specific patterns in fish occurrence as a function of shoreline development, macrophyte, and substrate type, sites were clustered into 5 groups using K-means cluster analysis (Tabachnick and Fidell, 1997). The data set used for this procedure consisted of sites sampled only once and seasonal means of sites sampled weekly (N=386, 384, 383 for development zones 122, 244, 488 m respectively). For each cluster, total fish catch standardized to the number of sites per cluster was calculated for each species.

Analysis

Results from empirical studies in the literature suggested that habitat and development features as well as measures of fish abundance and richness in this study would be inter- and autocorrelated. For example, fish are often found in greater density and richness in areas with abundant and diverse aquatic vegetation (Chick and McIvor 1994; Randall et al. 1996; Weaver et al. 1997). Aquatic vegetation is often found in association with soft substrates and areas of low wind and wave energy (Keddy 1982). Residential shoreline development often occurs where substrates are hard or sandy and aquatic vegetation is absent (Bryan and Scarnecchia 1992). Not accounting for intercorrelation among environmental and fish variables would confound an analysis with too many potential explanations to account for patterns in fish measures. Spatial autocorrelation in ecological data sets can potentially lead to erroneous conclusions about effects (Hinch et al. 1994; Koenig 1999). For these reasons, effects of development on fish measures were tested after accounting for autocorrelation and variation in habitat features such as substrate, aquatic vegetation, and shoreline vegetation. Statistical significance at $P < 0.10$ was used to avoid being overly conservative given the variability in habitat measures and the nature of observational study, and to reduce the probability of Type II error. A mixed-model multiple regression analysis was used to assess effects of shoreline development density on fish abundance and richness. The effect of scale of observation on fish measures was also tested by repeating the analysis with two larger development zones (244 and 488-m).

The statistical model was built with the following terms:

$$\begin{aligned}\text{Log abundance (or square root richness)} &= \alpha + \beta_1(\text{water temperature}) + \beta_2(\text{day of year}) + \\ &\beta_3(\text{fetch}) + \beta_{4\text{-}10}(\text{substrate}) + \beta_{11\text{-}13}(\text{vegetation}) + \beta_{14}(\text{temporary docks}) + \\ &\beta_{15}(\text{permanent docks}) + \beta_{16}(\text{break walls}) + \beta_{17}(\text{bank stabilisation}) + \beta_{18}(\text{boathouses}) + \\ &\beta_{19\text{-}28}(\text{development interaction terms}) + e\end{aligned}$$

In this equation, α is the intercept, $\beta_{1\text{-}28}$ are the regression coefficients, and e is the error that models the variation around β. Substrate consists of the seven variables used in the analysis, while vegetation consists of three variables. Day of year is a way of accounting for season and represents the day number after January 1st. Fetch is an index of potential wind and wave energy at a site. Fetch was calculated using GIS software by taking the mean distance (km) to the shoreline from 32 compass readings (K. Minns, pers. comm., Department of Fisheries and Oceans, Great Lakes Laboratory for Fisheries and Aquatic Sciences, Bayfield Institute, Burlington, Ontario L7R 4A6, Canada).

Mixed-model rationale

Concern has arisen in the biostatistical literature (Legendre and Legendre 1998) that data often do not meet the assumptions of independence and similarity in the elements of the error vector. Such assumptions are the basic working assumptions of many statistical techniques such as multiple regression and analysis of variance. When these assumptions are violated, estimates of fixed and random effects can be biased or inappropriately estimated. An attempt to account for this potential error was made by using linear mixed-models. Mixed-models refers to the inclusion of fixed and random effects and allows one to model correlation around observations and to test for effects after accounting for such correlation. In this study, sites with repeat visits and sites visited only once can be viewed as a random factor since they consist of a sample from a population of many such locations (Tabachnick and Fidell 1996). The basic mixed-model equation is as follows:

$$y = \mu + X\beta + Zu + e$$

In this equation, β is a vector of fixed-effects parameters with design matrix X, *u* is a vector of random-effects parameters with design matrix Z, and *e* is an unknown random error vector with elements that no longer have to be independent and homogeneous. Both β and *u* are estimated by the model. Also, both *u* and *e* can be viewed as random variables with normal (Gaussian) distribution of means equal to zero and variances equal to G and R matrices, respectively. In mixed models, the variance of y is then described as:

$$V = ZGZ' + R$$

In studies with samples in different geographical locations, observations are often correlated in (at least) 2 spatial dimensions. In such a case, it is often assumed that the errors (*e*) are correlated. Correlation in the error can be reflected in the covariance matrix (G) of the random model effects (*u*) or in the covariance matrix (R) of the error term (*e*). A simple model that includes spatial correlation takes the following form:

$$y_i = \mu + e_i$$

Where y_i is the i^{th} observation and e_i is the corresponding error; both of these terms being from site s_i with two geographical coordinates. Generally, one can define spatial correlation by having

$$\mathrm{Var}(e_i) = \sigma_i \text{ and } \mathrm{Cov}(e_i, e_j) = \sigma_{ij}$$

The covariance is assumed to be a function of the distance between sites s_i and s_j (d_{ij}). The model then has the form

$$\mathrm{Cov}(e_i, e_j) = \sigma^2[f(d_{ij})]$$

The MIXED procedure in SAS (Littell et al 1996) is well suited for adjusting or removing spatial correlation to allow for more accurate estimates of means and testing effects. The MIXED procedure allows one to fit a diversity of structures to the function for $f(d_{ij})$. In addition, MIXED uses a likelihood-based estimation method (compared to a method of moment such as least squares) and allows estimation of model fit in the presence of missing data. Different criteria can be used to assess model fit using likelihood-based methods. Models with many parameters may provide a good fit, but provide estimates with low precision. Models with few parameters allow for generalisations, but can produce biased estimates and may not fit the data adequately. Log REML Likelihood is a criteria estimate that allows one to compare models that have a balance between fit and number of parameters (Littell et al 1996). The model with criteria values closest to zero is considered to be better (Littell et al. 1996; Verbeke

1997). In this study, several functions were tested and the power function was found to have the best fit as determined by the log REML likelihood criteria.

Results

Patterns in habitat, shoreline development, and fish catches

Bivariate plots of all variables used in the analysis are in Figure 2. Habitat features were distributed in a patchy fashion (Figure 3). The south and eastern shoreline of the lake consisted predominantly of sites with a mixture of soft and hard substrates and aquatic vegetation while the north and west shores of the lake consisted mainly of hard substrates (Figure 3a). Mean fetch, an indicator used here to represent the relative exposure of the shoreline, tended to be associated with sites having hard substrates and absence of vegetation (Table 2).

The distribution and intensity of shoreline development also appears patchy (Figure 3b-f). A high density of all development features occurs at the most northerly tip of the lake, in proximity to the city of Orillia. However, less development is found on the eastern shore of the lake (except for bank stabilization) where smaller towns are located.

Inter-correlations between habitat and shoreline development are also evident. For example, bank stabilisation, temporary docks, and boathouses are positively correlated to fetch (Table 2). Also, as a general rule, shoreline development tends to be positively associated with presence of hard substrates (rock and boulders) but negatively associated with soft substrates, and presence of vegetation (Table 2). The total fish catch for the study period was 415 440 individuals consisting of 46 species (Table 3). Young-of-the-year consisted of just over half (59%) of the catch. The five most

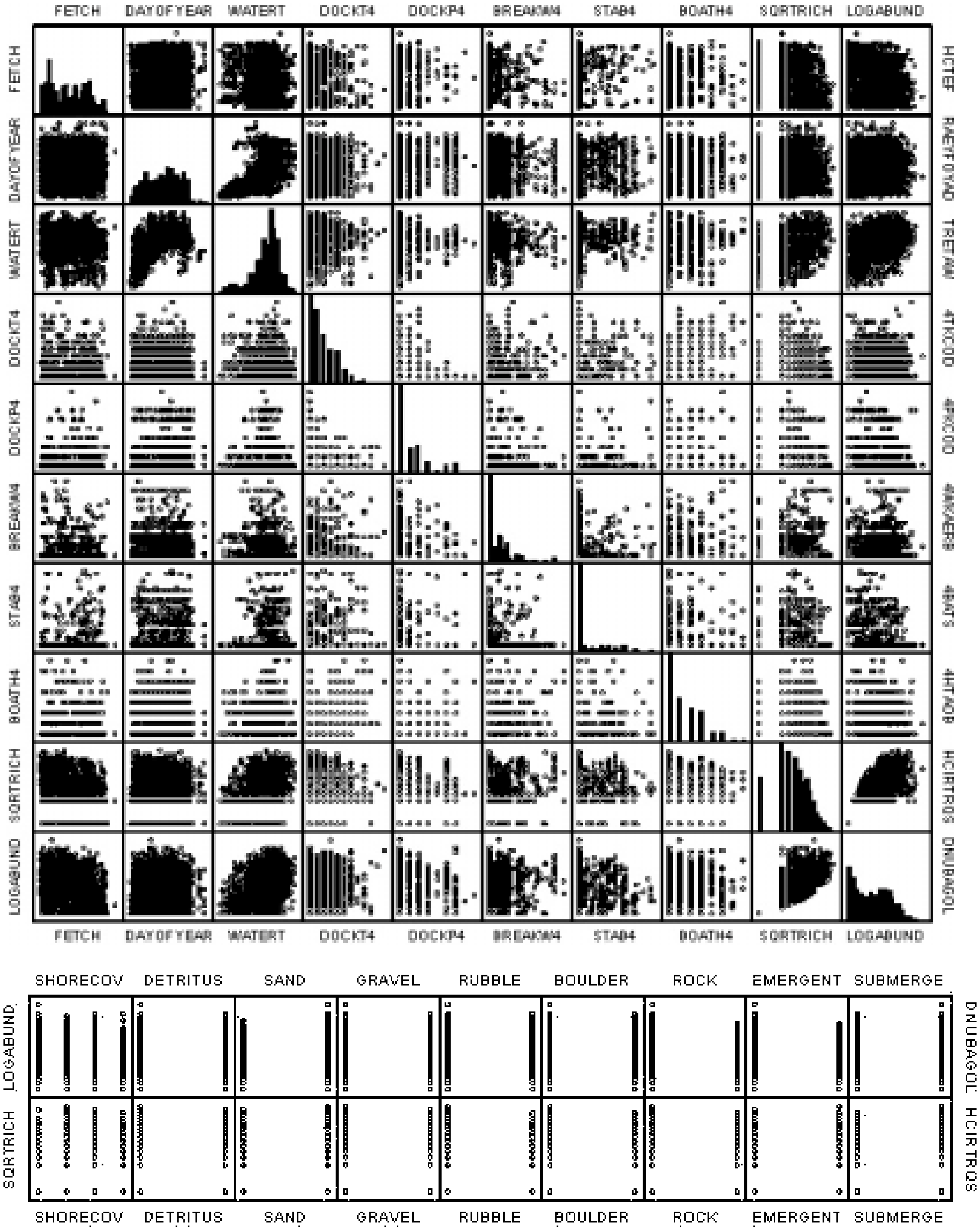

Figure 2 - Bivariate plots of substrate, vegetation, season, and shoreline development variables used in the analysis. The abbreviated variables are water temperature (WATERT), seasonal docks (DOCKT4), permanent docks (DOCKP4), boathouses (BOATH4), break walls (BREAKW4), bank stabilisation (STAB4), shoreline vegetation cover (SHORECOV), square root richness (SQRTRICH), and log abundance (LOGABUND).

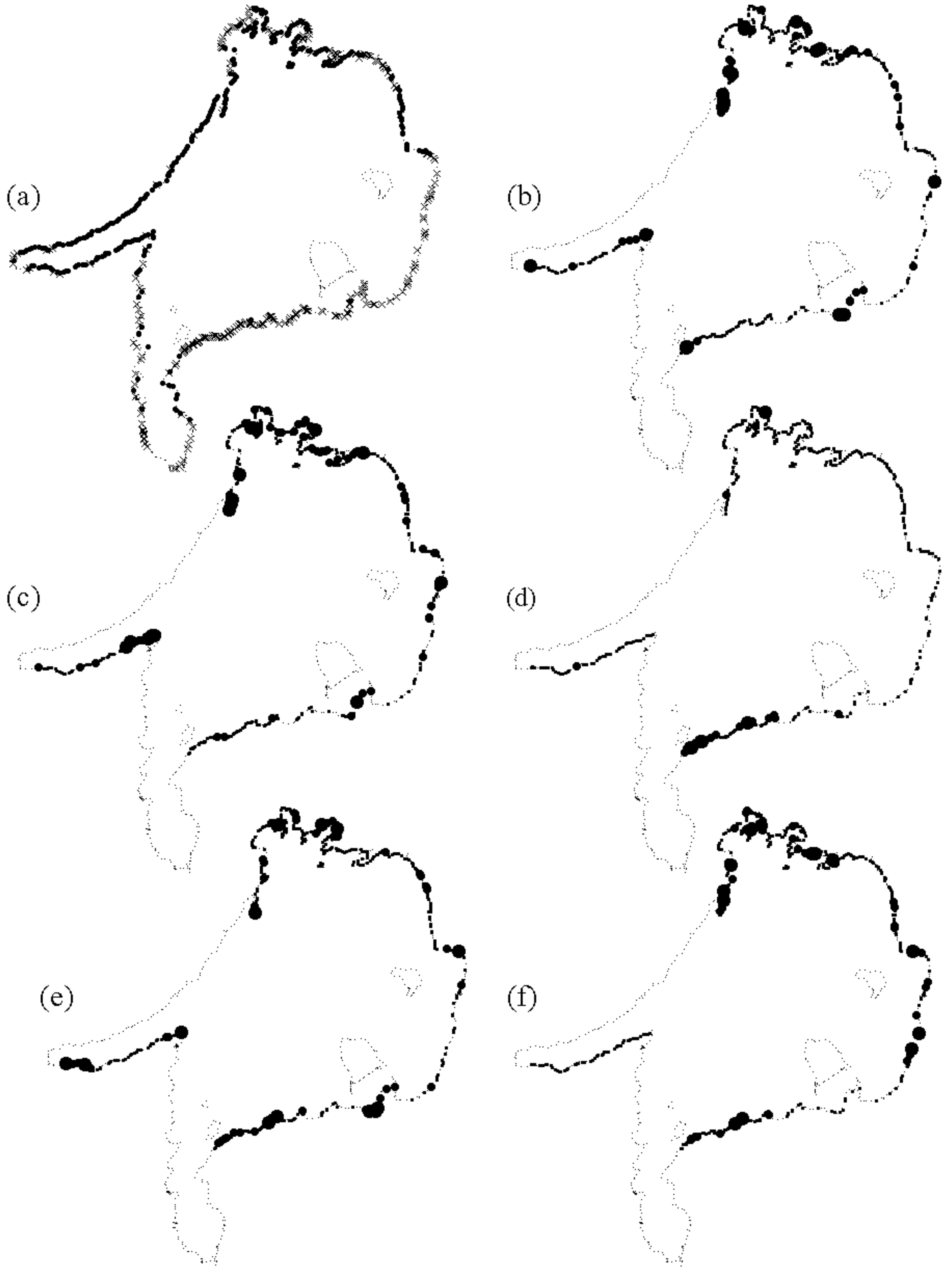

Figure 3 - Spatial frequency distribution maps of a) substrate and vegetation, b) boathouses (density 0-2, 3-4, 5-7 per 122 m), c) temporary docks (density 0-3, 4-7, 8-11 per 122 m), d) permanent docks (density 0-2, 3-5, 6-8 per 122 m), e) break walls (density 0-40 m, 41-81 m, 82-122 m per 122 m), f) and bank stabilisation structures (density 0-26 m, 27-53 m, 54-79 m per 122 m). Crosses in panel a) represent sites associated with hard and soft substrates along with aquatic vegetation while solid circles represent sites with only hard substrates. Circles of increasing size in panels b) to f) represent increasing density of features. Logistical constraints prevented sampling development on the western and southern shore of the lake as well as the islands (doted shoreline).

Table 2 – Product-moment correlation of variables used in the analysis. The abbreviated variables are richness (Rich), abundance (Abun), day of year (DOY), submergent (Sub) and emergent (Eme) vegetation, rock (Roc), boulder (Bou), rubble (Rub), gravel (Gra), sand (San), muck (Muc), detritus (Det), shoreline vegetation cover (SHORECOV), water temperature (Wat), seasonal docks (DoT), permanent docks (DoP), boathouses (Boa), break walls (Bre), bank stabilisation (Sta). Development variables are for the 122 m development zone. All probabilities are Bonferonni corrected.

	Abun	Rich	Fetch	DOY	Sub	Eme	Roc	Bou	Rub	Gra	San	Muc	Det	Cov	Wat	DoT	DoP	Bre	Sta
Rich	**.781**[3]																		
Fetch	**-.115**[2]	**-.190**[3]																	
DOY	**-.106**[2]	**-.107**[2]	**.099**[1]																
Sub	**.131**[3]	**.202**[3]	-.354	**.119**[2]															
Eme	.053	**.147**[3]	**-.115**[3]	-.018	**.205**[3]														
Roc	-.013	-.012	**.176**[2]	**.129**[2]	**-.242**[3]	**-.140**[3]													
Bou	**-.247**[3]	**-.284**[3]	**.165**[3]	.004	**-.178**[3]	**-.129**[2]	**-.239**[3]												
Rub	**-.281**[3]	**-.299**[3]	-.020	-.085	-.023	**-.212**[3]	**-.466**[3]	**.548**[3]											
Gra	**-.172**[3]	**-.199**[3]	-.082	-.047	.015	**-.152**[3]	**-.378**[3]	**.344**[3]	**.652**[3]										
San	**.292**[3]	**.246**[3]	-.078	-.025	**.105**[1]	**-.106**[2]	-.058	**-.228**[3]	**-.180**[3]	**-.106**[2]									
Muc	**.141**[3]	**.245**[3]	**-.248**[3]	.024	**.326**[3]	**.436**[3]	.011	**-.259**[3]	**-.318**[3]	**-.153**[3]	-.040								
Det	**.132**[3]	**.140**[3]	**-.155**[3]	**-.134**[3]	.069	**.328**[3]	-.071	**-.266**[3]	**-.335**[3]	**-.239**[3]	**.173**[3]	**.276**[3]							
Cov	**-.102**[2]	-.027	.002	**-.118**[2]	.056	**.204**[3]	-.069	.079	**.109**[2]	.005	**-.175**[3]	**.100**[1]	.031						
Wat	**-.189**[3]	-.209[3]	.077	**-.405**[3]	**-.195**[3]	**-.118**[2]	.055	.048	.071	.039	.063	**-.099**[1]	.042	.015					
DoT	.027	-.013	**.163**[3]	-.019	**-.120**[2]	**-.221**[3]	**.131**[3]	.072	**.102**[1]	.089	.025	**-.123**[2]	**-.113**[2]	**-.185**[3]	.013				
DoP	-.073	-.103[1]	.065	**.154**[3]	**-.158**[3]	-.090	**.213**[3]	**.127**[3]	-.089	-.064	.033	-.067	-.037	**-.114**[2]	**.106**[2]	-.019			
Bre	.015	-.038	.040	.040	-.097	**-.145**[3]	**.106**[2]	.030	-.008	-.015	**.113**[2]	-.056	-.061	**-.106**[2]	**.122**[2]	**.372**[3]	**.271**[3]		
Sta	**-.135**[3]	-.088	**.246**[3]	.029	**-.113**[2]	**-.108**[2]	**.171**[3]	.046	.022	.054	**-.191**[3]	-.042	**-.153**[3]	-.052	-.077	**.329**[3]	.033	.017	
Boa	.025	-.033	**.162**[3]	.018	**-.180**[3]	-.089	**.098**[1]	**.123**[2]	.018	.059	-.011	-.068	-.038	**-.171**[3]	.048	**.540**[3]	**.304**[3]	**.408**[3]	**.099**[1]

1.alpha < 0.1, 2. alpha < 0.005, 3. alpha < 0.001.

abundant fish caught in order of decreasing relative abundance consisted of yellow perch, spottail shiner, bluntnose minnow, unknown, and sand shiner (Table 3). Unknown represents fish that could not be identified due to their small size. Both abundance and richness of fish were significantly and positively associated with submergent vegetation as well as soft substrates like sand, muck, and detritus (Table 2). In addition, both fish measures were negatively associated with mean fetch as well as hard substrates such as boulder, rubble, and gravel (Table 2).

The five site-types delineated in the cluster analysis are presented for the three development zones (Figure 4-6). Sites associated with high occurrence of all development types, lack of vegetation, and presence of coarse substrate were described by cluster five. Sites associated with little or no development, presence of vegetation, and even representation of all substrate types were described by cluster two. Sites associated with permanent docks, break walls, boathouses, submergent vegetation and fine substrate were described by cluster one. Sites associated with temporary docks, break walls, shore cover, submergent vegetation, and detritus were described in cluster three. Finally cluster four described sites associated with temporary docks, bank stabilisation, submergent vegetation and coarse substrates.

Sites from cluster five, characterised with all forms of development and low occurrence of vegetation, tended to have the lowest total abundance and species richness, regardless of observational scale. Species not present in cluster five but present elsewhere were typically species not encountered frequently (density <10 individuals·site^{-1}) such as northern pike, brassy minnow, fathead minnow, black crappie, blackchin shiner, blacknose dace and johnny darter. With the exception of sand shiner, those species that

Table 3 - Lake Simcoe species list and total catch for the period 1982 to 1995.

Common name	**Species**	**Total catch**	**± 1 S.D.**
Yellow perch	*Perca flavescens*	111 982	408
Spottail shiner	*Notropis hudsonius*	78 965	345
Bluntnose minnow	*Pimephales notatus*	62 357	140
Unknown	*Unknown*	47 908	517
Sand shiner	*Notropis stramineus*	39 003	168
Emerald shiner	*Notropis atherinoides*	37 681	855
White sucker	*Catostomus commersoni*	7 748	76
Logperch	*Percina caprodes*	5 123	20
Banded killifish	*Fundulus diaphanus*	3 690	27
Golden shiner	*Notemigonus crysoleucas*	3 682	61
Pumpkinseed	*Lepomis gibbosus*	3 568	22
Blackchin shiner	*Notropis heterodon*	2 824	88
Iowa darter	*Etheostoma exile*	2 033	14
Largemouth bass	*Micropterus salmoides*	1 540	7
Smallmouth bass	*Micropterus dolomieui*	1 490	5
Spotfin shiner	*Cyprinella spiloptera*	941	27
Rock bass	*Ambloplites rupestris*	925	4
Fathead minnow	*Pimephales promelas*	599	42
Blacknose shiner	*Notropis heterolepis*	499	33
Longnose dace	*Rhinichthys cataractae*	452	7
Brook stickleback	*Culaea inconstans*	425	36
Common shiner	*Luxilus cornutus*	352	8
Brassy minnow	*Hybognathus hankinsoni*	302	24
Rainbow smelt	*Osmerus mordax*	278	30
Johnny darter	*Etheostoma nigrum*	249	11
Trout-perch	*Percopsis omiscomaycus*	227	11
Brown bullhead	*Ictalurus nebulosus*	186	3
Creek chub	*Semotilus atromaculatus*	142	11
Northern redbelly dace	*Phoxinus eos*	68	10
Mottled sculpin	*Cottus bairdi*	48	1
Northern pike	*Esox lucius*	36	3
Central mudminnow	*Umbra limi*	31	1
Blacknose dace	*Rhinichthys atratulus*	30	2
Bowfin	*Amia calva*	10	1
Carp	*Cyprinus carpio*	6	2
Eastern silvery minnow	*Hybognathus regius*	6	0
Northern hog sucker	*Hypentelium nigricans*	5	0
Black crappie	*Pomoxis nigromaculatus*	3	0
Finescale dace	*Phoxinus neogaeus*	3	0
Muskellunge	*Esox masquinongy*	3	0
Brook trout	*Salvelinus fontinalis*	2	0
Hornyhead chub	*Nocomis biguttatus*	2	0
Walleye(yellow pickerel)	*Stizostedion vitreum vitreum*	2	0
Black bullhead	*Ictalurus melas*	1	0
Fallfish	*Semotilus corporalis*	1	0
Mimic shiner	*Notropis volucellus*	1	0
River chub	*Nocomis micropogon*	1	0

Cluster	**1**	**2**	**3**	**4**	**5**	**Total**	
N (sites per cluster)	20	253	57	42	14	386	
Rock	•	•	•	●	⬤		Substrate
Boulder	●	•	•	●	●		
Rubble	•	●	●	●	•		
Gravel	•	●	●	●	•		
Sand	●	●	●	•	•		
Muck	•	•	●	•	●		
Detritus	⬤	●	●	•	·		
Submergent veg.	●	●	●	•	•		Vegetation
Emergent veg.	·	⬤	·	·	·		
Shore cover	•	●	●	●	•		
Dock temporary	●	•	●	●	•		Development 122 r
Dock permanent	•	•	●	●	●		
Stabilization	·	·	·	⬤	⬤		
Break wall	⬤	·	●	·	●		
Boat house	●	·	●	•	●		
Banded killifish	8	11	5	3		27	Arthropodivore
Black crappie	<1	<1				<1	
Blackchin shiner		11	<1	3		13	
Blacknose dace		<1	<1			<1	
Blacknose shiner	1	2		<1		2	
Brook stickleback	13	<1	2	<1		15	
Brown bullhead		1	<1	<1		1	
Common shiner	1	1	<1	2		4	
Creek chub		<1	<1	<1		<1	
Emerald shiner	15	106	17	26	1	166	
Iowa darter	1	5	7	1	1	15	
Johnny darter		<1	1	<1		1	
Logperch	8	11	14	14	2	49	
Longnose dace		1	<1	<1	<1	1	
Mottled sculpin		<1	<1	<1		<1	
Pumpkinseed	8	7	1	5		21	
Rainbow smelt	<1	<1	<1		<1	<1	
River chub		<1				<1	
Rock bass	2	2	1	2	<1	7	
Sand shiner	70	96	94	24	116	401	
Spotfin shiner	16	1	1	<1		18	
Spottail shiner	128	159	199	45	31	562	
Trout-perch	<1	1	<1	<1	1	2	
White sucker	1	20	17	7		46	
Yellow perch	48	283	80	102	19	532	
Bluntnose minnow	139	132	120	60	2	452	Omnivore
Brassy minnow		<1				<1	
Carp		<1		<1		<1	
Central mudminnow		<1				<1	
Fathead minnow	22	<1	<1	1		23	
Golden shiner	<1	5	2	24		31	
Bowfin		<1		<1		<1	Piscivore
Brook trout		<1				<1	
Largemouth bass	1	4	1	3	<1	9	
Muskellunge		<1				<1	
Northern pike		<1				<1	
Smallmouth bass	1	4	2	2	1	10	
Walleye		<1				<1	
Northern redbelly dace	<1	<1	<1			<1	Her
Unknown	55	77	244	9		385	
Richness	**24**	**40**	**29**	**29**	**13**	**40**	
Abundance	**539**	**939**	**806**	**335**	**173**	**2792**	

Legend	
0-9%	·
10-14%	•
15-19%	•
20-24%	●
25-34%	●
>35%	⬤

Figure 4 - Summary of the cluster analysis for the Lake Simcoe Littoral Zone study, emphasizing species-specific catch within site type (cluster) for the development zone of 122 m. The symbols represent the percentage occurrence of a variable at a site; thus, the percentages across clusters for a given variable (row) sums to 100.

Cluster	**1**	**2**	**3**	**4**	**5**	**Total**	
N (sites per cluster)	76	233	21	33	21	384	
Rock	●	∙	•	•	⬤		Substrate
Boulder	∙	●	•	●	●		
Rubble	•	●	•	⬤	•		
Gravel	●	●	•	⬤	∙		
Sand	●	•	●	•	•		
Muck	⬤	⬤	∙	∙	●		
Detritus	●	•	⬤	•	∙		
Submergent veg.	●	⬤	●	●	∙		Vegetation
Emergent veg.	∙	⚫	·	·	·		
Shore cover	•	●	●	●	•		
Dock temporary	•	∙	⬤	⬤	●		Development 244 r
Dock permanent	⬤	∙	∙	∙	⬤		
Stabilization	·	·	·	⚫	⚫		
Break wall	●	·	⚫	·	⬤		
Boat house	⬤	∙	•	•	⬤		
Banded killifish	4	12	6	6	1	29	Arthropodivore
Black crappie	<1		<1			<1	
Blackchin shiner	2	11		4		17	
Blacknose dace	<1	<1	<1	<1		<1	
Blacknose shiner		2		1	1	4	
Brook stickleback	2	<1	11	<1	<1	13	
Brown bullhead	<1	1	<1	<1		1	
Common shiner	2	1	1	1		4	
Creek chub	<1	<1		<1		<1	
Emerald shiner	42	30	40	552	0	665	
Iowa darter	5	5	7	3	<1	19	
Johnny darter	1	<1				1	
Logperch	9	11	20	23	6	69	
Longnose dace	<1	<1	<1	5	1	6	
Mottled sculpin	<1	<1		<1		<1	
Pumpkinseed	2	7	7	7	1	23	
Rainbow smelt	<1	<1	<1	<1	<1	<1	
River chub		<1				<1	
Rock bass	1	2	1	2	<1	7	
Sand shiner	79	57	226	249	81	691	
Spotfin shiner	1	1	15	2		18	
Spottail shiner	142	139	197	162	33	673	
Trout-perch	1	1	<1	<1	1	2	
White sucker	6	19	21	25	15	86	
Yellow perch	107	263	116	249	78	813	
Bluntnose minnow	116	99	163	289	28	696	Omnivore
Brassy minnow	<1	<1		1		1	
Carp	<1					0	
Central mudminnow	<1	<1				0	
Fathead minnow	5	<1	6	<1	<1	10	
Golden shiner	2	6	<1	27	<1	35	
Bowfin		<1		<1		<1	Piscivore
Brook trout		<1		<1		<1	
Largemouth bass	1	4	<1	2	<1	8	
Muskellunge		<1				<1	
Northern pike		<1				<1	
Smallmouth bass	2	3	2	4	1	12	
Walleye		<1		<1		<1	
Northern redbelly dace	<1	<1	<1		<1	<1	Her
Unknown	178	64	183	51	40	516	
Richness	33	38	26	32	22	40	
Abundance	**706**	**736**	**1021**	**1667**	**288**	**4418**	

Legend	
0-9%	·
10-14%	∙
15-19%	•
20-24%	●
25-34%	⬤
>35%	⚫

Figure 5 - Summary of the cluster analysis for the Lake Simcoe Littoral Zone study, emphasizing species-specific catch within site type (cluster) for the development zone of 244 m. The symbols represent the percentage occurrence of a variable at a site; thus, the percentages across clusters for a given variable (row) sums to 100.

Cluster	**1**	**2**	**3**	**4**	**5**	**Total**	
N (sites per cluster)	88	194	40	34	27	383	
Rock	⚫	∙	•	●	●		Substrate
Boulder	∙	●	•	⚫	●		
Rubble	•	●	•	●	●		
Gravel	•	●	•	●	●		
Sand	●	•	⚫	∙	●		
Muck	⚫	●	•	∙	●		
Detritus	●	•	⚫	·	•		
Submergent veg.	•	●	●	∙	●		Vegetation
Emergent veg.	⚫	⬤	·	·	·		
Shore cover	●	●	●	•	●		
Dock temporary	•	∙	●	⚫	●		Development
Dock permanent	⚫	·	∙	●	⚫		
Stabilization	·	·	·	⬤	⬤		
Break wall	•	·	⬤	·	⚫		
Boat house	•	·	●	●	⚫		
Banded killifish	6	12	9	4	1	32	Arthropodivore
Black crappie	<1		<1			<1	
Blackchin shiner	5	12	1	<1	<1	17	
Blacknose dace	<1	<1	<1		<1	<1	
Blacknose shiner		2		1		4	
Brook stickleback	<1	<1	9	<1		9	
Brown bullhead	1	<1	<1		<1	1	
Common shiner	<1	1	3	<1	<1	4	
Creek chub	1	<1	<1		<1	1	
Emerald shiner	11	37	76	521	17	662	
Iowa darter	6	3	13	2	2	25	
Johnny darter	<1	<1	1	<1		1	
Logperch	9	9	16	13	31	79	
Longnose dace	0	1	<1	<1	1	2	
Mottled sculpin	<1	<1	<1	<1	<1	<1	
Pumpkinseed	7	7	5	1	1	21	
Rainbow smelt	<1	<1	<1			<1	
River chub	<1					<1	
Rock bass	3	2	2	<1	<1	7	
Sand shiner	70	65	65	255	140	595	
Spotfin shiner	<1	1	9	<1	1	11	
Spottail shiner	233	115	75	93	162	677	
Trout-perch	1	1	<1	<1	<1	1	
White sucker	7	24	8	2	32	72	
Yellow perch	235	228	153	247	84	947	
Bluntnose minnow	95	111	221	168	43	638	Omnivore
Brassy minnow	<1	<1	<1	1		1	
Carp		<1	<1			<1	
Central mudminnow	<1	<1	<1			<1	
Fathead minnow	1	<1	11		<1	12	
Golden shiner	8	7	4	3		23	
Bowfin	<1	<1				<1	Piscivore
Brook trout	<1	<1				<1	
Largemouth bass	3	4	3	<1	1	10	
Muskellunge	<1	<1				<1	
Northern pike	<1	<1	<1			<1	
Smallmouth bass	3	3	2	3	3	14	
Walleye		<1				<1	
Northern redbelly dace	<1	<1	<1			<1	Her
Unknown	84	75	291	16	29	494	
Richness	37	38	34	25	24	40	
Abundance	**787**	**718**	**976**	**1330**	**548**	**4360**	

Legend	
0-9%	·
10-14%	∙
15-19%	•
20-24%	●
25-34%	⚫
>35%	⬤

Figure 6 - Summary of the cluster analysis for the Lake Simcoe Littoral Zone study, emphasizing species-specific catch within site type (cluster) for the development zone of 488 m. The symbols represent the percentage occurrence of a variable at a site; thus, the percentages across clusters for a given variable (row) sums to 100.

occurred in all clusters tended to have a low abundance in cluster five. Cluster two, characterised by little or no shoreline development and presence of vegetation always had the highest species richness at all spatial scales, and the highest abundance at the smallest scale. Patterns in fish assemblages and coarse indicators of abundance and richness for clusters one, three, or four were not consistent among observational scales.

Regression analysis

For the purpose of comparison and to explore incremental contributions of individual variables, estimates of regression parameters using classical, randomisation, and bootstrap techniques are included in Appendix II. Results from the classical method are not presented here, since estimates can be biased in the presence of autocorrelation. Results of the randomisation and bootstrap techniques are also not discussed here, since their validity in the presence of autocorrelation is poorly known (B. Allen and N. Roslin, pers. comm. Ashton Consulting Lab, University of Guelph).

Examination of plots of environmental variables and shoreline development versus abundance and richness of fish demonstrated a hump shaped pattern with shore cover (Figure 2). As such, a quadratic effect was introduced in the mixed model.

Tables 4-7 display the mixed model regressions of log abundance (model 1) and square root of richness (model 2). Of the environmental variables in the mixed model, only water temperature, day of the year and presence of rock, boulder, sand, and muck contributed significantly (alpha = 0.10) to prediction of both log abundance and square root richness of fish. Square root

Table 4 – Regression estimates of fixed-effect parameters from the log abundance model with interaction terms.

Log Abundance	122 m (888 d.f.)			244 m (888 d.f.)			488 m (885 d.f.)		
Variable	Estimate	F	Pr > F	Estimate	F	Pr > F	Estimate	F	Pr > F
Model (RML)	3071.40			3101.06			3123.50		
Water temp.	**0.086**	**132.22**	**0.000**	**0.086**	**133.84**	**0.000**	**0.087**	**134.65**	**0.000**
Day of year	**-0.010**	**112.11**	**0.000**	**-0.010**	**111.88**	**0.000**	**-0.010**	**110.86**	**0.000**
Fetch (mean)									
Rock[1]	**-0.269**	**6.37**	**0.012**	**-0.283**	**7.00**	**0.008**	**-0.299**	**7.87**	**0.005**
Boulder[1]	**-0.284**	**18.49**	**0.000**	**-0.292**	**19.32**	**0.000**	**-0.290**	**19.40**	**0.000**
Rubble[1]	**-0.173**	**3.57**	**0.059**	**-0.187**	**3.99**	**0.046**	**-0.214**	**5.23**	**0.022**
Gravel[1]	-0.013	0.04	0.834	-0.016	0.06	0.808	-0.003	0.00	0.964
Sand[1]	**0.315**	**28.44**	**0.000**	**0.320**	**28.69**	**0.000**	**0.323**	**29.52**	**0.000**
Muck[1]	**0.200**	**3.99**	**0.046**	**0.209**	**4.07**	**0.044**	**0.216**	**4.45**	**0.035**
Detritus[1]	-0.029	0.18	0.673	-0.037	0.27	0.603	-0.030	0.18	0.668
Submergent veg.[1]	0.084	2.35	0.126	0.081	2.15	0.143	0.088	2.50	0.114
Emergent veg.[1]	-0.047	0.17	0.679	-0.030	0.07	0.794	-0.047	0.16	0.687
Shore cover (SC)	0.012	0.01	0.930	0.011	0.01	0.937	0.000	0.00	0.998
SC X SC	-0.016	0.35	0.556	-0.015	0.30	0.585	-0.013	0.22	0.640
Dock temporary	0.003	0.01	0.918	0.015	0.42	0.517	0.008	0.23	0.631
Dock permanent	-0.023	0.36	0.548	0.041	1.88	0.170	0.031	1.28	0.258
Stabilization	**-0.003**	**6.12**	**0.014**	-0.001	2.07	0.151	-0.001	1.30	0.254
Break wall	-0.001	1.55	0.213	-0.000	0.79	0.375	-0.000	0.87	0.352
Boat house	0.075	1.38	0.241	0.043	1.04	0.307	0.017	0.35	0.552
DockT X DockP	-0.007	0.21	0.645	-0.003	0.26	0.607	-0.002	1.13	0.288
DockT X BreakW	0.000	1.95	0.163	0.000	0.13	0.723	**0.000**	**4.07**	**0.044**
DockP X BreakW	**0.001**	**3.75**	**0.053**	0.000	0.26	0.611	-0.000	0.02	0.892
DockT X Stab	0.000	1.11	0.293	0.000	0.01	0.933	0.000	0.02	0.893
DockP X Stab	0.000	0.24	0.624	-0.000	0.14	0.708	0.000	0.03	0.856
BreakW X Stab	0.000	0.24	0.624	0.000	1.20	0.274	-0.000	0.00	>0.9
DockT X BoatH	-0.001	0.02	0.893	-0.003	0.72	0.397	-0.001	0.90	0.343
DockP X BoatH	-0.019	1.58	0.208	**-0.010**	**3.42**	**0.065**	-0.001	0.11	0.738
BreakW XBoatH	-0.000	2.11	0.147	0.000	0.03	0.864	**-0.000**	**2.85**	**0.092**
Stab X BoatH	-0.001	1.67	0.197	-0.000	0.17	0.680	0.000	1.05	0.307

Table 5 – Regression estimates of fixed-effect parameters from the log abundance model with no interaction terms.

Log Abundance	122 m (887 d.f.)			244 m (888 d.f.)			488 m (887 d.f.)		
Variable	Estimate	F	Pr > F	Estimate	F	Pr > F	Estimate	F	Pr > F
Model (RML)	2958.80			2966.65			2972.84		
Water temp.	**0.086**	**131.55**	**0.000**	**0.086**	**132.55**	**0.000**	**0.086**	**131.94**	**0.000**
Day of year	**-0.010**	**109.62**	**0.000**	**-0.010**	**109.74**	**0.000**	**-0.010**	**108.48**	**0.000**
Fetch (mean)	-0.002	0.01	0.905	0.001	0.00	0.975	-0.003	0.04	0.834
Rock[1]	**-0.298**	**8.25**	**0.004**	**-0.319**	**9.41**	**0.002**	**-0.328**	**9.91**	**0.002**
Boulder[1]	**-0.290**	**19.62**	**0.000**	**-0.302**	**21.19**	**0.000**	**-0.288**	**19.23**	**0.000**
Rubble[1]	**-0.198**	**4.82**	**0.028**	**-0.196**	**4.60**	**0.032**	**-0.219**	**5.68**	**0.017**
Gravel[1]	-0.010	0.02	0.875	-0.011	0.03	0.867	-0.014	0.05	0.829
Sand[1]	**0.318**	**29.96**	**0.000**	**0.315**	**28.82**	**0.000**	**0.319**	**29.02**	**0.000**
Muck[1]	**0.184**	**3.46**	**0.063**	**0.203**	**4.05**	**0.045**	**0.188**	**3.43**	**0.064**
Detritus[1]	-0.034	0.25	0.619	-0.034	0.23	0.628	-0.031	0.19	0.663
Submergent veg.[1]	0.083	2.27	0.132	0.082	2.17	0.141	0.085	2.31	0.129
Emergent veg.[1]	-0.042	0.14	0.709	-0.051	0.20	0.656	-0.022	0.04	0.851
Shore cover (SC)	0.044	0.11	0.742	0.012	0.01	0.932	-0.000	0.00	0.998
SC X SC	-0.022	0.63	0.426	-0.015	0.31	0.580	-0.013	0.22	0.640
Dock temporary	0.032	2.31	0.129	0.013	1.06	0.303	**0.014**	**2.80**	**0.094**
Dock permanent	-0.015	0.31	0.576	0.015	0.77	0.381	0.005	0.17	0.681
Stabilization	**-0.002**	**11.52**	**0.000**	**-0.001**	**6.83**	**0.009**	-0.000	1.20	0.275
Break wall	-0.000	0.22	0.635	-0.000	0.00	0.977	0.000	0.12	0.728
Boat house	0.001	0.00	0.966	0.001	0.01	0.937	-0.006	0.29	0.592

Table 6 – Regression estimates of fixed-effect parameters from the square root richness model with interaction terms.

Sqrt. Richness	122 m (886 d.f.)			244 m (886 d.f.)			488 m (886 d.f.)		
Variable	Estimate	F	Pr > F	Estimate	F	Pr > F	Estimate	F	Pr > F
Model (RML)	2747.163			2733.96			2756.44		
Water temp.	**0.066**	**104.22**	**0.000**	**0.066**	**103.33**	**0.000**	**0.067**	**106.24**	**0.000**
Day of year	**-0.008**	**94.70**	**0.000**	**-0.008**	**94.46**	**0.000**	**-0.008**	**94.68**	**0.000**
Fetch (mean)	0.000	1.09	0.297	**-0.037**	**7.55**	**0.006**	**-0.040**	**8.15**	**0.004**
Rock[1]	**-0.174**	**3.39**	**0.066**	**-0.192**	**4.39**	**0.036**	**-0.192**	**4.42**	**0.036**
Boulder[1]	**-0.349**	**37.03**	**0.000**	**-0.350**	**39.05**	**0.000**	**-0.350**	**39.16**	**0.000**
Rubble[1]	-0.093	1.33	0.249	-0.078	0.94	0.331	-0.088	1.22	0.270
Gravel[1]	0.002	0.00	0.969	-0.001	0.00	0.982	0.005	0.01	0.923
Sand[1]	**0.218**	**18.07**	**0.000**	**0.208**	**17.25**	**0.000**	**0.211**	**17.77**	**0.000**
Muck[1]	**0.340**	**15.41**	**0.000**	**0.327**	**14.48**	**0.000**	**0.344**	**16.26**	**0.000**
Detritus[1]	**-0.102**	**2.89**	**0.090**	**-0.131**	**4.72**	**0.030**	**-0.129**	**4.68**	**0.031**
Submergent veg.[1]	0.070	2.12	0.146	0.049	1.06	0.303	0.052	1.17	0.280
Emergent veg.[1]	0.008	0.01	0.935	-0.032	0.11	0.743	-0.028	0.08	0.774
Shore cover (SC)	0.127	1.16	0.282	0.127	1.19	0.276	0.136	1.38	0.241
SC X SC	-0.033	1.84	0.175	-0.033	1.94	0.164	-0.034	2.13	0.144
Dock temporary	0.012	0.19	0.664	-0.002	0.01	0.916	0.005	0.13	0.717
Dock permanent	-0.024	0.56	0.455	**0.040**	**2.95**	**0.086**	**0.046**	**4.36**	**0.037**
Stabilization	-0.001	1.82	0.177	-0.001	0.56	0.456	-0.000	0.11	0.739
Break wall	-0.001	1.76	0.185	-0.000	0.76	0.383	0.000	0.26	0.611
Boat house	0.038	0.46	0.497	0.040	1.32	0.252	0.012	0.24	0.622
DockT X DockP	-0.002	0.03	0.870	-0.006	1.82	0.117	**-0.003**	**2.86**	**0.091**
DockT X BreakW	0.000	0.39	0.532	0.000	0.00	0.962	0.000	0.08	0.777
DockP X BreakW	0.000	0.33	0.565	-0.000	0.23	0.629	**-0.000**	**2.81**	**0.094**
DockT X Stab	-0.000	0.00	0.980	0.000	0.01	0.935	-0.000	0.44	0.508
DockP X Stab	0.000	0.69	0.405	-0.000	0.00	0.961	0.000	0.03	0.859
BreakW X Stab	0.000	0.26	0.613	0.000	0.90	0.343	0.000	0.13	0.723
DockT X BoatH	-0.003	0.08	0.777	0.000	0.04	0.848	0.000	0.04	0.847
DockP X BoatH	-0.001	0.00	0.951	-0.005	1.45	0.228	-0.001	0.14	0.706
BreakW XboatH	-0.000	0.98	0.323	-0.000	0.04	0.835	-0.000	1.20	0.274
Stab X BoatH	0.000	0.03	0.854	-0.000	0.73	0.397	0.000	0.25	0.617

Table 7 – Regression estimates of fixed-effect parameters from the square root richness model without interactions.

Sqrt. Richness	122 m (887 d.f.)			244 m (888 d.f.)			488 m (887 d.f.)		
Variable	Estimate	F	Pr > F	Estimate	F	Pr > F	Estimate	F	Pr > F
Model (RML)	2588.91			2588.13			2596.26		
Water temp.	**0.066**	**103.29**	**0.000**	**0.066**	**104.36**	**0.000**	**0.066**	**104.50**	**0.000**
Day of year	**-0.008**	**92.28**	**0.000**	**-0.008**	**93.63**	**0.000**	**-0.008**	**93.50**	**0.000**
Fetch (mean)	**-0.040**	**9.35**	**0.002**	**-0.035**	**7.07**	**0.008**	**-0.038**	**7.95**	**0.005**
Rock[1]	**-0.202**	**5.02**	**0.025**	**-0.200**	**5.04**	**0.025**	**-0.205**	**5.33**	**0.021**
Boulder[1]	**-0.338**	**36.61**	**0.000**	**-0.355**	**41.01**	**0.000**	**-0.349**	**39.59**	**0.000**
Rubble[1]	-0.091	1.38	0.241	-0.093	1.43	0.231	-0.098	1.57	0.211
Gravel[1]	0.003	0.00	0.961	0.003	0.00	0.963	0.006	0.01	0.920
Sand[1]	**0.211**	**18.11**	**0.000**	**0.204**	**17.09**	**0.000**	**0.204**	**16.92**	**0.000**
Muck[1]	**0.315**	**14.13**	**0.000**	**0.324**	**14.78**	**0.000**	**0.315**	**14.03**	**0.000**
Detritus[1]	**-0.126**	**4.47**	**0.035**	**-0.131**	**4.88**	**0.027**	**-0.129**	**4.68**	**0.031**
Submergent veg.[1]	0.053	1.25	0.264	0.052	1.18	0.278	0.055	1.35	0.246
Emergent veg.[1]	-0.015	0.03	0.874	-0.033	0.11	0.737	-0.014	0.02	0.886
Shore cover (SC)	0.149	1.68	0.194	0.139	1.48	0.225	0.138	1.45	0.229
SC X SC	-0.037	2.49	0.115	-0.035	2.28	0.131	-0.035	2.26	0.133
Dock temporary	0.013	0.55	0.458	-0.003	0.10	0.757	0.000	0.00	0.983
Dock permanent	-0.014	0.39	0.531	0.008	0.35	0.554	0.002	0.05	0.819
Stabilization	-0.001	1.33	0.250	-0.001	2.12	0.146	-0.000	1.13	0.289
Break wall	**-0.001**	**3.43**	**0.064**	-0.000	1.37	0.242	0.000	0.05	0.816
Boat house	0.021	0.76	0.385	0.022	2.23	0.136	0.008	0.74	0.390

richness could be further described with information about detritus, while log abundance was further described with information on rubble. Mean fetch was significant and negatively associated with square root richness, but not log abundance. Information on presence of aquatic vegetation and extent of shoreline terrestrial vegetation adjacent to the site was never significant in explaining patterns in the two models. Apparently information on substrate composition and seasonal predictors such as water temperature and day of year were more important in explaining patterns in richness and abundance than was information on aquatic vegetation.

Shoreline residential development affected both square root richness and log abundance of fish. However, the specific type of feature that affected fish was different depending on the scale of observation and whether interaction terms for development features were modelled.

Within 122 meters development zones, no development effects were detectable in the square root richness model with interaction terms, but break walls were significant and negative in the model with no interaction. Bank stabilising structures (negative) and permanent dock X break wall (positive) were significantly associated with log abundance of fish in the interaction model while only stabilisation (negative) was significant in the model with no interaction.

Within the 244 meter development zone, permanent docks (positive) were significantly associated with square root richness in the model with interactions while in the model without interaction terms, development features were not significant. In the abundance model with interaction terms, permanent docks X boathouse (negative) was significant, but in the model with no interactions, stabilisation (negative) was significant.

Within the 488 meter development zone, permanent docks (positive), temporary docks X permanent docks (negative), and permanent docks X break walls (negative) were significant in the square root richness model with interaction terms; no development was significant in the model with no interactions. In the log abundance model, temporary docks X break walls (positive) and break walls X boathouse (negative) were significant in the interaction model; in the model with no interactions, temporary docks (positive) was the only significant term.

Overall model fit was assessed at the three different observational scales and for equations with and without interaction terms. According to the likelihood ratio statistic (Littell et al. 1996), models with spatial (power) covariance structure provided a significantly better fit than models without ($p<0.0001$ for all model), confirming the presence of spatial autocorrelation. Covariance parameter estimates indicate that a correlation of 0.2 is present among sites 895 m and 614 m apart for abundance and richness respectively. A correlation of 0.1 is present among sites 1588 m and 1308 m apart for abundance and richness respectively. According to the log REML likelihood criteria, model fit decreased with increasing development zone size for the abundance model with and without interactions and the richness model with interactions (Tables 2, 3, 4). Fit for the richness model without interactions was similar for the 122-m and 244-m development zone and slightly reduced for the 488-m zone (Table 5).

Discussion

Testing for effects in observational studies involves detecting patterns within a background of measurement error and system variability. In ecological impact studies it is important to account for variability and correlation between variables in order to narrow potential causes of effects and avoid detecting spurious patterns. In the Lake Simcoe data set, correlation analysis (Table 2), spatial frequency distribution maps (Figure 3b-e), and cluster analysis (Figures 4-6) revealed that variables describing fish catches, shoreline development, substrate, and vegetation were spatially clumped and inter-correlated, likely reflecting preferences of fish and humans for specific environmental features. Both abundance and richness of fish were significantly and positively associated with submergent vegetation as well as soft substrates like sand, muck, and detritus while negatively associated with mean fetch as well as hard substrates such as boulder, rubble, and gravel (Table 2). Similar observations have previously been reported for fish in lentic systems (Chick and McIvor 1994; Randall et al. 1996; Weaver et al. 1997), as a result of preferences for areas with aquatic vegetation to find refuge, feed and reproduce.

Mean fetch, an indicator of potential wind and wave energy, tended to be associated with sites with hard substrates and without vegetation (Table 2). This observation is also documented in the literature on hydraulic processes associated with sediment mixing and erosion (Chamber 1987; Cyr 1998). The distribution and intensity of shoreline development in Lake Simcoe appears patchy (Figure 3b-e), likely due to land-use constraints and human preferences. For example, bank stabilisation is positively correlated to fetch (Table 2). This may reflect the tendency of landowners to build greater densities of shoreline hardening structures as protection from erosion in areas exposed to high wind and wave energy. Other permanent structures such as break walls and permanent docks were not significantly associated with fetch. Perhaps no pattern is apparent between permanent docks and fetch because such docks seem to be used in medium to high densities mainly on the southern shore of the lake (Figure 3c). However, it is interesting to note that break walls are not positively associated with fetch, even when their purpose is to prevent shoreline erosion from wind and waves.

Nevertheless, most developmental features tend to be positively associated with the presence of hard substrates including rock and boulders, and mean fetch, but negatively associated with soft substrates and the presence of vegetation. These correlations may reflect a preference by lakeshore residents for hard shorelines and ‘clean’ beaches devoid of muck and vegetation. It is also possible that residential development altered the littoral habitat by changing littoral wind and wave dynamics, aquatic vegetation densities and near-shore terrestrial vegetation (i.e. from woodland to lawn). The likelihood of these two plausible scenarios cannot be assessed in this study because pre-development measurements are not available. Such inter-correlation and inherent bias introduces spatial and site-specific patterns that must be accounted for in an impact assessment of shoreline habitat alteration on fish occurrence.

Taking into account the above patterns of association between organisms and their environment, by including them in the mixed model, demonstrated that habitat alteration in the form of shoreline residential development was significant in predicting patterns in both fish abundance and species richness in Lake Simcoe (Table 4-7). However, development did not always have a negative effect on fish. In addition, the specific pattern of effects of shoreline development on fish depended on the scale of observation.

In the log fish abundance model, temporary docks, permanent dock X break wall interactions, and temporary dock X break wall interactions were significant and positive at two scales of observation (Table 4 and 5). In the same model, bank stabilisation, permanent dock X boathouse, and break wall X boathouse interaction terms were significant and negative in three development zones. In the square root richness model, permanent docks were significant and positive in both larger development zones while permanent dock X temporary dock and permanent dock X break wall interaction terms were significant and negative in the larger development zone (Table 6 and 7).

The preponderance of significant interaction terms and rarity of significant main effects (single feature) in both abundance and richness models may indicate that combinations of features, regardless of type, are more important in predicting fish measures than single features. That site-types identified with cluster analysis consisted of multiple development features instead of individual features supports this observation (Figure 4-6). Two likely explanations can account for this. First, segments of shoreline with multiple forms of development, such as combinations of docks, boathouses and shoreline hardening structures, and hence high complexity may be more important in describing occurrence of fish than are sites where individual features occur in isolation. Secondly, significant interaction terms may indicate that segments of shoreline developed with more structures are indicative of another causal factor involving human use such as heavy boat traffic, pesticide runoff from lawn care or increased and localised fishing pressure. Regardless of these explanations, results suggest that not including interactions among factors representing habitat alterations would bias detection of effects in an impact assessment.

Human-made structures: fish attracting or fish repulsing

Many factors may be involved in attracting or repulsing fish to structures built along the shoreline of lakes, however, caution should be exercised when interpreting single and interaction effects in observational studies. Such studies are particularly vulnerable to confounding effects since the experimenter does not control the factors. Cause should never be inferred from the significance of terms until experimental manipulations have specifically identified effects through a carefully designed experiment. These analyses can only be found to partition variation in or be correlated with fish abundance and species richness. Nevertheless, an attempt at dissecting patterns in fish occurrence and shoreline residential development does provide evidence for a significant relationship.

Structures providing overhead cover have long been suspected to attract fish. Such structures are thought to provide an area with a concentrated food supply, used as scratching or cleaning station for eliminating parasites, offer protection from predators, act as a ‘supernormal’ companion that fish school around, or serve as a visual reference point for spawning and other aggregation (Helfman 1979; Bohnsack et al. 1991). Experiments with floating structures demonstrated that fish, particularly Centrarchidae like smallmouth bass, rock bass and pumpkinseed, aggregate under them during bright days, presumably because shaded cover provides a visual shelter from predators in a sunlit environment (Helfman 1979, Bohnsack et al. 1991). Temporary docks and boathouses may offer such shelter. Break walls, under-filling of permanent docks, and other structures constructed of coarse materials may also provide shelter in spaces and cracks between building units (Johnson 1993; Jennings et al. 1999). However, development structures such as retaining walls may act negatively on occurrence of fish by increasing depth at the water edge, discouraging use by fish that prefer shallow waters. Bank stabilising structures could act indirectly on fish by restricting riparian vegetation from the land-water interface. Evidence from the cluster analysis of specific development feature effects at the species level is equivocal (Figure 4-6). For example, smallmouth bass, rock bass and pumpkinseed show no consistent pattern of association among clusters, except between clusters five and two where abundance is greatest in the later cluster. Cluster five represents sites with high occurrence of all shoreline development features, absence of vegetation and presence of coarse substrate. Cluster two represent sites with low shoreline residential development, presence of vegetation and even distribution of all substrate types. That smallmouth bass and rock bass are found in higher density in sites associated with vegetation than without is contrary to the findings of previous studies (e.g. Weaver et al. 1997), suggesting a plastic response of fish to habitat in order to avoid developed sites.

However, the sampling protocol and choice of measuring habitat alteration may not be sensitive to the functional role of specific features. For example, the beach seine cannot be used efficiently to sample under docks and boathouses and over the slope of break walls. Similarly, development zones used in this study include features in the ‘vicinity’ of sampling sites, not only those immediately under or over the site. As such, those shoreline development terms demonstrating an effect on fish occurrence, may in fact, represent a different dimension than that of the features’ functional structures.

Similarly, difference in significance of specific effects of habitat alterations at different scales of observation is further evidence that development affects fish in a dimension not explained by substrate, vegetation, or development structure. For example, development structures may impede movement of fish travelling along the shoreline (Collins et al. 1995). Sites in the vicinity of shoreline hardening structures associated with deeper water and absence of riparian vegetation may be avoided by small fish due to higher occurrence of piscivorous fish from deeper water and avian predators. There is also evidence from the literature that by-products of motorised boat use may affect fish through chemical and mechanical effects (Liddle and Scorgie 1980; Mosisch and Arthington 1998). Evidence from this study demonstrated that increased density of shoreline residential development was not necessarily associated with reduced fish abundance and species richness. Although not always significant, abundance and richness measures indicated that fish may be attracted to single development features such as permanent docks and repelled from other structures such as bank stabilisation (Table 4 and 6). For structures found in combination with each other such as docks and break walls, fish abundance tended to increase but species richness decreased (Table 5 and 7). Cluster analysis suggested that variation in total richness among site-types was influenced by the presence and absence of species that occurred rarely (density <10 individuals$\cdot$site^{-1}) during the study period. These included most piscivores except bass, most of the omnivores except golden shiner, and several arthropodivores like black crappie, blackchin shiner, blacknose dace and johnny darter. These species may have been poorly sampled with the beach seine, or they may be sensitive indicator species.

The mixed model also demonstrated that features found in combination, such as docks and boathouses or break walls and boathouses, although not always significant, appeared generally to repulse fish, since lower abundance and lower richness were associated with them (Table 5 and 7). Cluster analysis appeared to support an even more general assertion. Sites associated with high occurrence of all forms of development and low occurrence of vegetation, tended to have the lowest total abundance and species richness, regardless of observational scale (Figure 4-6). That species-specific patterns were not consistent at all spatial scales suggests that individual fish species may experience their environment at different scales.

Scale dependent patterns

The study of patterns and processes and how they relate at different scales (spatial, temporal, organizational) is one that pervades theoretical and applied ecology (Levin 1992). The study of patterns at different scales is a first step in understanding underlying mechanisms at work. In an applied framework, an examination of patterns at different scales may provide insight on how alterations impact occurrence of organisms. Similarly, studying effects of scale may shed light on where to permit and not permit alterations. In addition, when alterations are permitted, impact studies examining effects of scale may provide insight on where and when repercussions may be expected.

Previous work that examined the effects of habitat alterations at different scales demonstrated that watershed-level indicators of disturbance were better predictors of species richness (i.e. accounted for more variance) than were shoreline-level disturbances (Christensen et al. 1996; Whittier 1997; Allen at al. 1999; Jennings et al. 1999). These findings may indicate that effects of shoreline development are more easily detectable at large spatial scales than at small scales. However, the effects of habitat alteration in many north temperate lakes are not necessarily more understandable or manageable at larger scales. For example, residential development often occurs at a scale of several meters but its impact, both local and cumulative across the system, is of interest to proponents and opponents of development as well as regulatory agencies (Lewis et al. 1996). Yet patterns in effects of habitat alterations at different scales are poorly understood in impact assessment. In this study, scale of observation influenced conclusions about effects of habitat alteration on fish. Initial selection of measurement scale for development zones was arbitrary, but sought to test for the influence of proximity of shoreline alteration on fish occurrence. Results from the mixed model indicated that both near and far shoreline development affected fish. In the mixed model for example, the effects of several single and interaction terms representing development were only significant in the largest development zone while other features were only significant in the smallest development zone (Table 4-7). In the cluster analysis, fish species that occurred in all site-types were less abundant in the cluster associated with high density of all development features (cluster five) than in other clusters, but only in the small development zone (Figure 4-6). The pattern was not apparent in the largest development zone. These results suggest that an impact assessment conducted at only one scale of observation would likely not have detected effects of certain shoreline alterations. In addition, such findings may have broad implications for waterscape conservation. For example, landowners wishing little or no impact of their development activities on lakes should not only be concerned with development on their property but also that of adjacent landowners and beyond. Similarly, sections of shoreline used intensively by fish such as nursery or spawning grounds and sites identified for conservation may be influenced by shoreline development up to several hundred meters away.

Conclusion

This study demonstrates that shoreline alterations are important in explaining patterns in fish abundance and species richness. In addition, the specific development features associated with these patterns changes with the scale of observation, possibly indicating that fish respond to proximally and distantly located habitat alterations. Although the causal factors with which shoreline development features influence the occurrence of fish at different scales are not clear, a pattern of association between sites with greater development impact and those with less is evident. The different response of fish abundance and species richness to shoreline development may be due to the structure of the development such as building material type or it may be due to functional role such as shelter. In addition, the effects of shoreline development detected may also be a function of a dimension not explained by substrate, vegetation, or development structure. For example, development may be associated with other causal factors such as chemical and mechanical effects from boat activity (Liddle and Scorgie 1980, Mosisch and Arthington 1998) or development may act as a barrier to fish movement along the shoreline (Collins et al. 1995). Regardless of the mechanisms of action affecting fish occurrence, fish may exhibit a plastic response to habitat alteration, simply moving away or toward development features and not affecting overall system productivity. However, that my findings apply to all sites sampled, which includes greater than 75% of the lake periphery, provides evidence that shoreline residential development is a likely agent causing system-wide disruption to fish, after taking into account spatial and seasonal patterns in fish-environmental relationships. Whether these disruptions are ‘harmful’ to fish as described in Canada’s Fisheries Act needs to be identified through experimental habitat manipulations, continued monitoring, and public debate.

Future impact assessments testing for effects of habitat alterations on organisms should not only select a scale of measurement at which the development is physically occurring but also at other scales at which the organism may experience the alteration. Conversely, my findings that significance of specific features varies with scale suggests that conclusions based on impacts drawn from studies using one scale of observation may only apply to the scale of observation chosen and not beyond. Finally, experimental manipulations used to elucidate the causal mechanisms responsible for patterns in habitat alterations should be aware of potential cumulative effects across spatial scales and the plasticity of responses fish may exhibit.

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Appendix I

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Appendix II

Rationale

This Appendix describes results of three alternative regressions analysis, classical, bootstrap, and randomization, used to compliment testing of a hypothesis on detecting effects of habitat alteration on fish abundance and richness. I used the classical regression as a benchmark to demonstrate how detection of effects in an impact assessment may be influenced when autocorrelation is not taken into accounted. The regression by randomization was used as a null model to test if patterns of association between habitat alteration and fish measures were significantly different from random. Finally, the bootstrap method was used to examine robustness of patterns between habitat alteration and fish measures by resampling the data set. Both the bootstrap and randomisation methods are non-parametric resampling techniques that provide valid estimates of fixed effects regardless of sampling distribution of the data (i.e. non-normal data). It addition, both of these resampling techniques can be valid in the presence of autocorrelation, but simulation studies have not yet been conducted to test this (Manly 1991, Efron and Tibshirani 1993).

Methods

All statistical models are built according to the equation outline in the section Methods and materials in the body of the thesis.

Classical model

A sequential multiple regression without spatial covariance structure was used to determine if addition of information on shoreline development improved predictions of the dependent variables log abundance and square root richness of fish beyond that afforded by season, substrate, aquatic and terrestrial vegetation. The independent variables were entered in the model in sequential steps representing season (log water temperature, day of year), substrate (rock, boulder, rubble, gravel, sand, muck, detritus), terrestrial (shore vegetation cover) and aquatic vegetation (submergent, emergent), and log shoreline residential development (temporary docks, permanent docks, bank stabilisation, break wall, boathouses) (Tabachnick and Fidell 1996).

Null model

Multiple regression was used with the same variables as described in the classical method above. However, the probability of regression coefficients and R-squared are assessed using a method of permutation (Legendre et al. 1994). This procedure computes regression coefficients of all independent variables, randomly permutes the dependent column of the data and re-computes the regression coefficients. The permutation and calculation of regression coefficients is repeated 999 times. The probability of obtaining the observed relationship between fish measures and development can then be evaluated under the null hypothesis that the observed relationship is not different from random after accounting for habitat and seasonal effects.

Bootstrap model

The same multiple regression model described in the classical approach was tested by resampling the data with replacement (see ftp.sas.com/pub/neural/jackboot.sas). This bootstrap method of estimating regression coefficients and 95% confidence intervals is valid even for non-normal sampling distributions (Efron and Tibshirani 1993). I chose to resample observations instead of residuals since I suspected that observations were autocorrelated (Efron and Tibshirani 1993).

Results and discussion

The classical sequential regression method demonstrated the importance of developmental features after accounting for habitat and shoreline development variables, but only for the log abundance model. Building the abundance model in sequence by adding the seasonal dimension first yields, $R^2 = 0.075$, $F_{inc}(2, 1267) = 51.96$, $p < 0.001$. Addition of the substrate dimension to the model predicting log abundance by season increased fit significantly, $R^2 = 0.230$, $F_{inc}(7, 1267) = 36.55$, $p < 0.001$. The next step added the vegetation dimension to the model predicting log abundance by season with substrate and this also increased fit significantly, $R^2 = 0.235$, $F_{inc}(3, 1267) = 3.22$, $p = 0.022$. Finally the development dimension was added to the model predicting log abundance by season with substrate and vegetation providing a significant increase in fit, $R^2 = 0.253$, $F_{inc}(5, 1267) = 5.85$, $p < 0.001$). The only significant terms in the abundance model were log temporary docks (positive) and log bank stabilisation (negative) (Table A1).

Table A1 – Regression coefficients (significance or 95% confidence interval) for fish abundance computed on the 122 meters development zone using classical, randomization, bootstrap, and mixed regressions.

	Model Type			
	Classical[2]	Null[3,4]	Bootstrap[4]	Mixed
Model	-2REML_LL = 3105.32			-2REML_LL = 2897.81
Log water temp.	**-0.269 (0.000)**	**0.217 (0.001)**	**33.00 (23,43)**	**(0.000)**
Day of year	**-0.228 (0.000)**	**-0.187 (0.001)**	**-3.32 (-5,-1)**	**(0.000)**
Rock[1]	**-0.077 (0.017)**	-0.056 (0.056)	-71.00 (-157,17)	**(0.001)**
Boulder[1]	-0.056 (0.068)	0.042 (0.106)	56.42 (-25,137)	**(0.000)**
Rubble[1]	**-0.237 (0.000)**	**-0.139 (0.003)**	**-137.49 (-225,-49)**	(0.066)
Gravel[1]	-0.012 (0.720)	0.039 (0.137)	41.84 (-20,105)	(0.583)
Sand[1]	**0.215 (0.000)**	**0.130 (0.001)**	**147.45 (87,208)**	**(0.000)**
Muck[1]	**0.065 (0.028)**	-0.020 (0.265)	-23.28 (-125,78)	**(0.046)**
Detritus[1]	-0.037 (0.192)	0.045 (0.079)	78.87 (-26,182)	(0.711)
Submergent vegetation[1]	0.038 (0.181)	0.031 (0.168)	24.98 (-49,99)	**(0.037)**
Emergent vegetation[1]	-0.041 (0.168)	**-0.055 (0.045)**	-109 (-226,12)	(0.489)
Shore vegetation cover	-0.047 (0.074)	-0.034 (0.145)	-17 (-45,10)	(0.197)
Log dock temporary	**0.076 (0.026)**	**0.076 (0.030)**	26.80 (-1,55)	**(0.032)**
Log dock permanent	-0.019 (0.513)	0.032 (0.153)	12.61 (-32,57)	(0.952)
Log stabilization	**-0.119 (0.000)**	**-0.082 (0.001)**	**-0.97 (-1.4,-0.6)**	**(0.000)**
Log break wall	-0.004 (0.879)	0.008 (0.359)	-0.007 (-0.4,0.4)	(0.702)
Log boat house	0.043 (0.185)	-0.030 (0.193)	-13.47 (-43,15)	(0.818)

1 - Coefficient and significance of these variables is for presence information.

2 - $R^2 = 0.253$. Model uses log abundance.

3 - $R^2 = 0.093$.

4 - Model uses untransformed variables and may exhibit regression coefficients of opposite magnitude than those of classical and mixed models (e.g. water temperature).

No development effects were detected in the square root richness model, contrary to results from the null, randomisation, and mixed model techniques (Table A2). However, results from the post-hoc Durbin-Watson test shows a departure from unity for both abundance and species richness models, indicating positive autocorrelation (Tabachnick and Fidell 1996). Sufficient doubt has been raised in the literature to question the validity of classical regression estimates in the presence of autocorrelation (Cliff and Ord 1981). Furthermore, exploratory analysis and results not shown here demonstrate that direction, magnitude, and significance of estimates using the classical regression method change as a function of data-normalising transformations applied to independent variables. Since autocorrelation are often present in ecological data sets and normalising procedures are often required for classical parametric statistics, I investigated the usefulness of randomisation and bootstrapping regression techniques.

It is often assumed that assemblages are structured in a non-random manner with their environment. Although non-random associations have been demonstrated in fish community-environmental relationships (Jackson et al. 1992) this pattern has yet to be demonstrated for habitat alteration and indices of fish occurrence. As such, I tested if the effects of developmental features were significantly and non-randomly associated with fish abundance and species richness after accounting for habitat and environmental effects. Temporary docks were significantly and positively associated with abundance, while bank stabilisations were negatively associated with abundance. Permanent docks were significantly and negatively associated with richness, while break walls were positively associated with richness. In regression using randomisation techniques, error terms are assumed to be independent, normally distributed with means zero and constant

Table A2 –Regression coefficients (significance or 95% confidence interval) for species richness computed on the 122 meters development zone using classical, randomization, bootstrap, and mixed regressions.

	Model Type			
	Classical[2]	Null[3]	Bootstrap	Mixed
Model	-2REML_LL = 2798.32			-2REML_LL = 2518.745
Log water temp.	**-0.251 (0.000)**	**0.294 (0.001)**	**0.25 (0.2,0.3)**	**(0.000)**
Day of year	**-0.221 (0.000)**	**-0.296 (0.001)**	**-0.03 (-0.04,-0.03)**	**(0.000)**
Fetch (mean)	**-0.076 (0.005)**	**-0.076 (0.002)**	**-0.10 (-0.2,-0.0)**	**(0.004)**
Rock[1]	**-0.066 (0.038)**	-0.044 (0.095)	-0.34 (-0.8,0.1)	**(0.025)**
Boulder[1]	**-0.074 (0.017)**	**-0.059 (0.025)**	**-0.38 (-0.7,-0.0)**	**(0.000)**
Rubble[1]	**-0.216 (0.000)**	**-0.223 (0.001)**	**-1.32 (-1.8,-0.8)**	(0.354)
Gravel[1]	-0.050 (0.123)	-0.041 (0.100)	-0.25 (-0.6,0.1)	(0.675)
Sand[1]	**0.193 (0.000)**	**0.203 (0.001)**	**1.23 (0.9,1.5)**	**(0.000)**
Muck[1]	**0.115 (0.000)**	**0.119 (0.001)**	**1.11 (0.5,1.7)**	**(0.000)**
Detritus[1]	**-0.076 (0.007)**	**-0.066 (0.019)**	**-0.51 (-1.0,-0.5)**	(0.064)
Submergent vegetation[1]	**0.063 (0.029)**	**0.056 (0.027)**	**0.33 (0.0,0.7)**	(0.129)
Emergent vegetation[1]	0.019 (0.513)	0.031 (0.134)	0.34 (-0.4,0.3)	(0.749)
Shore vegetation cover	0.002 (0.936)	-0.037 (0.061)	-0.11 (-0.27,0.04)	(0.263)
Log dock temporary	0.060 (0.074)	-0.002 (0.510)	-0.00 (-0.1,0.1)	**(0.052)**
Log dock permanent	-0.025 (0.385)	**-0.053 (0.033)**	**-0.12 (-0.2,-0.1)**	(0.664)
Log stabilization	-0.042 (0.129)	-0.029 (0.131)	-0.002 (-0.0,0.0)	(0.142)
Log break wall	-0.026 (0.354)	**0.046 (0.031)**	0.002 (-0.00,0.00)	(0.252)
Log boat house	0.029 (0.373)	-0.005 (0.412)	-0.01 (-0.1,0.1)	(0.738)

1 - Coefficient and significance of these variables is for presence information.

2 - R^2 = 0.273. Model uses square root richness.

3 - R^2 =0.308.

4 - Model uses untransformed variables and may exhibit regression coefficients of opposite magnitude than those of classical and mixed models (e.g. water temperature).

variance but no mention is made of F-tests being valid in the presence of dependent or autocorrelated errors (Manly 1991). However, since the significance of effects is tested against the distribution of the data set that contains the autocorrelation, one could assume that F-tests are valid regardless of the correlation in the error term. The uncertainty in the randomization procedure associated with autocorrelation left me unsure of the exact validity of regression estimates but confirmed that non-random and significant patterns exist between shoreline development and fish measures.

The bootstrap method was used to investigate the robustness of effects by resampling the data set with replacement. The resampling procedure allows testing of an hypothesis with a slightly different data set, providing a confidence interval around the regression estimate. Estimates computed using bootstrapping may be valid in the presence of autocorrelation, particularly if original observations are resampled instead of residuals (Efron and Tibshirani 1993). Some researchers include terms in the model that take into account correlations in the error terms (Elkinton et al. 1996) but the validity of such tests without these terms is not fully understood (Elkinton pers. comm.). In my analysis, bootstrap estimates of confidence intervals that do not include the value zero demonstrated the significance of an effect. Bank stabilisation was found to be significant and negative in the abundance model, while permanent docks were significant and negative in the richness model (Table A1 and A2).

Professional statisticians discourage the use of techniques with intractable calculations and untested assumptions (Brian Allen and Nicky Roslin, pers. comm. Ashton Consulting Lab, University of Guelph). For this reason, I decided not to interpret the specific results of randomisation and bootstrap technique in the thesis, in favour of the more tractable mixed-model technique. Results from the classical regression method were not discussed in the thesis since these give poor results in the presence of correlated errors.

In conclusion, the variability in the significance of specific effects determined using classical, randomization, and bootstrap regression on the same data set should be of concern to scientists using these techniques. Ecologists should be aware that their ability to detect effects in observational studies could be a function of the technique used to analyze the data. I recommend that the specific mechanisms by which results do not converge be investigated in a study using data generated randomly and with a structure in order to simulate impacts of effect-size and correlated errors.

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