

Nearshore Community Characteristics Related to Shoreline Properties in the Great Lakes

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ABSTRACT. Successful protection and restoration of Great Lakes nearshore ecosystems will likely rely on management of terrestrial resources along Great Lakes shorelines. However, relationships between biological communities and changing shoreline environmental properties are poorly understood. We sought to begin understanding the potential roles of shoreline geomorphological and land cover properties in structuring nearshore biological communities in the Laurentian Great Lakes. Despite high variability in densities (benthic macroinvertebrates and zooplankton) and catch per unit effort (CPUE, shallow water and nearshore fish) within and among lake areas, several biological community patterns emerged to suggest that nearshore aquatic communities respond to shoreline features via the influences of these features on nearshore substrate composition and stability. Benthic macroinvertebrate densities were not different between shoreline types, although they were generally lower at nearshore sites with less stable substrates. Shallow water fish CPUE and zooplankton densities were generally lower for nearshore areas adjacent to developed mid-bluff shorelines and sites characterized by less stable substrates. Larger fish CPUE appeared to be unresponsive to local shoreline and substrate properties of nearshore zones. The emergence of these patterns despite significant ecological differences among lake areas (e.g., productivity, community composition, etc.) suggests that shoreline development may have comparable influences on nearshore ecosystems throughout the Great Lakes, providing a terrestrial-based indicator of relative nearshore biological and ecological integrity.

INDEX WORDS: Great Lakes, nearshore ecology, biological communities, shoreline land use.

INTRODUCTION

Great Lakes nearshore zones factor significantly in the life histories of many Great Lakes native fish species (Goodyear *et al.* 1982; Lane *et al.* 1996a,b), as well as providing important habitat for their prey (e.g., Jude and Tesar 1985, Evans 1992, Madenjian *et al.* 2002). Steedman and Regier (1987) referred to “centers of organization” within nearshore areas that provide essential fish habitat, both in terms of physical features and consumable resources (Hayes *et al.* 1996), that are of greater importance than their lim-

ited spatial extent would suggest. However, nearshore areas are particularly susceptible to anthropogenic stressors because they serve as an interface between terrestrial and open-water environments. As such, human activities along shorelines may directly influence nearshore areas through exchanges of materials such as sediment, nutrients, and chemical pollutants. However, the degree to which shoreline activities influence nearshore habitats and biological communities is poorly understood.

Shoreline hardening to prevent natural erosion processes alters nearshore littoral transport of substrates, eliminates shoreline migration as Great

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Lakes water levels change, and reduces aquatic habitat diversity (Steedman and Regier 1987, Edsall and Charlton 1997). In addition, straightened shorelines lose structural irregularities that drive variations in alongshore currents and local substrates. Therefore, the type, distribution, and stability of substrates within nearshore areas is expected to change as shoreline features are altered by human activities. The distribution and availability of different substrate types contributes to habitat heterogeneity, a significant factor in determining fish community structure and production (Eadie and Keast 1984, Benson and Magnuson 1992, Leslie and Timmins 1993). Biological uses of these habitats are directly related to available surface area, pattern, distribution, and relative stability of substrates comprising the lakebed within the nearshore zone (Mackey and Liebenthal 2005). As nearshore substrate properties (e.g., composition and stability) are altered by nearshore-shoreline interactions, community structure is expected to change as well. Given the importance of nearshore areas to Great Lakes fauna of multiple taxonomic groups, changes in community structure could have dramatic effects on Great Lakes fisheries and productivity over time. Understanding nearshore community responses to shoreline features that drive nearshore substrate composition, distribution, and stability will contribute greatly to managers' abilities to make informed decisions about shoreline development and other activities that may affect these ecosystems.

In an effort to begin understanding the role of shoreline features in Great Lakes nearshore ecology, we conducted biological community studies of six Great Lakes nearshore areas associated with varying local shoreline geomorphology and human development. We sought to identify community and functional/taxonomic group patterns associated with regional (lake area) and local shoreline properties via density measurements of major taxonomic groups. We hypothesized that densities of native fish, benthic macroinvertebrates, and zooplankton would be higher at nearshore areas associated with lower levels of shoreline development and structure placement (i.e., unique shorelines) compared to heavily engineered, mid-size bluff (< 30 m tall) shorelines (i.e., mid-bluff shorelines). We expected that these patterns would remain consistent among several lake areas of the basin, including southern Lake Erie (SLE), eastern Lake Michigan (ELM), and western Lake Michigan (WLM). We also hypothesized that native biological community density measures would be higher in nearshore areas with relatively stable vs. highly unstable substrates.

METHODS

Study Sites

Nearshore biological communities were surveyed in SLE, ELM, and WLM regions of the Great Lakes basin during 1999 and 2000 (Fig. 1). Selected sampling sites were categorized as two main groups. Unique sites were examples of shoreline types that were distinctive for each lake area. Sheldon Marsh (SM, Erie Co., Ohio) was characterized as a shallow embayment of Lake Erie with organic rich sandy and muddy-sand substrates. The Ludington site (LD, Mason Co., Michigan) was characterized as a sandy beach/dune shoreline with a nearshore area comprised almost exclusively by an extensive sand sheet. Port Washington (PW, Ozaukee Co., Wisconsin) was characterized as a high bluff (i.e., > 40 m) shoreline with mixed sand and glacially deposited (e.g., cobbles and boulders) nearshore substrates. The mid-bluff sites were moderate bluff (i.e., < 30 m) shorelines with typically sand-starved nearshore areas that occurred in all three lake areas surveyed. Mid-bluff sites included Painesville (PV, Lake Co., Ohio), St. Joseph (SJ, Berrien Co., Michigan), and Two Rivers (TR, Manitowoc Co., Wisconsin). Substrates at these sites were variable, although they were principally comprised of sparse sandy areas with exposed cobbles, boulders, and clay. Unique shorelines generally had very little local human development and land use, while the mid-bluff shorelines were extensively modified by erosion control structures and human land uses.

Sampling Procedures

Nearshore substrate composition and stability were determined for each study area based on georeferenced Geographic Information Systems (GIS) interpretations of sidescan sonar mosaics. Detailed methods used to derive these data are provided in Mackey and Liebenthal (2005). Study sites were designated as having high substrate stability (SM, SJ, LD, and PW) or low substrate stability (TR and PV) based on comparisons of substrate mosaics between 1999 and 2000. These substrate stability groups served as statistical grouping factors for evaluating potential differences in nearshore biological communities in response to local substrate stability regime.

At each site, three transects were established perpendicular to the shoreline with sampling stations at 1.0, 3.0, and 6.0 m water depths along each transect. Nearshore substrate characteristics at each sampling station were determined based on bottom

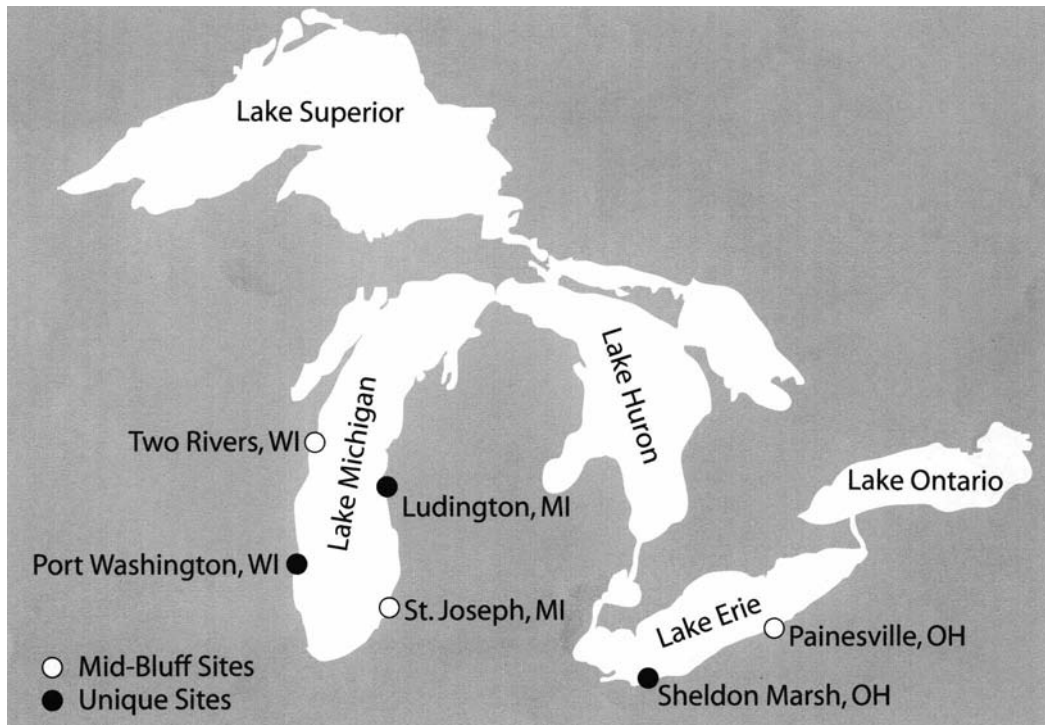


FIG. 1. Locations of the six nearshore study sites within the Laurentian Great Lakes basin.

grab samples and SCUBA reconnaissance. A Petit Ponar[®] grab was deployed from the boat to provide an initial characterization of local substrates. High-volume samples indicated that soft substrates (e.g., sand) were prevalent at the sampling station, while sparse grab samples suggested the presence of hard substrates and/or clay. Divers assessed substrates at stations where sparse grab samples were observed to determine the local substrate composition.

Three animal community types were sampled along each transect: benthic macroinvertebrates, zooplankton, and fish, including shallow water (≤ 1.0 m depth) and nearshore (3.0 m depth) fish. Three samples were collected at each sampling station to characterize the benthic community. Benthic samples were collected using a Petit Ponar[®] dredge (0.023 m²) at stations with soft sand/silt substrate. At sampling stations dominated by rocky, hard, or clay substrates, surveyors with SCUBA equipment used a custom vacuum sampler to remove biota from a 0.063-m² template area. Stations with both hard and soft substrates were sampled proportionately using both methods to reflect the relative contribution of each substrate type in the vicinity of the sampling station. Benthic samples were preserved using 95% ethanol (EtOH) in the field, and inverte-

brates were later identified to the lowest practical level necessary for analysis and counted in the laboratory.

Only native benthic taxa were used in benthic community analyses because the non-native dreissenids were not reliably and comparably collected in benthic samples during the surveys. Benthic macroinvertebrate data were standardized by dividing the number of invertebrates present in a sample by the area sampled using each technique (i.e., vacuum and Ponar[®]) to provide density measurements for each taxonomic and group. Benthic invertebrates were grouped into taxonomic groups that often fell along formal class divisions (Insects, Gastropods) or other similar groupings (Oligochaeta, Peracarida).

Zooplankton were sampled using three vertical tows of a 30 cm diameter, 90 cm long, 80 μ m mesh plankton net at each sampling station. For each sample, the plankton net was deployed from the boat and allowed to sink to 0.5 m above the lake bottom. It was then towed vertically through the water column. Plankton samples were preserved in 95% EtOH in the field and were later processed in the laboratory. At least 100 zooplankton specimens were identified in each sample. A plankton splitter

TABLE 1. Biological sample dates for nearshore areas in Lakes Erie and Michigan during the summers of 1999 and 2000. Study sites included Sheldon Marsh, Ohio (SM), Ludington, MI (LD), Port Washington, WI (PW), Painesville, OH (PV), Saint Joseph, MI (SJ), and Two Rivers, WI (TR). P = benthic Ponar grab sample; V = benthic vacuum sample. *Benthic invertebrates collected from two transects. **Beach seines and gillnets completed along two transects.

Taxonomic Group	Study Site					
	SM	LD	PW	PV	SJ	TR
Zooplankton	15-Aug-00	24-Aug-00	13-Sep-00	07-Jun-00	22-Aug-00	10-Oct-00
Benthic Invertebrates	15-Aug-00 (P)	24-Aug-00 (P)	13-Sep-00 (V/P)	10-Aug-99* (V)	22-Aug-00 (P)	10-Oct-00 (V/P)
Shallow Water Fish (Beach Seines)	15-Aug-00	24-Aug-00	12-Sep-00	3-Oct-00**	21-Aug-00	26-Sep-00
Nearshore Fish (Gillnets)	15-Aug-00	24-Aug-00	12-Sep-00	7-Jun-00**	21-Aug-00	25-Sep-00

was used to divide the samples into manageable numbers if samples were large (i.e., greater than 1,000 individuals). Zooplankton were classified primarily by coarse taxonomic groups (Cladocera, Calanoida, and Cyclopoida). Although many zooplankton taxa were too infrequently encountered to conduct statistical analyses for lower taxonomic groupings, *Daphnia* spp. occurred in sufficient numbers that the data were analyzed both as part of the cladoceran dataset as well as separately. Data were standardized by dividing the number of individual zooplankton in each sample by the volume of the water column sampled (i.e., depth multiplied by the area of the net opening) to produce a density measurement (number/m³) for each taxonomic and/or functional group.

Shallow water and nearshore fish communities were sampled using beach seines and gill nets. Three replicate beach seine hauls were used to characterize the shallow water fish communities (i.e., ≤ 1.0 m) at the shoreward base of each transect. A 10 m, 6.4 mm mesh seine was hauled for a 10 m distance parallel to the shore after dusk for each replicate. Nearshore fish communities were sampled using three limited-duration scientific gillnet (38.0 m long, 2.4 m deep) sets. The gillnets were comprised of five 7.6 m sections, each with a different mesh size (i.e., 2.5 cm, 3.8 cm, 5.1 cm, 6.4 cm, and 7.6 cm). Gillnets were anchored at the 3.0 m depth station along each transect and were deployed from a boat in an offshore direction resulting in a perpendicular orientation to the shoreline. One gillnet was set along each transect after sundown and was fished for a maximum of 4 hours. Fish captured using the

beach seines and gillnets were identified, counted, and released. Mortality rates for all fish samples collected were negligible. Beach seine and gillnet data were standardized by calculating catch per unit effort (CPUE) estimates for each sample. These CPUE estimates were used as surrogates for density measures for fish species and overall fish communities. Fish species richness measures were determined for each site, and fish species were classified according to feeding guild (i.e., piscivore, planktivore and benthivore) and species origin (i.e., native and non-native) for analysis.

Statistical Analysis

Repeated attempts to normalize the field data using transformations were unsuccessful. Therefore, nonparametric Kruskal-Wallis (K-W) tests were conducted to determine whether density and CPUE data for each taxonomic and functional group were different between shoreline types (unique vs. mid-bluff) and among lake areas (SLE, ELM, WLM). Nearshore density and CPUE measures were also used to determine whether these measures were different between the substrate stability regimes. An alpha level of 0.05 was used for all statistical tests.

RESULTS

Summary

Biological communities were primarily surveyed during late summer and early fall of 2000 (Table 1). Inclement weather conditions prevented benthic invertebrate surveys at the PV site in 2000, necessi-

TABLE 2. Substrate compositions and characteristics (% of survey area) of nearshore areas adjacent to six Great Lakes shorelines surveyed during summer 2000. Substrate data were interpreted from side-scan sonar mosaics. Classifications of sites according to overall substrate stability and associated shoreline types are provided. Sites surveyed include Ludington, MI (LD); Painesville, OH (PV); Port Washington, WI (PW); Saint Joseph, MI (SJ); Sheldon Marsh, OH (SM); and Two Rivers, WI (TR). Adapted from Mackey and Liebenthal (2005).

Substrate Type	Survey Site					
	SM	PV	LD	SJ	PW	TR
Sand Substrates (% of site)	65	23	100*	66	34	17
Thin-Sand Substrates (% of site)	18	61	0	24	25	49
Muddy-Sand Substrates (% of site)	17	0	0	9	0	0
Cobble/Boulder Substrates (% of site)	0	14	0	0	41	35
Substrate Change, 1999 to 2000 (% of site)	21	12	0	25	9	31
Sand Lost (% of 1999 sand)	14	30	0	17	15	56
Area of Stable Sand Substrate (% of site)	63	13	100*	57	37	13
Substrate Stability Class	High	Low	High	High	High	Low
Shoreline Class	Unique	Mid-Bluff	Unique	Mid-Bluff	Unique	Mid-Bluff

* Actual sand composition and substrate stability for the LD site are unknown, but are assumed to be high in comparison to other sites given the near-infinite extent of the sand sheet in the vicinity of the shoreline reach surveyed.

tating the use of data collected during late summer 1999. Benthic samples among sites were principally comprised of nine coarse groups that included 18 taxonomic classifications (Appendix I). Seventeen zooplankton taxa were observed across all sites, including two non-native species, *Cercopagis pengoi* and *Bythotrephes cederstroemi* (Appendix II). Twenty-seven fish species were observed across all survey sites, including seven non-native species (Appendix III). Nearshore substrates classified based on sidescan sonar surveys ranged widely among sites. Predominant substrates observed were sands, thin sands (e.g., thin layers of sand over clay), organic-rich sands, muddy-sands, clays, and cobble and boulder glacial deposits (Table 2).

Benthic Macroinvertebrates

There was great variability in the community composition and densities of benthic invertebrates within and among study sites and lake areas (Fig. 2a-b and Appendix I). Total native benthic invertebrate densities were not significantly different between shoreline types (Fig. 3a and Table 3). However, overall benthic macroinvertebrate densities were different between lake areas, with the greatest densities in WLM and the lowest in SLE (Fig. 3b and Table 3). Aquatic insect densities were not different between shoreline types ($p = 0.40$), although they were higher in ELM compared to both

WLM and SLE (Fig. 2a-b and Table 3). Oligochaete densities exhibited great variability among sites and within lake areas and were consistently two orders of magnitude greater at one of the two sites in each lake area. However, this pattern was not consistent between shoreline types, and densities were not different among lake areas (Fig. 2a-b and Table 3). Amphipods and isopods dominated benthic invertebrate samples at WLM sites and were detected at very low levels at only one of the remaining four sites (PV). Because amphipods and isopods were consistently observed in only one lake area (WLM), analyses to detect differences between shoreline types were deemed inappropriate. Gastropods were absent from SLE samples, and they were generally observed in low densities at the remaining sites. Gastropod densities were not significantly different between shoreline types, although they were marginally higher in WLM compared to SLE (Fig. 2a-b and Table 3). Sphaeriid densities were not different between shoreline types or among lake areas (Fig. 2a-b and Table 3).

Overall benthic macroinvertebrate densities were greater at sites with higher substrate stability (Fig. 3c and Table 3). Larval aquatic insect and oligochaete mean densities also occurred in greater densities at higher substrate stability sites ($p < 0.001$ and $p < 0.001$, respectively) (Fig. 2c and Table 3). Both

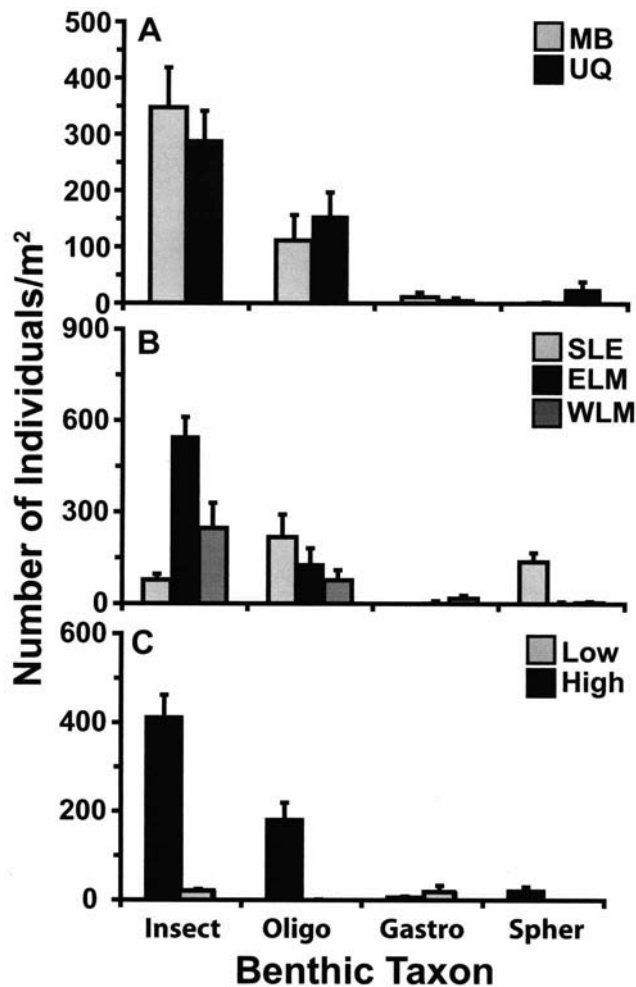


FIG. 2. Mean (\pm 1S.E.) benthic invertebrate densities (number of individuals/ m^2) segregated according to coarse taxonomic groups for shoreline types, lake areas, and substrate stability regimes based on surveys of Great Lakes nearshore areas during summers 1999 and 2000. Taxonomic groups include larval aquatic insects (Insects), oligochaetes (Oligo), gastropods (Gastro), and sphaeriid clams (Spher).

gastropod and sphaeriid densities were similar between substrate stability regimes (Fig. 2c and Table 3). Amphipods and isopods were absent or nearly absent at four of the six sites; hence, they were excluded from the substrate stability regime analysis.

Zooplankton

Zooplankton densities were highly variable among sites and were especially high in SLE (and at SM, in particular), often 1–2 orders of magni-

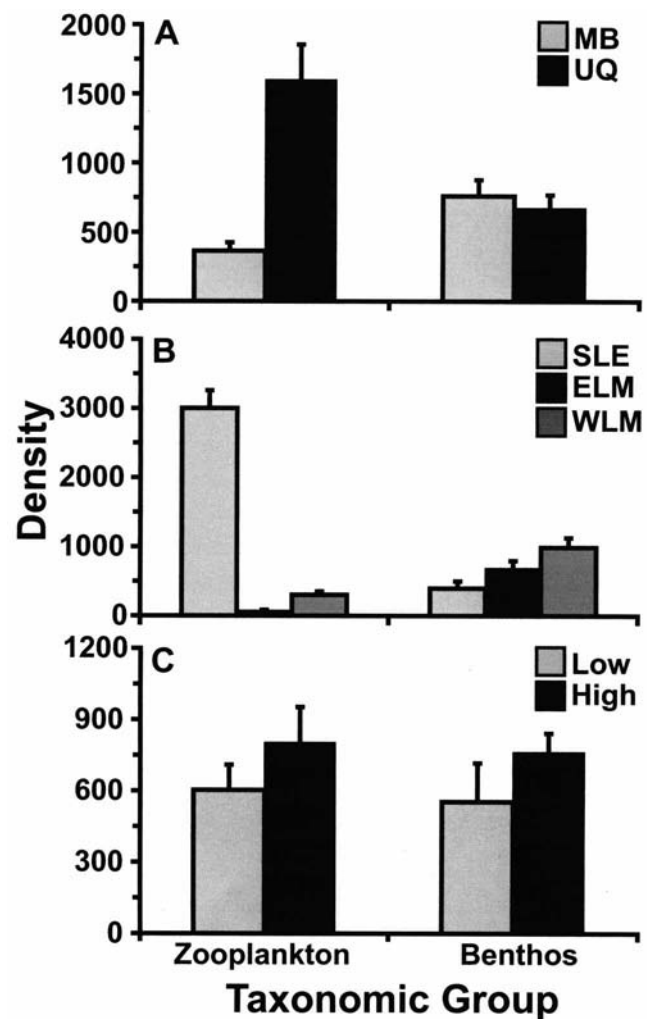


FIG. 3. Total mean (\pm 1S.E.) benthic invertebrate densities (number of individuals/ m^2) and total mean zooplankton densities (number of individuals/ m^3) for shoreline types, lake areas, and substrate stability regimes based on surveys of Great Lakes nearshore areas during summers 1999 and 2000.

tude greater than the other sites and lake areas. Unique shorelines were characterized by higher total zooplankton densities, and the SLE lake area exhibited far greater total zooplankton densities than the other lake areas (Fig. 3a–b and Table 3). Cladoceran densities were higher at unique shorelines and were higher in SLE compared to both ELM and WLM (Fig. 4a–b and Table 3). Densities of *Daphnia* spp. were also different between shoreline types and were highest for the SLE lake area

TABLE 3. Results of Kruskal-Wallis nonparametric tests for nearshore community density (benthos and zooplankton) and catch per unit effort (CPUE, fish) data to determine whether statistically significant differences existed among shoreline types, lake areas, and substrate stabilities. Chi-square (χ^2) values and statistical significance (*p*) values are provided for each nonparametric test. All results were considered significant at $\alpha = 0.05$.

Taxon/Group	Shoreline Type		Lake Area		Substrate Stability		
	χ^2	<i>p</i>	χ^2	<i>p</i>	χ^2	<i>p</i>	
Benthos Density	Aquatic Insect Larvae	0.71	0.40	39.52	< 0.001	33.41	< 0.001
	Oligochaetes	2.89	0.09	3.81	0.15	14.27	< 0.001
	Gastropods	0.03	0.86	5.99	0.05	0.54	0.44
	Spheriid clams	2.75	0.10	5.22	0.06	2.42	0.11
	Total Benthos	0.02	0.88	13.53	0.001	6.71	0.009
Zooplankton Density	Cladocerans	7.84	0.01	95.06	< 0.001	0.00	1.00
	Daphnia spp.	13.39	< 0.001	115.94	< 0.001	8.67	0.004
	Calanoids	14.31	< 0.001	90.87	< 0.001	4.9	0.03
	Cyclopoids	6.57	0.01	114.35	< 0.001	7.71	0.005
	Nauplii	49.73	< 0.001	47.91	< 0.001	6.53	0.009
	Harpacticoids	N/A	N/A	N/A	N/A	0.57	0.46
	Non-native Zooplankter	5.28	0.022	88.76	< 0.001	23.7	< 0.001
Total Zooplankton	5.03	0.03	112.01	< 0.001	4.31	0.04	
Shallow Water Fish CPUE	Benthivore	0.71	0.40	15.60	< 0.001	2.76	0.11
	Planktivore	4.86	0.02	11.69	0.004	10.37	< 0.001
	Native	9.78	0.003	0.10	0.95	6.82	0.009
	Non-native	2.69	0.09	5.77	0.06	7.89	0.005
	Total CPUE	9.45	0.002	0.88	0.64	7.95	0.007
Nearshore Fish CPUE	Benthivore	0.04	0.84	7.43	0.02	0.49	0.47
	Planktivore	0.07	0.81	N/A	N/A	0.90	0.32
	Piscivore	0.00	1.00	9.00	0.01	0.18	0.67
	Native	0.04	0.84	9.78	0.009	0.56	0.45
	Non-native	1.35	0.25	11.55	0.00	0.18	0.67
	Total CPUE	0.23	0.62	9.14	0.02	0.28	0.62

(Fig. 4a–b and Table 3). Calanoid densities were greater for unique shorelines and were highest for the SLE lake area (Fig. 4a–b and Table 3). Cyclopoid densities were higher for unique shorelines and were highest for the SLE lake area (Fig. 4a–b and Table 3). Harpacticoids were observed in very low densities across study sites and were absent or nearly absent at four of the six sites. Hence, statistical tests to detect differences between shoreline types and lake areas were not conducted for harpacticoids. Nauplii densities were higher at unique shoreline sites and were greatest in the SLE lake area, primarily due to the particularly high nauplii densities observed at the SM site (Fig. 4a–b and Table 3). Densities of non-native zooplankton were higher at mid-bluff compared to unique sites

and were greatest in the ELM lake area (Fig. 4a–b and Table 3). These differences in non-native zooplankton were primarily due to the particularly high densities observed at the SJ site.

Total zooplankton densities were greater for sites characterized by higher substrate stability (Fig. 3c and Table 3). Daphnia, calanoids, nauplii, and non-native zooplankter densities were also higher at higher substrate stability sites (Fig. 4c and Table 3). In contrast, cyclopoid densities were lower at sites characterized by high substrate stability regimes (Fig. 4c and Table 3). Densities of cladocerans and harpacticoids were not significantly different between the substrate stability regimes (Fig. 4c and Table 3).

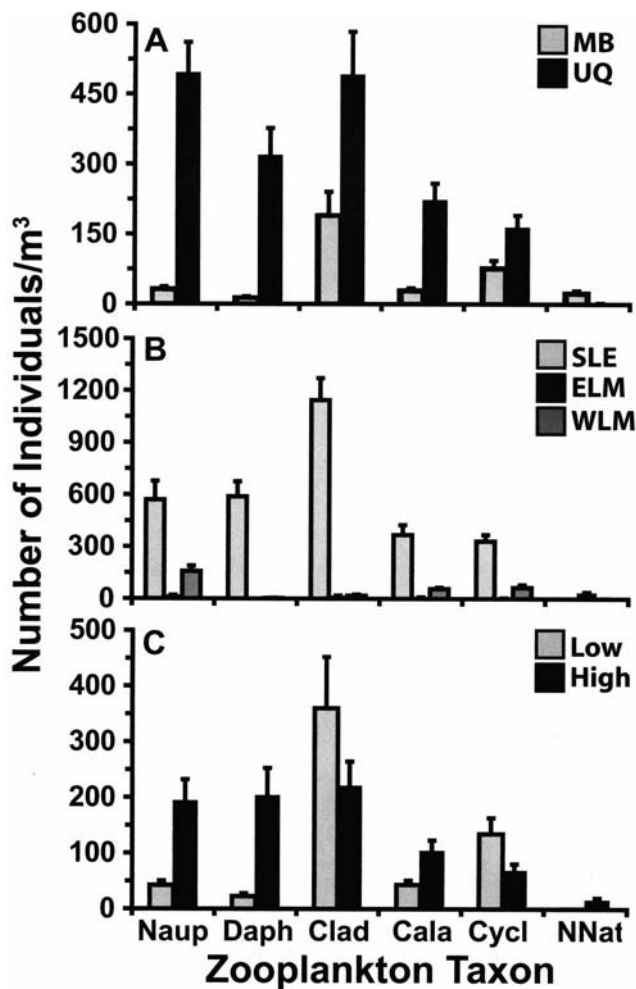


FIG. 4. Mean ($\pm 1S.E.$) zooplankton densities (number of individuals/ m^3) segregated according to coarse taxonomic groups for shoreline types, lake areas, and substrate stability regimes based on surveys of Great Lakes nearshore areas during Summer 2000. Taxonomic groups include nauplii (Naup), *Daphnia* spp. (Daph), cladocerans (Clad), calanoids (Cala), cyclopoids (Cycl), and non-native (NNat). Non-native zooplankton includes two species, *Cercopagis pengoi* and *Bythotrephes cederstroemi*.

Shallow Water Fish Communities

No shallow water fish were common to all sites; hence, statistical analyses were based on trophic classifications and fish origins (i.e., native and non-native). Unique shorelines were characterized by higher overall CPUE, but there was no statistically significant difference in total CPUE among lake areas (Fig. 5a–b and Table 3). Benthivore CPUE

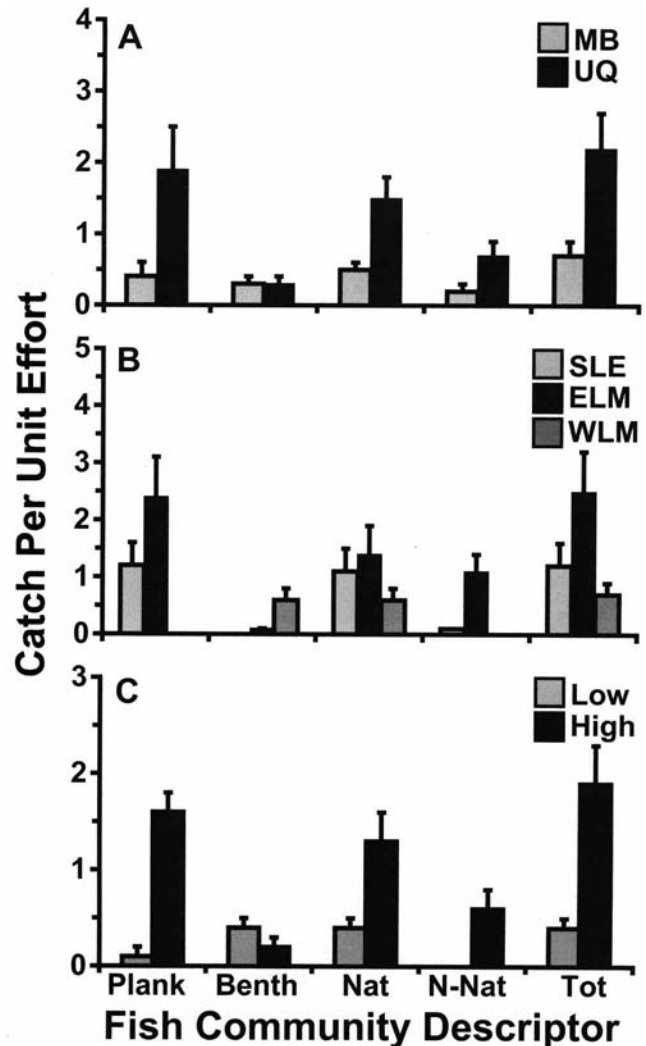


FIG. 5. Mean ($\pm 1S.E.$) shallow water fish catch per unit effort (CPUE) segregated according to trophic guilds and species origins for shoreline types, lake areas, and substrate stability regimes based on surveys of Great Lakes nearshore areas during Summer 2000. Overall CPUE of shallow water fish is also provided.

was not different between shoreline types, although it was greater in WLM (Fig. 5a–b and Table 3). Planktivore CPUE was higher for unique shoreline sites and was lowest in SLE (Fig. 5a–b and Table 3). Unique shoreline sites exhibited greater native fish CPUE, and native fish CPUE was similar among the three lake areas (Fig. 5a–b and Table 3). Non-native fish CPUE was nearly significantly higher at unique sites and in ELM (Fig. 5a–b and Table 3).

Total CPUE was greater for nearshore areas char-

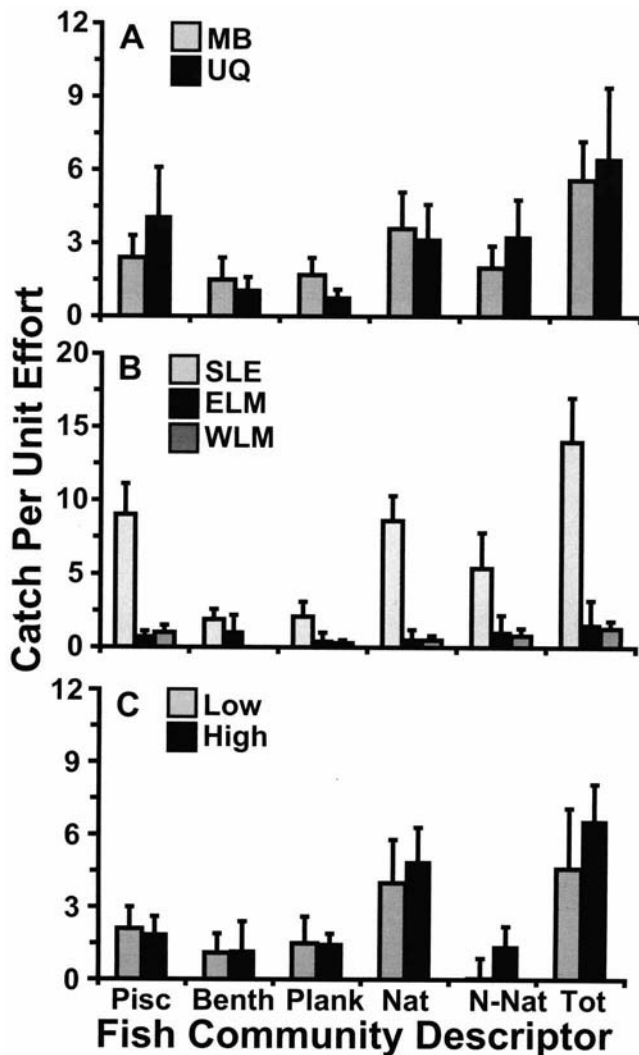


FIG. 6. Mean (± 1 S.E.) nearshore fish catch per unit effort (CPUE) segregated according to trophic guilds and species origins for shoreline types, lake areas, and substrate stability regimes based on surveys of Great Lakes nearshore areas during summer 2000. Overall CPUE of shallow water fish is also provided.

acterized by higher substrate stability regimes (Fig. 5c and Table 3). Sites with high substrate stability were characterized by higher planktivore, native, and non-native CPUE (Fig. 5c and Table 3). Benthivore CPUE was not different between substrate stability regimes (Fig. 5c and Table 3).

Nearshore Fish Communities

Similar to the shallow water fish communities, no nearshore fish species were present at all sites;

hence, the nearshore fish analyses were based on trophic classifications and fish origins. Overall CPUE was not significantly different between shoreline types, but it was significantly greater in the SLE lake area (Fig. 6a–b and Table 3). Benthivore CPUE was not different between the shoreline types, although it was higher in SLE compared to the other lake areas (Fig. 6a–b and Table 3). Planktivore CPUE was very similar between shoreline types, although no planktivores were detected in gill net samples in WLM (Fig. 6a–b and Table 3). Piscivore CPUE was not different between shoreline types, but it was significantly greater for the SLE lake area (Fig. 6a–b and Table 3). Native fish CPUE was similar between shoreline types, and it was highest in SLE (Fig. 6a–b and Table 3). Non-native fish CPUE was not different between shoreline types, although it was higher in SLE (Fig. 6a–b and Table 3).

Total CPUE was not significantly different between nearshore areas with low vs. high substrate stability regimes (Fig. 6c and Table 3). CPUE measures for trophic classes were also not significantly different between substrate stability regimes, including piscivores, planktivores, and benthivores (Fig. 6c and Table 3). Native and non-native fish CPUE were not significantly different between high and low substrate stability regimes (Fig. 6c and Table 3).

DISCUSSION

Biological community properties of the Great Lakes nearshore areas surveyed during 1999 and 2000 varied greatly within and among sites and lake areas. Not surprisingly, most biological community measures were different among lake areas, largely as a result of the comparatively high productivity of Lake Erie. The majority of abundance measures for zooplankton and nearshore fish were significantly higher in SLE. Despite this high variability among sites and lake areas, several biological community patterns emerged to suggest that nearshore areas immediately adjacent to highly developed shorelines are characterized by lowered biological and ecological integrity. These patterns were evident based on both the shoreline type and substrate stability. While benthic macroinvertebrate densities were not different between shoreline types, overall benthic, aquatic insect, and oligochaete densities were lower at sites with low substrate stability. Zooplankton densities and shallow water fish CPUE were, with few exceptions,

significantly lower for developed mid-bluff sites and sites with lower stability substrate regimes. In contrast to the other communities sampled, nearshore fish CPUE did not differ between shoreline types or substrate stability regimes, suggesting that larger fish may respond to larger scale processes while their prey, including benthos, zooplankton, and small non-game fish, may respond more to local habitat features.

Benthic Macroinvertebrates

Overall and individual taxonomic group densities for native benthos were not different between shoreline types. This may have been due, in part, to the high variability in benthic densities within and among lake areas. Lake area analyses revealed that overall benthic and individual taxonomic group densities were consistently lower in SLE. We expected the higher overall productivity of Lake Erie to be reflected in the benthic community measures, but this was not the case. In addition, the mid-bluff site in ELM (SJ) had the second highest overall benthic densities observed, and they were considerably higher than the unique site in the same lake area (LD). However, benthic macroinvertebrate densities (overall, aquatic insect, and oligochaete) were often greater at sites with high substrate stability regimes (i.e., LD, SJ, PW, and SM). This was expected given that benthic invertebrate taxa and communities are strongly influenced by substrate type and stability. However, the inconsistent results between shoreline type and substrate stability suggest that efforts to predict nearshore substrate characteristics important for benthos based solely on shoreline features must be tempered with caution. Even though all three mid-bluff sites had similar shoreline features, substrate stability regimes were similar only between two of the three sites. Spatiotemporal factors not considered in this study (e.g., shoreline orientation, shore structure age, etc.) may cause substrate stability regimes to vary within shoreline types.

The loss of sand and exposure of large, glacially deposited substrates (i.e., cobbles and boulders) is another consequence of altered substrate dynamics in Great Lakes nearshore areas. Shoreline features, including erosion control structures and land development, can cause shifts in substrate dynamics to favor decreased sand availability, thus exposing hard substrates that are ideal for *Dreissena polymorpha* colonization. The colonization of hard substrates by *D. polymorpha* can actually increase local

habitat complexity, creating additional habitat for local native benthos (Dermott *et al.* 1993, Stewart and Haynes 1994, Wisenden and Bailey 1995, Botts *et al.* 1996, Stewart *et al.* 1998). The increased substrate complexity provided by the dreissenid shells and the higher rate of organic matter deposition in the form of dreissenid fecal and pseudofecal material can contribute to increased abundances of native benthic taxa (Dermott *et al.* 1993, Stewart and Haynes 1994, Ricciardi *et al.* 1997, Thayer *et al.* 1997, Stewart *et al.* 1998). However, native benthic taxa were largely underrepresented at the low substrate stability sites, particularly the PV site. The low benthic densities at the PV site were likely the result of a second non-native species that favors the exposed cobbles and boulders, *Neogobius melanostomus*. Manipulative studies have demonstrated that densities of benthic invertebrates decline significantly in the presence of *N. melanostomus* (Kuhns and Berg 1999). This non-native benthivore has been reported to rely heavily on native benthic taxa as food sources, primarily during the juvenile stages (Jude *et al.* 1995). Densities of *N. melanostomus* at PV were about 16 individuals/m² (at 3.0 m water depth) based on SCUBA observations. These densities were extremely high compared to SCUBA observations and beach seine hauls at other sites, suggesting that the high densities of *N. melanostomus* at the PV site depressed native benthic communities.

Larval aquatic insect and oligochaete density patterns were inconsistent between shoreline types. While mean density measures for both groups were lower for mid-bluff sites in SLE and WLM, they were higher for the mid-bluff site in ELM. These inconsistencies may have been due, in part, to the temporal discontinuity among sites for benthic samples. Although PV benthic samples were collected within a comparable seasonal period to most sites, they were collected a year earlier, and conditions may have been sufficiently different during 1999 that the benthic densities were not comparable for the site in 2000. Benthic samples were also collected considerably later in the season at TR compared to the other sites, which may have contributed its lower aquatic insect and oligochaete densities. However, if substrate stability is considered, both TR and PV emerged as having low substrate stability compared to all other sites, including SJ, the other mid-bluff site. The TR and PV sites were also quite comparable in terms of the aquatic insect and oligochaete densities, while aquatic insect and oligochaete densities at SJ were generally

more similar to other sites with high substrate stability. Given these considerations, we concluded that larval aquatic insect densities were meaningful for all sites despite the temporal discontinuity of the data and that aquatic insect and oligochaete densities were lower for sites with lower substrate stability. Sands were prominent substrate features of sites with higher substrate stability regimes, and chironomid larvae were found to occur in higher densities (and comprised the bulk of aquatic insect communities) at these sites. Oligochaetes were also associated with organic rich sands and other fine substrates, and the abundance of sands at the higher substrate stability sites likely contributed to higher densities of these taxa in comparison with nearshore areas characterized by lower substrate stability regimes. Larval aquatic insects overall appeared to be better adapted to Great Lakes nearshore areas with comparably higher substrate stability regimes. However, given that the data used to come to this conclusion are derived from a short-term study (i.e., ≤ 2 years), additional study over a larger time frame is needed to confirm this conclusion.

Zooplankton

Zooplankton are generally thought to be more susceptible to larger scale phenomena (e.g., wind direction and alongshore currents) than specific nearshore areas and associated shorelines. However, the PV and TR sites were both heavily colonized by *D. polymorpha*, and these sites comprised two of the three mid-bluff sites and both of the low substrate stability sites. Indirect competition of *D. polymorpha* for phytoplankton at these sites may have been responsible for these comparatively lower zooplankton densities (Dettmers *et al.* 2003). Thus, it appears that zooplankton communities may be linked to shoreline development via the influences that altered shoreline properties have on nearshore substrate dynamics, shifting habitats to favor colonization of a highly successful indirect benthic competitor for shared food resources.

There is some question as to whether the observed differences in zooplankton communities were in response to shoreline/nearshore factors or temporal discontinuity of samples. Boat mechanical problems and inclement weather precluded collection of temporally consistent zooplankton samples among all sites. Zooplankton populations can vary widely among seasons (e.g., Dettmers *et*

al. 2003), and seasonal differences in zooplankton community structure may have been responsible for the observed patterns. Most samples were collected during late summer 2000, although zooplankton surveys were conducted at PV in June 2000 and at TR in October 2000. Great Lakes zooplankton populations build seasonally, peaking in the late summer (Dettmers *et al.* 2003). Samples were therefore collected at two of the three mid-bluff sites before and after peak zooplankton densities were expected. This may have skewed results, especially because the third mid-bluff site was sampled concurrently with the unique site in the same lake area, resulting in similar mean overall zooplankton densities between sites. Because we cannot segregate shoreline and seasonal effects for the zooplankton analysis, additional studies to segregate these effects are needed to more definitively determine if zooplankton communities in nearshore areas are related to development of adjacent shorelines.

Shallow Water and Nearshore Fish

Although shallow water fish community composition varied widely among sites and lake areas, fish CPUE was largely similar among lake areas. The lower shallow water fish CPUE (i.e., overall, planktivore, and native fish) observed suggested that developed mid-bluff sites exhibited lower biological integrity compared to unique sites. Lower overall and native fish CPUE at low substrate stability sites also suggested that developed shorelines influenced biological integrity of nearshore areas. Similar biological criteria (e.g., trophic guilds, native species contributions to communities, abundance inferred by density measures) have been used to define biological integrity of freshwaters based on fish communities (e.g., Karr 1981, Minns *et al.* 1994, Thoma 1999), and the patterns that we interpreted as indicating lowered biological integrity were consistent with components of these studies. This was not surprising given that habitat availability and spatiotemporal variability are significant drivers of fish population variability (Eadie and Keast 1984, Fahrig 1992). Shallow water fish communities were comprised principally of species that serve as forage for piscivores in nearshore areas. Small-bodied, less mobile fish species are more likely to be affected by local changes in resource heterogeneity resulting from shoreline development than large, highly mobile predators (Kelso and Minns 1996), making small fish ideal for assessing relative bio-

logical integrity of nearshore areas. Large predatory fish, which did not exhibit differences in CPUE between shoreline types or substrate stability classes, are considered to be more important from a recreational and commercial perspective. However, loss of diversity and abundance of prey fish resulting from shoreline development and changes in nearshore habitats may have long-term, cumulative effects on Great Lakes fisheries production due to lost foraging opportunities. Therefore, protection, restoration, and remediation of nearshore habitats and shorelines will likely be necessary to improve the biological integrity of nearshore zones and ensure the sustainability of prey fish resources to support Great Lakes fisheries.

Differences in shallow water fish CPUE for shoreline types and substrate stability classes may have also been due to greater seining success on sandy substrates generally associated with unique sites (except PW, where substrates were more variable and estimates were comparably lower than other unique sites). The structurally complex substrates characteristic of mid-bluff sites can decrease seining efficiency and lower capture probabilities. High variability in catch rates among seine hauls further suggests that shallow water fish are patchily distributed and that variable substrate and/or wave conditions influenced seining efficiencies both within and among sites. Regardless, the generally consistent higher CPUE and higher native species richness of shallow water fish along sandy shorelines suggests that shallow water habitats are important for Great Lakes prey fish communities.

SUMMARY

Despite the high variability in abundance measures within and among lake areas, several biological community patterns emerged to suggest that nearshore aquatic communities respond to shoreline features via the influences of shorelines on nearshore substrate composition and stability. The fact that these patterns emerged despite significant ecological differences among lake areas (e.g., productivity, community composition, etc.) suggests that shoreline development may have comparable influences on nearshore ecosystems throughout the Great Lakes, providing a terrestrial-based indicator of relative nearshore biological and ecological integrity. Of course, the results presented here should be considered preliminary given the low level of replication for sites within and among lake areas.

They do, however, provide the basis for additional studies to more explicitly define relationships between nearshore ecosystems and adjacent shorelines. They also indicate a pressing need for sustainable development, restoration, and remediation of Great Lakes shorelines to ensure that ecosystem services, such as fisheries and their prey base, remain viable into the foreseeable future.

Of particular interest is the apparent connection between shoreline development and alteration of littoral transport processes that can transform Great Lakes nearshore substrates from stable sand to unstable sand within a matrix of larger, harder substrates (Mackey and Liebenthal 2005). This transformation directly influences community composition with respect to prey fish and benthic macroinvertebrate communities by altering available physical habitat. It also increases the likelihood of successful colonization by non-native species, such as *D. polymorpha* and *N. melanostomus*, that can compete with and depress local fish, benthic, and zooplankton communities. As food sources are converted over time, the ability of nearshore ecosystems to support prey fish and invertebrates may become diminished, reducing foraging opportunities for piscivores that have great value as recreational and commercial fisheries.

Our study, though limited in scope, suggests that identifying shifts in nearshore communities related to local shoreline features may provide a convenient means for modeling and predicting nearshore biological integrity in the Great Lakes. A terrestrial-based tool would facilitate assessment, prioritization, protection, restoration, and remediation of nearshore resources in the Great Lakes. However, the sites comprising this study likely represented somewhat subtle gradations in environmental perturbation that confounded statistical analysis in the absence of more specific criteria for classification and replication of appropriate classes. Changes in littoral transport, plankton distribution, fish movements and migrations, etc., are linked to, if not dependent upon, larger scale processes not considered in this study. In order to more effectively identify community and habitat changes related to anthropogenic manipulations within the Great Lakes basin, future studies must consider multiple spatial and temporal scales that influence nearshore ecosystems. We can then begin studying nearshore ecosystems more effectively to identify management and protection priorities to enhance

the long-term viability of the Great Lakes basin ecosystem.

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APPENDIX I. Macrobenthic taxa identified in samples collected from hard and soft substrates (1-, 3-, and 6 m depths) of Great Lakes nearshore study sites. Study sites included Sheldon Marsh, Ohio (SM), Ludington, MI (LD), Port Washington, WI (PW), Painesville, OH (PV), Saint Joseph, MI (SJ), and Two Rivers, WI (TR).

Class	Taxonomic Group Order, Family, Genus	Unique Sites			Midbluff Sites		
		SM	LD	PW	PV	SJ	TR
Insecta (Aquatic Larvae and Nymphs)	Ephemeroptera, Heptageniidae, <i>Stenonema</i> sp.	X			X		X
	Trichoptera, Leptoceridae, <i>Oecetis</i> sp.			X			
	Diptera, Chironomidae (Larvae)	X	X	X	X	X	X
	Diptera, Ceratopogonidae					X	
	Diptera, Ephydriidae			X			
Gastropoda	<i>Bithynia</i> sp.						X
	Limnophila, Physidae, <i>Physa</i> sp.	X		X			X
	Mesogastropoda, Valvatidae, <i>Valvata</i> sp.		X				X
	Mesogastropoda, Pleuroceridae, <i>Elimia</i> sp.			X			X
Hirudinea Oligochaeta		X		X			
		X	X	X		X	X
Malacostraca	Amphipoda	X		X	X		X
	Isopoda			X			X
Turbellaria (Flatworms)				X			
Decapoda (Crayfish)				X			
Hydrachnida (Water Mites)						X	X
<i>Bivalvia</i>	Dreissenidae, <i>Dreissena polymorpha</i>	X		X	X	X	X
	Sphaeriidae	X	X	X		X	
Total number of morphospecies/Site		10	7	15	4	10	13

APPENDIX II. Zooplankton taxa observed in vertical plankton tows (i.e., 3 m and 6 m depths) in nearshore waters of six Great Lakes shoreline areas. Study sites included Sheldon Marsh, Ohio (SM), Ludington, MI (LD), Port Washington, WI (PW), Painesville, OH (PV), Saint Joseph, MI (SJ), and Two Rivers, WI (TR).

Taxonomic Grouping	Morphospecies/Genus	Unique			Mid-Bluff		
		SM	LD	PW	PV	SJ	TR
Non-Native	<i>Cercopagis pengoi</i>		X	X		X	X
	<i>Bythotrephes cederstroemi</i>	X	X		X		
Cladocerans	<i>Leptodora</i> sp.	X	X	X	X		
	<i>Polyphemus</i> sp.		X			X	
	<i>Diaphanosoma</i> sp.	X	X		X	X	
	<i>Eubosmina</i> sp.	X				X	
	<i>Bosmina</i> sp.		X	X	X	X	X
	<i>Chydorus</i> sp.	X				X	X
	<i>Daphnia retrocurva</i> <i>Daphnia galeata</i>	X X	X X	X X	X X	X X	X X
Diaptomidae	<i>Limnocalanus</i> sp.	X		X			
	<i>Skistodiaptomus</i> sp.		X			X	X
	<i>Leptodiaptomus</i> sp.			X	X		
Cyclopoidae	<i>Diacyclops</i> sp.	X	X	X	X	X	X
Harpacticoid				X	X		X
Nauplii		X	X	X	X	X	X
Total Taxa/Site		10	10	10	10	10	9

APPENDIX III. Fish species observed in beach seines (S) and gill nets (G) fished in nearshore waters of six Great Lakes shoreline areas. Fish species observed in beach seines (S) and gill nets (G) fished in nearshore waters of six Great Lakes shoreline areas Study sites included Sheldon Marsh, Ohio (SM), Ludington, MI (LD), Port Washington, WI (PW), Painesville, OH (PV), Saint Joseph, MI (SJ), and Two Rivers, WI (TR). Feeding guild designations are also provided, including planktivore (plank), benthivore (benth), and piscivore (pisc).

Family	Common Name	Scientific Name	Feeding Guild	Unique			Midbluff		
				SM	LU	PW	PV	SJ	TR
Atherinidae (Silversides)	Brook Silverside	<i>Labidesthes sicculus</i>	Plank	S	S	S	S		
Catostomidae (Suckers)	Golden Redhorse	<i>Moxostoma erythrurum</i>	Benth						SG
	Longnose Sucker	<i>Catostomus catostomus</i>	Benth			G			
	White Sucker	<i>Catostomus commersoni</i>	Benth		G	G			
Centrarchidae (Sunfishes and Black Basses)	Smallmouth Bass	<i>Micropterus dolomieu</i>	Pisc						SG
Clupeidae (Herrings)	Alewife	<i>Alosa pseudoharengus</i>	Plank		S	S		S	S
	Gizzard Shad	<i>Dorosoma cepedianum</i>	Plank	SG	SG		G	G	
Cottidae (Sculpins)	Mottled Sculpin	<i>Cottus bairdi</i>	Benth						S
Cyprinidae (Carp and Minnows)	Emerald Shiner	<i>Notropis atherinoides</i>	Plank	S	S		S	S	
	Longnose Dace	<i>Rhinichthys cataractae</i>	Benth		S	S		S	S
	Spottail Shiner	<i>Notropis hudsonius</i>	Benth	S	S		S	S	S
	Carp	<i>Cyprinus carpio</i>	Benth	G			G		
Cyprinodontidae (Killifish)	Banded Killifish	<i>Fundulus diaphanus</i>	Plank					S	
Gobiidae (Gobies)	Round Goby	<i>Neogobius melanostomus</i>	Benth	S			S		
Ictaluridae (Catfish and Bullheads)	Channel Catfish	<i>Ictalurus punctatus</i>	Pred	G			G		
Osmeridae (Smelts)	Rainbow Smelt	<i>Osmerus mordax</i>	Plank		S		S		
Moronidae (Temperate Basses)	White Bass	<i>Morone chrysops</i>	Plank	SG			SG		
	White Perch	<i>Morone americana</i>	Plank	SG			S		
Percidae (Perches and Darters)	Walleye	<i>Sander vitreus</i>	Pred	G			G	G	
	Yellow Perch	<i>Perca flavescens</i>	Pred	G	S	G	G	SG	
Percopsidae (Troutperches)	Trout-perch	<i>Percopsis omiscomaycus</i>	Benth		S				S
Salmonidae (Salmon and Trout)	Brown Trout	<i>Salmo trutta</i>	Pred			G			
	Chinook Salmon	<i>Onchorhynchus tshawytscha</i>	Pred		G	G		G	G
	Coho Salmon	<i>Onchorhynchus kisutch</i>	Pred		G				G
	Lake Trout	<i>Salvelinus namaycush</i>	Pred			G			
	Rainbow Trout	<i>Onchorhynchus mykiss</i>	Pred				S		
Sciaenidae (Drums)	Freshwater Drum	<i>Aplodinotus grunniens</i>	Benth	G			G	G	
Total Number of Species				12	12	9	13	14	6