Development of ecological indicators for the U.S. Great Lakes coastal region – A summary of applications in Lake Huron

Gerald J. Niemi,[1,*] Valerie J. Brady,[1] Terry N. Brown,[1] Jan J. H. Ciborowski,[2] Nicholas P. Danz,[1] Dana M. Ghioca,[3] JoAnn M. Hanowski,[1] Tom P. Hollenhorst,[1] Robert W. Howe,[4] Lucinda B. Johnson,[1] Carol A. Johnston,[5] Euan D. Reavie[6]

[1]*Center for Water and the Environment, Natural Resources Research Institute, University of Minnesota Duluth, 5013 Miller Trunk Highway, Duluth, Minnesota 55811-1442, USA*

[2]*Department of Biological Sciences, University of Windsor, Windsor, Ontario N9B 3P4, Canada*

[3]*Department of Biology, 205 Compton Science Center, Frostburg State University, 101 Braddock Road, Frostburg, Maryland 21532-2303, USA*

[4]*Department of Natural and Applied Sciences, Cofrin Center for Biodiversity, University of Wisconsin-Green Bay, Green Bay, Wisconsin 54311-7001, USA*

[5]*Center for Biocomplexity Studies, South Dakota State University, Box 2207B, Brookings, South Dakota 57007-0869, USA*

[6]*Ely Field Station, Center for Water and the Environment, Natural Resources Research Institute, University of Minnesota Duluth, 1900 East Camp Street, Ely, Minnesota 55731, USA*

**Corresponding author: gniemi@d.umn.edu*

*Our overall goal was to develop indicators that both estimate ecological condition and suggest plausible causes of ecosystem degradation across the U.S. Great Lakes coastal region. Here we summarize data gathered along the U.S. Lake Huron coastline for breeding bird, diatom, fish, invertebrate, and wetland plant communities. We sampled these biotic communities on 88 sites in Lake Huron coastal wetlands, uplands, estuaries/bays, and high-energy shorelines. The sites were selected as part of a larger, stratified random design for the entire U.S. Great Lakes coastal region using gradients of anthropogenic stress that incorporated over 200 stressor variables (e.g. agriculture, land cover, human populations, and point source pollution). The U.S. Lake Huron coastal region exemplified wide variation in human-related stress relative to the entire U.S. Great Lakes coast. In general, levels of stress decreased from south to north partly reflecting the change in climate and physiography, but also due to the greater human influences in the southern region as compared with the north. The primary stressors in the southern region are due to agriculture and human development, while the northern region has substantially less agriculture and less human population. The biotic communities sampled were strongly related to the environmental stress gradients, especially agriculture and urbanization. The following indicators were developed based on responses to stress: 1) an index of biological condition for breeding bird communities corresponding to land use, 2) a diatom-inferred total phosphorus indicator corresponding to water quality, 3) exotic fish (carp [*Cyprinus carpio*] and goldfish [*Carassius auratus*]) corresponding to agriculture, and 4) a multi-taxa index for wetland plants corresponding to a cumulative stress index. These communities can all serve as*

Aquatic Ecosystem Health & Management, 12(1):77–89, 2009. ISSN: 1463-4988 print / 1539-4077 online
DOI: 10.1080/14634980802711943

useful indicators of the ecological condition of the Lake Huron coast. The ecological indicators provide a baseline on selected conditions for the U.S. Lake Huron coastal region and a means to detect change over time.

Keywords: Birds, diatoms, fish, macroinvertebrates, plants, wetlands

Introduction

Recently there has been substantial interest in the development of environmental indicators to assess condition and to potentially diagnose causes for current or future changes in conditions (Niemi and McDonald, 2004). In 2001 we initiated an extensive study of selected biotic communities in the U.S. Great Lakes coastal region to develop indicators of ecological conditions and potentially to diagnose causes for these conditions (Niemi et al. 2006). Our study, the Great Lakes Environmental Indicators (GLEI) project, was part of a large scale effort by the U.S. Environmental Protection Agency (U.S. EPA) to develop indicators for the entire U.S. coastal region (marine and Great Lakes) (Niemi et al. 2004; Brady, 2007). Results from GLEI were intended to supplement and complement on-going efforts in indicator development within the Great Lakes region (e.g. Bertram and Stadler-Salt, 1998; Lawson, 2004; Environment Canada and U.S. EPA, 2005; Seilheimer and Chow-Fraser, 2006).

Here our primary goal is to report on selected results from the GLEI project for data gathered on the U.S. portion of the Lake Huron coastal region. In a previous analysis, we found that lake identification was an important classification factor to consider in indicator development (Brazner et al., 2007a). Included in the data gathered here are biotic communities for birds, diatoms, fish and macroinvertebrates, and wetland vegetation. A substantial amount of information for the entire U.S. basin has already been published and is summarized in Niemi et al. (2006, 2007, also http://glei.nrri.umn.edu). However, this paper represents the only paper specifically dedicated to an analysis of Lake Huron from the GLEI efforts.

Methods

Study sites were selected across gradients of anthropogenic stress using a stratified random design as part of the larger sampling design for the entire U.S. Great Lakes coastal region (Danz et al., 2005); over 88 sites in coastal wetlands, uplands, estuaries/bays, and high-energy shoreline were selected in the Lake Huron basin (Figure 1). For site selection, land-based stress was quantified in a geographic information system (GIS) for 762 coastal segment-sheds that encompassed the entire U.S. basin; each segment-shed consisted of the land area that drained into a segment of coastline extending in either direction from 2nd-order or larger streams to one-half the distance to the adjacent stream. Since the original selection of the sites by Danz et al. (2005), and also described in detail by Johnston et al. (2007), more detailed watersheds were delineated specific to each sampled site (Hollenhorst et al. 2007). Sampled sites were represented within the GIS by polygons encompassing the sampling points for all GLEI indicator groups at a selected locale. Watersheds were delineated specifically for wetlands and embayments from 30 m digital elevation models (DEMs) using ArcInfo's WATERSHED command (ESRI, 2000). Watersheds for high-energy sites were delineated using ArcHydro (Maidment, 2002) and agglomerated until an area size-threshold was reached (Hollenhorst et al., 2007).

For each type of watershed summary, over 200 environmental variables in seven categories of environmental variation (Danz et al., 2005) were summarized. Principal components analysis (PCA) within each category of environmental variation was used to reduce dimensionality and derive overall gradients (Danz et al., 2007). Similar gradients were created for atmospheric deposition, human population and development, land cover, point source pollution, and soils. Variations of these gradients used in analyses for particular biotic assemblages are described in their respective sections below.

Birds

Birds were sampled at 321 points (69 in Lake Huron) in 215 watershed polygons (45 in Lake Huron) using a standard protocol described by Ribic et al. (1999). A reference gradient of anthropogenic stress (Howe et al., 2007) was derived by PCA analysis of 39 variables describing land use (e.g. proportion of cultivated land within 100 m, 500 m, 1 km, and 5 km of wetland center), wetland attributes (e.g. proportion wetland area within 100 m, 500 m, 1 km, and 5 km), and eight principal component scores from the Danz et al. (2005) analysis (e.g.

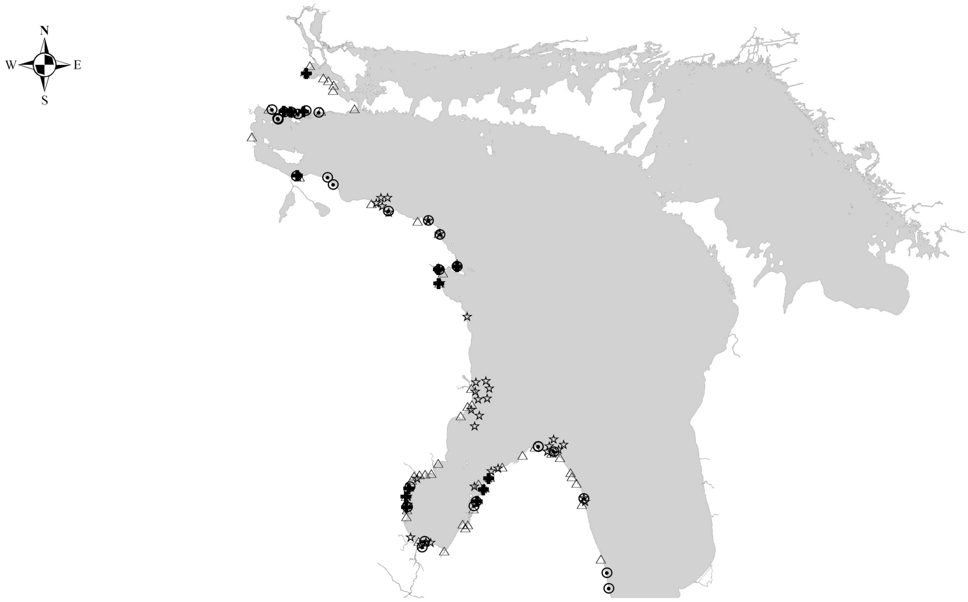

Figure 1. Location of study sites for breeding birds, diatoms, fish and invertebrates, and wetland vegetation in Lake Huron (triangles = birds, stars = diatoms, circles = fish and invertebrates, and plus sign = wetland vegetation).

agricultural stress gradient PC1, atmospheric deposition stress gradient PC1). Scores from the first five principal components of this analysis, accounting for 68% of the overall variation, were scaled from lowest to highest level of anthropogenic impact and combined into a single value by weighting each principal component score by the percent variation associated with each principal component. Results were scaled to form a reference gradient ranging from 0 (poorest condition or highest anthropogenic stress) to 10 (best condition or lowest anthropogenic stress). Bird sample points were assigned to categories based on the wetland reference condition (0 to 10). Among categories of reference condition, the proportions of points at which a given bird species was observed (Figure 2) defined a four parameter logistic function reflecting the response of the species to anthropogenic stress. Once the logistic functions were established, a bird community indicator, or IBC, was calculated for specific wetlands using the probability method of Howe et al. (2007). We limited our analysis to 23 species of birds (Table 1) that showed the strongest responses, either positive or negative, to the anthropogenic stress gradient. Sites with highly sensitive species such as swamp sparrow (*Melospiza georgiana*) and sandhill crane (*Grus canadensis*) yielded high values of biotic condition, whereas sites with tolerant species like common grackle yielded low values of condition.

Diatoms

Coastal sample locations were selected as described in detail by Danz et al. (2005) (Figure 1) and diatom assemblages were collected from surface sediments and other substrates; sampling and processing protocols are described in detail by Reavie et al. (2006). A set of water quality measurements was concurrently collected at each sample location to be related to diatom assemblages (see Reavie et al., 2006).

Using weighted averaging regression and calibration, we developed and tested several diatom-based transfer functions derived from the diatom assemblages and corresponding water quality data (Reavie et al. 2006). In brief, the Great Lakes coastal diatoms were calibrated for selected water quality variables. Using phosphorus as an example, species coefficients (optima and tolerances) for phosphorus were calculated by relating diatom assemblages to corresponding phosphorus measurements. These coefficients comprised the phosphorus transfer function (indicator model), which were then used to provide diatom-inferred estimates of phosphorus from a given assemblage. This was performed

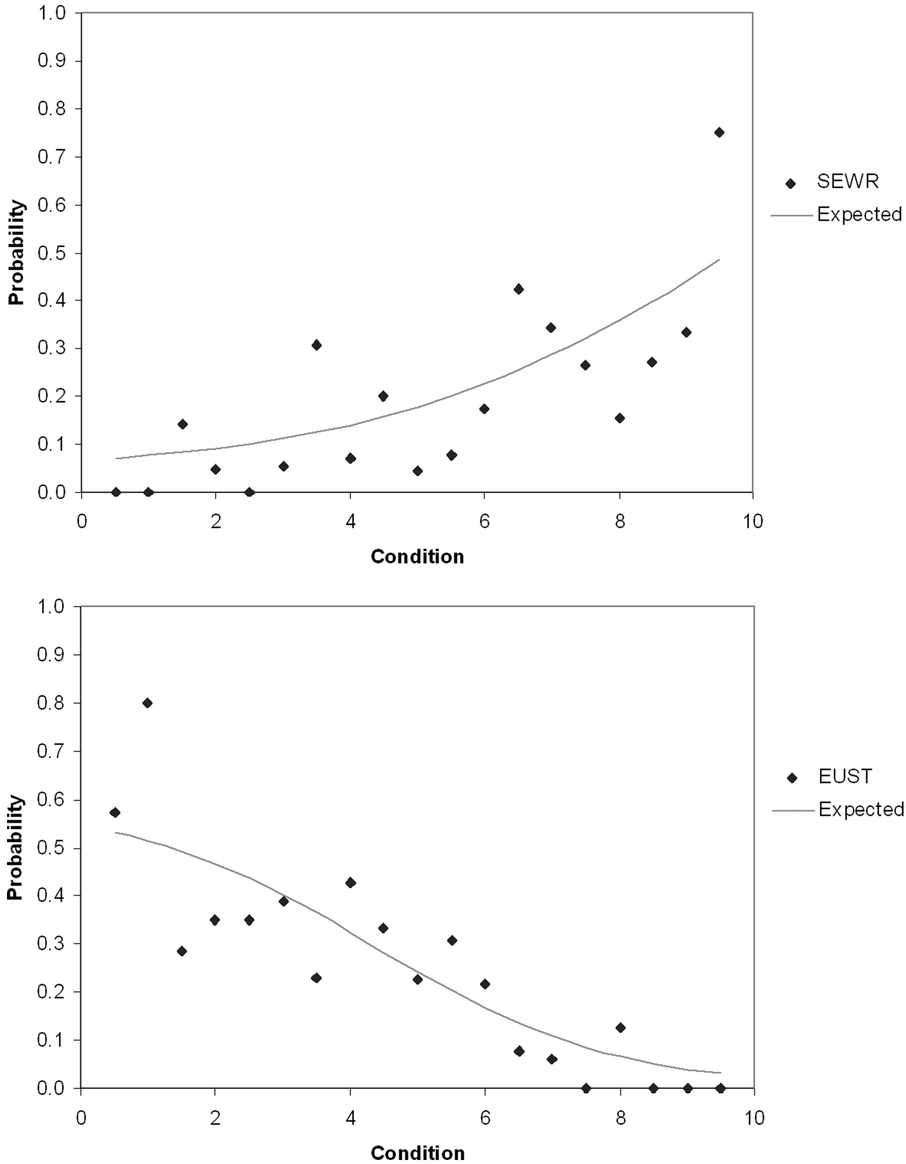

Figure 2. Species-specific responses to environmental condition for sedge wren (SEWR), a sensitive species, and European starling (EUST), a tolerant species. Probability (y-axis) is the probability of observing the species in a coastal wetland during a 10-minute breeding season point count. Condition is based on a multivariate analysis of land cover and other environmental variables, where 0 = highly impacted by human activities (maximally stressed) and 10 = least impacted by human activities (minimally stressed). Solid line represents the best-fit logistic function described by Howe et al. (2007).

by taking the variable optimum of each taxon in the assemblage, weighting it by its percent abundance in that sample, and calculating the average of the combined weighted optima (Battarbee et al. 2001).

Reavie et al. (2006) developed diatom transfer functions to infer nutrient concentrations, water clarity, and loading from road salt pollution. Total phosphorus (TP) was found to be strongly related to patterns in the diatom communities, and was selected for transfer function development because of its ecological and management importance. Diatom-inferred total phosphorus (DITP) was regressed against anthropogenic (e.g. agricultural and urban development) and natural (e.g. soil characteristics) watershed properties (i.e. respective PC1

Table 1. Bird species used to calculate indices of biotic condition for Great Lakes coastal wetlands. List includes 23 species exhibiting the strongest associations with a reference gradient based on intensity of human activities. P(10) – P(0) describes the difference in probability of finding the species at minimally stressed sites vs. the probability of finding the species at highly stressed sites. Species with positive values of P(10) – P(0) are sensitive to stress (i.e. they are more likely to be found at minimally stressed sites), whereas species with negative values are tolerant of anthropogenic stress (i.e. they are more likely to be found at highly stressed sites). Scientific names are from AOU (1998) and recent supplements.

Common name	Scientific name	P(10)-P(0)
Swamp sparrow	*Melospiza georgiana*	0.62
Common grackle	*Quiscalus quiscula*	−0.61
Common yellowthroat	*Geothlypis trichas*	0.55
Sandhill crane	*Grus canadensis*	0.55
American robin	*Turdus migratorius*	−0.54
European starling	*Sturnus vulgaris*	−0.52
Northern cardinal	*Cardinalis cardinalis*	−0.48
Sedge wren	*Cistothorus platensis*	0.46
Mallard	*Anas platyrhynchos*	−0.42
American goldfinch	*Carduelis tristis*	−0.40
Mourning dove	*Zenaida macroura*	−0.38
Alder flycatcher	*Empidonax alnorum*	0.35
Marsh wren	*Cistothorus palustris*	−0.35
Gray catbird	*Dumetella carolinensis*	−0.28
Bobolink	*Dolichonyx oryzivorous*	0.26
Baltimore oriole	*Icterus galbula*	−0.25
American redstart	*Setophaga ruticilla*	0.25
Bald eagle	*Haliaeetus leucocephalus*	0.24
Northern harrier	*Circus cyaneus*	0.22
Brown-headed cowbird	*Molothrus ater*	−0.21
Brown thrasher	*Toxostoma rufum*	0.20
White-throated sparrow	*Zonotrichia albicollis*	0.20
Killdeer	*Charadrius vociferus*	−0.20

scores) using multiple linear regression to identify the ability of diatom assemblages to reflect watershed stressors.

Fish and invertebrates

Fish and macroinvertebrates were collected from 17 Lake Huron coastal wetlands in 2002 and 2003. Fish were collected using fyke nets set overnight (see details in Brady et al., 2007). Benthic macroinvertebrates were collected using D-frame dip nets. Habitat data collected throughout each wetland included aspects of physical structure, vegetation, and human disturbance. Measured water quality variables included water clarity, pH, conductivity, temperature, and dissolved oxygen. Water quality parameters were measured at each sample location with a multi-probe YSI 556. Probe calibration for dissolved oxygen and pH occurred daily based on standard procedures (see below) and verified by technicians on individual field sheets. Remaining parameters were calibrated approximately every nine days. Lake Huron fish and macroinvertebrate species and metrics were regressed against five stress PCs (agriculture, atmospheric deposition, point sources, urbanization, and land cover) as well as a cumulative stress gradient (sum of the five PCs, see Danz et al., 2007).

Wetland plants

A total of 14 Lake Huron wetlands were sampled for wetland vegetation. Sampling was done in 1 m × 1 m plots distributed along randomly placed transects (Bourdaghs et al., 2006; Johnston et al., 2007). Within each plot all vascular plant species were identified to the lowest taxonomic division possible, and percent cover was estimated visually for each taxon according to modified Braun-Blanquet cover class ranges: <1%, 1 to <5%, 5 to <25%, 25 to <50%, 50 to <75%, 75 to 100%. Vegetation cover data were used to compute an FQI for each of the 14 sites (Bourdaghs et al., 2006). Cover data for individual plant species were analyzed using hierarchical partitioning to identify taxa sensitive to anthropogenic stress, using methods described in Brazner et al. (2007a). These candidate taxa for Lake Huron wetlands were used in a stepwise multiple regression against the stress index developed for site selection by Danz et al. (2007) to create a multi-taxa vegetation indicator (Johnston et al., 2008).

Results

Altogether 88 Lake Huron coastal sites were sampled by GLEI investigators studying birds, diatoms, fish and macroinvertebrates, and wetland plants (Figure 1). These include 67 wetlands, 3 embayments, and 18 high energy/open water sites. The U.S. Great Lakes coastal region of Lake Huron shows relatively poor condition in the southern regions compared with relatively low overall stress in the northern regions (Figure 3). This is primarily due to heavy agricultural land use, higher human population densities (e.g. near Detroit and Saginaw), and point sources in the south, while the north is primarily forested with relatively sparse human population densities. In Lake Huron, gradients of stress are long compared to gradients in the other lakes and across the basin as a whole (from Danz et al. 2007). For example, segment-sheds in Lake Huron covered 91% of the gradient in land cover from heavily forested areas to non-forested agricultural areas, while the gradient in point sources was relatively narrow in Lake Huron due to a lack of segment-sheds with high densities of point source dischargers (Table 2).

Birds

Bird species indicating high quality biotic condition (Table 1) are characteristic of a variety of natural wetland habitats, including shallow marshes (sandhill crane), wooded wetlands (alder flycatcher), and mixed upland-wetland mosaics (bobolink). The index of biotic condition (IBC) based on birds, therefore, can be applied to sites with different vegetation attributes. Species adapted to agricultural or urbanized landscapes (common grackle, American robin, European starling) indicate generally lower quality conditions.

In coastal wetlands of Lake Huron, the IBC based on birds (Figure 4) ranged from 0.0 to 9.8, nearly the entire range of possible values (0–10). Reference condition covered a similarly broad but somewhat narrower range (1.5-8.7). Bird-based IBCs in Lake Huron wetlands were similar to values across the Great Lakes (Table 3) and similar to IBC values for Lake Michigan coastal wetlands. Lake Superior wetlands yielded the highest IBC values, whereas lowest values were found in Lake Erie and Lake Ontario, respectively. Overall, bird communities of Lake Huron coastal wetlands appear to be representative of the Great Lakes as a whole, covering nearly the full range of conditions.

Highest indices of biotic condition (based on birds) were recorded in the northernmost part of Lake Huron between St. Ignace and Drummond Island, near Presque Isle (north of Alpena), and in Wigwam Bay on the western coast of Saginaw Bay. Lowest IBCs were recorded mainly in southern Lake Huron (e.g. near Port Hope north of Harbor Beach), at several localities in Saginaw Bay, and near Cheboygan in northern Lake Huron. Interestingly, IBCs based on birds tended to be higher than reference condition along the western coast of Saginaw Bay but lower than reference condition along the eastern coast of Saginaw Bay, although there were several exceptions (e.g. near Fish Point). On average, IBCs in Lake Huron were similar to reference condition (Table 3), unlike Lakes Ontario and Erie where bird-based IBCs tended to be lower than reference condition and Lake Superior, where IBCs tended to be higher than reference condition (Table 3).

Diatoms

Reavie et al. (2006) confirmed that the diatom-based transfer function was able to provide robust reconstructions of phosphorus concentrations along Great Lakes coastlines. Also, DITP was strongly correlated with the watershed properties that determine nutrient conditions in these coastal areas (Figure 5). Most remarkably, DITP provided a set of phosphorus inferences that were more highly correlated to watershed characteristics than were the corresponding snapshot TP measurements, owing to the ability of algae indicators to integrate environmental information. Lake Huron was particularly

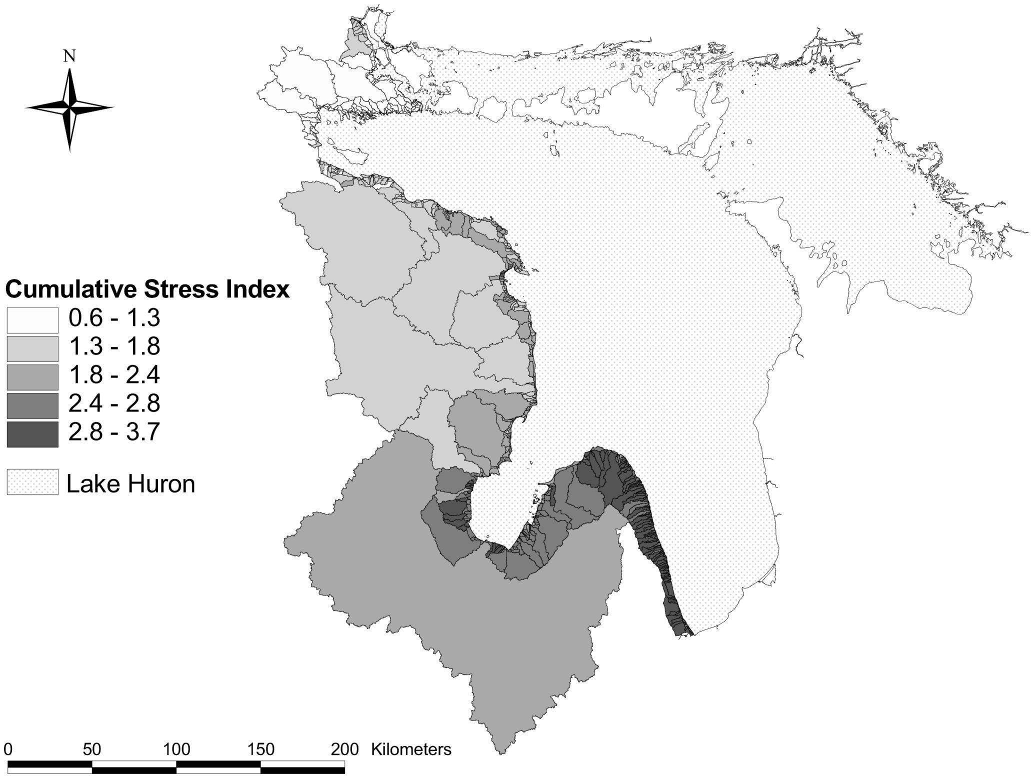

Figure 3. A cumulative stress index consisting of 5 component stress gradients (agriculture, human population, land cover, atmospheric deposition, and point source pollution, see Danz et al., 2007) for Lake Huron watersheds. The index was created by scaling each gradient from 0-1 (low to high stress) and summing.

well suited to these diatom-based approaches developed using the whole Great Lakes basin because Lake Huron spans much of the anthropogenic stressor gradient, including agricultural development, and to a lesser degree, urban development (Figure 5). When shown in the context of DITP, soil characteristics have a relatively narrow gradient in Lake Huron's watershed, and thus Huron provides a case where anthropogenic influences are less confounded by this natural gradient (Kireta et al., 2007). Contrast this with Lake Erie, where inter-correlations are much stronger among natural (e.g. arable land) and anthropogenic (e.g. agriculture) factors, so teasing apart natural and anthropogenic controls on

Table 2. Relative length of environmental gradients on a scale of 0-1. Values indicate the within-lake difference between the segment-shed, with the minimum and maximum values as a proportion of the total basin-wide range in the gradient (gradients are first principal components from PCAs using 762 segment-sheds, see METHODS).

	Category						
Lake	Agriculture	Atm. dep.	Land cover	Human pop.	Point source	Soils	CSI*
Erie	0.42	0.16	0.36	0.45	0.88	0.60	0.39
Huron	0.76	0.41	0.91	0.58	0.69	0.62	0.75
Michigan	0.84	0.50	0.80	0.87	1	1	0.92
Ontario	0.23	0.50	0.64	0.43	0.70	0.65	0.33
Superior	0.33	0.28	0.77	0.70	0.80	0.90	0.64

*Cumulative stress index comprised of the five individual stress gradients (i.e. excludes soils)

Table 3. Mean values of environmental condition for coastal wetland sites in the U.S. portion of Great Lakes. Reference condition is based on a multivariate analysis of land use and human-related environmental stressors. The index of biotic condition is based on occurrences of 23 bird species with documented responses to anthropogenic stress (Table 1). Condition scores range from 0 (poorest condition) to 10 (best condition). Standard deviations are indicated in parentheses.

Lake	Mean reference condition	Mean index of biotic condition (birds)	Sample points
Erie	3.48 (2.13)	1.83 (1.80)	40
Huron	4.99 (2.01)	4.88 (2.60)	69
Michigan	5.38 (2.07)	4.98 (2.65)	110
Ontario	3.49 (1.73)	2.51 (2.49)	80
Superior	6.87 (1.76)	8.09 (0.93)	72
All lakes	5.03 (2.25)	4.75 (3.01)	371

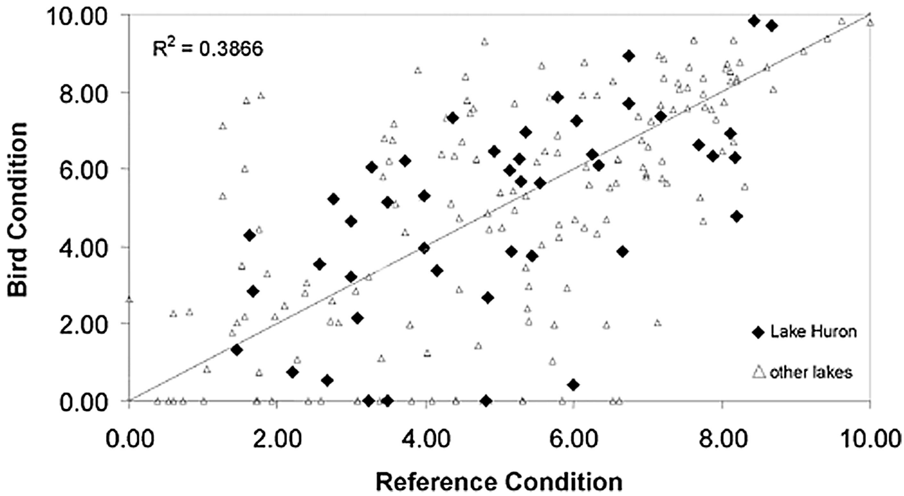

Figure 4. Relationship between index of biotic condition (IBC) in coastal wetlands, based on presence absence of 23 indicator bird species (Bird Condition), and Reference Condition, based on land use and other variables associated with anthropogenic stress. Values for Lake Huron (solid diamonds) are shown with values (open triangles) for wetlands of Lakes Superior, Michigan, Erie, and Ontario.

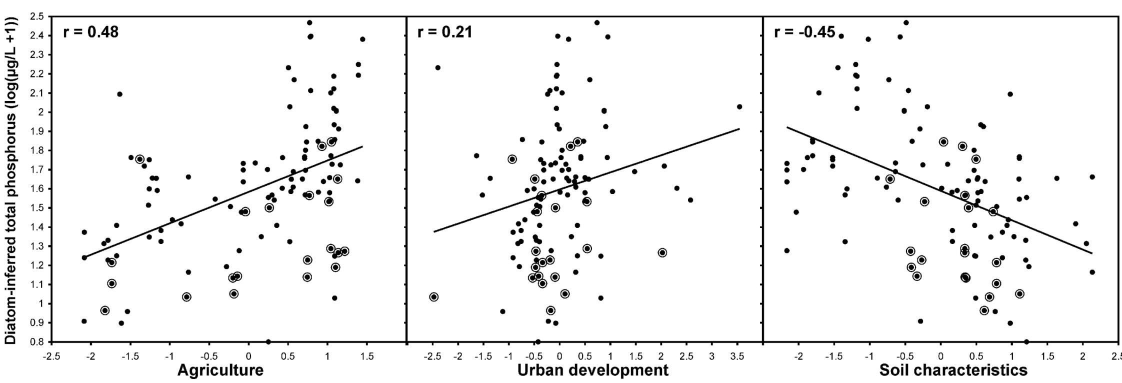

Figure 5. Examples of watershed characteristics (scores derived from principal components analysis) for Great Lakes coastal locations regressed against diatom-inferred total phosphorus concentrations. Encircled samples are from Lake Huron.

indicator assemblages can be more difficult. Because the diatoms clearly respond to anthropogenic stressor influences from the watershed, monitoring and management programs on Lake Huron will benefit from diatom assessments in the future.

Fish and invertebrates

Across the Great Lakes basin, bluegill (*Lepomis macrochirus*) and carp (*Cyprinus carpio*)+goldfish (*Carassius auratus*) were found to be consistent indicators of disturbance, while rock bass (*Ambloplites rupestris*) were found to be associated with less disturbance (Brazner et al. 2007a, 2007b). Two community metrics, the proportion of turbidity-intolerant fish species and the proportion of nest-guarding species, also were found to be associated with relatively low amounts of disturbance (Brazner et al., 2007a).

In Lake Huron, these patterns were generally consistent with those found for the Great Lakes basin as a whole. Carp+goldfish and turbidity-intolerant species responded to agricultural land use in Lake Huron in a manner consistent with the rest of the Great Lakes (Figure 6) because the full range of agricultural stress is represented within the Lake Huron basin, while the urban gradient is restricted to a much smaller range (Table 2). As a result, indicators that respond to basin-wide agricultural stress are also apparently effective for use in the Lake Huron basin, whereas the only fish indicator of urban stress in the Lake Huron basin was carp+goldfish. Lake Huron sites differed from those of the entire basin in the lack of response of fish indicators to a point-source stressor gradient.

In contrast to fish, for which individual metrics or species were found to respond to stress over large geographic ranges, invertebrate indicators were restricted to a particular ecoregion and geomorphic type (L. Johnson et al. Natural Resources Research Institute, University of Minnesota Duluth, USA, unpublished data). For Lake Huron, no single invertebrate indicator was found to respond to the cumulative stress index. In contrast, clingers, burrowers, predators, and filter-gatherer taxa all responded to agricultural land use. Burrowers and mayflies in the genus Ephemeroptera: *Caenis* were positively influenced by urban land use (Figure 7); predators, filter-gatherers, and clingers were negatively impacted by both urban and agricultural land use. The negative impacts of these stressors are primarily due to the effects of high turbidity and excessive sediments, which inhibit macrophyte growth and reduce habitat or food quality for clinging and filtering species, and increase habitat for burrowing species.

In summary, many of the fish species-specific indicators of stress that were observed for the Great Lakes as a whole also were applicable to Lake Huron due to the broad range of cumulative stress. In contrast, the number of invertebrate indicators of stress and their specificity to individual stressor types increased when the geographic range was restricted to the Lake Huron basin from the Great Lakes as a whole.

Wetland vegetation

The development of indicators for Lake Huron was complicated by distinct differences in the vegetation of Saginaw Bay coastal wetlands in comparison with wetlands elsewhere on Lake Huron. In addition to being floristically different, these two groups are in different ecoprovinces and have different types and levels of anthropogenic stress: Saginaw Bay wetlands are subject to more stress, particularly from agricultural sources.

The FQI, an existing index that performed well within the Laurentian ecoprovince (Bourdaghs et al. 2006), was not a good indicator of anthropogenic stress for coastal wetlands within Lake Huron. When FQI values were plotted against the GLEI segment-shed stress index (Danz et al., 2007), they were highly clumped into the two geographic groups (Figure 8a).

The multi-taxa index developed for wetland vegetation in Lake Huron (Johnston et al., 2008) was strongly related ($R^2 = 0.73$) to the segment-shed stress index (Figure 8b). This multi-taxa index used mean percent cover of two plant species which are individually significantly related to the overall stress index: *Schoenoplectus tabernaemontani* (formerly *Scirpus validus*) and *Populus deltoides* seedlings. The multi-taxa index developed from these two species did a much better job of indicating environmental condition than did FQI, and requires far less information.

Discussion

As far as we are aware, this is the first time that comparative data on the relative amount of environmental variation for the U.S. Great Lakes coastal region has been quantified. The U.S. Lake Huron coastal region has a wide variation in the degree of

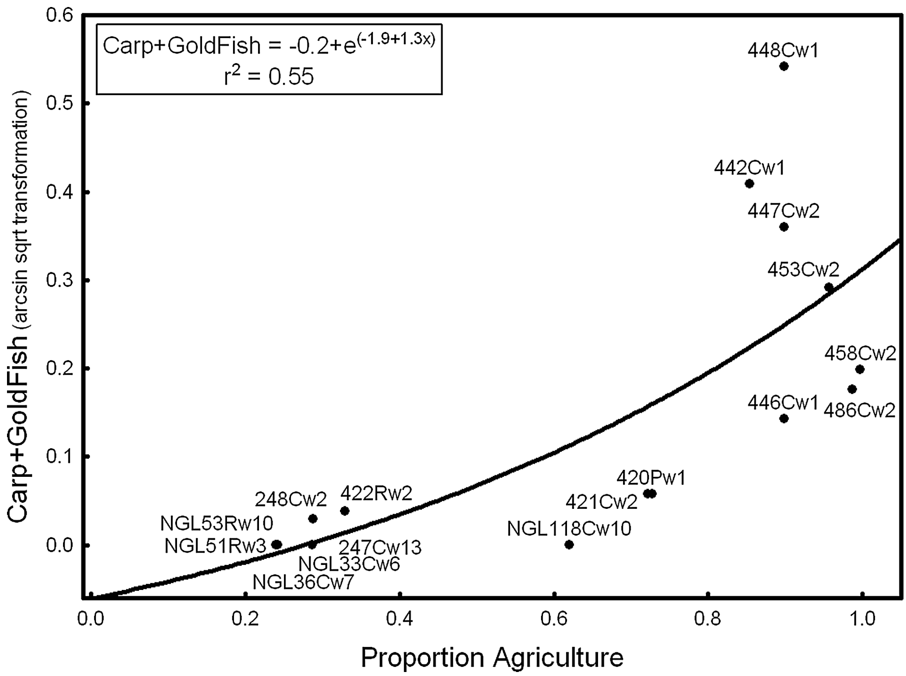

Figure 6. Proportion of carp+goldfish as a function of the proportion of agricultural land use in the U.S. Lake Huron basin.

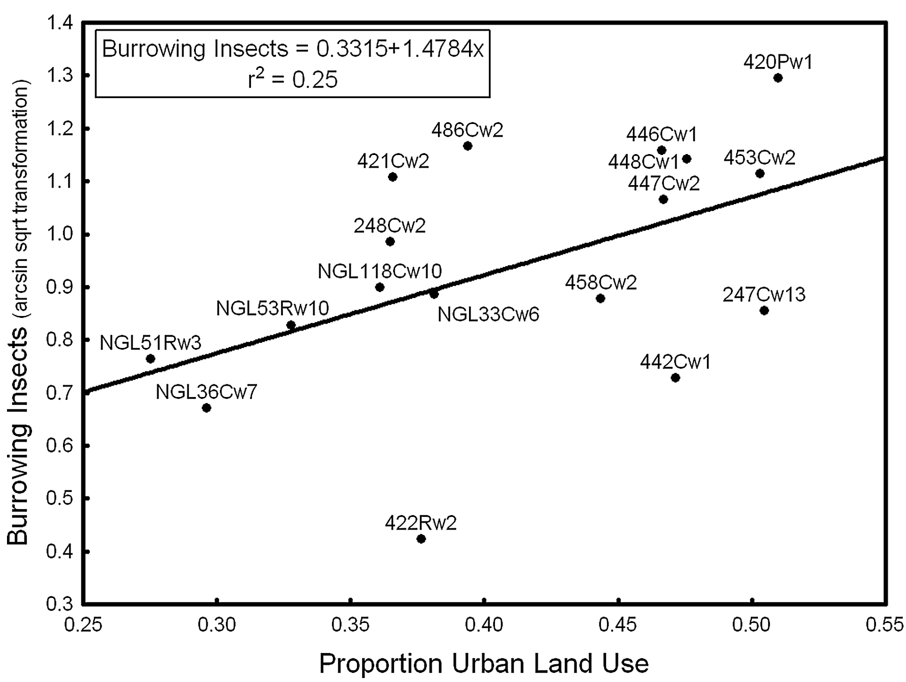

Figure 7. Proportion of burrowing insects as a function of the proportion of urban land use in the U.S. Lake Huron basin.

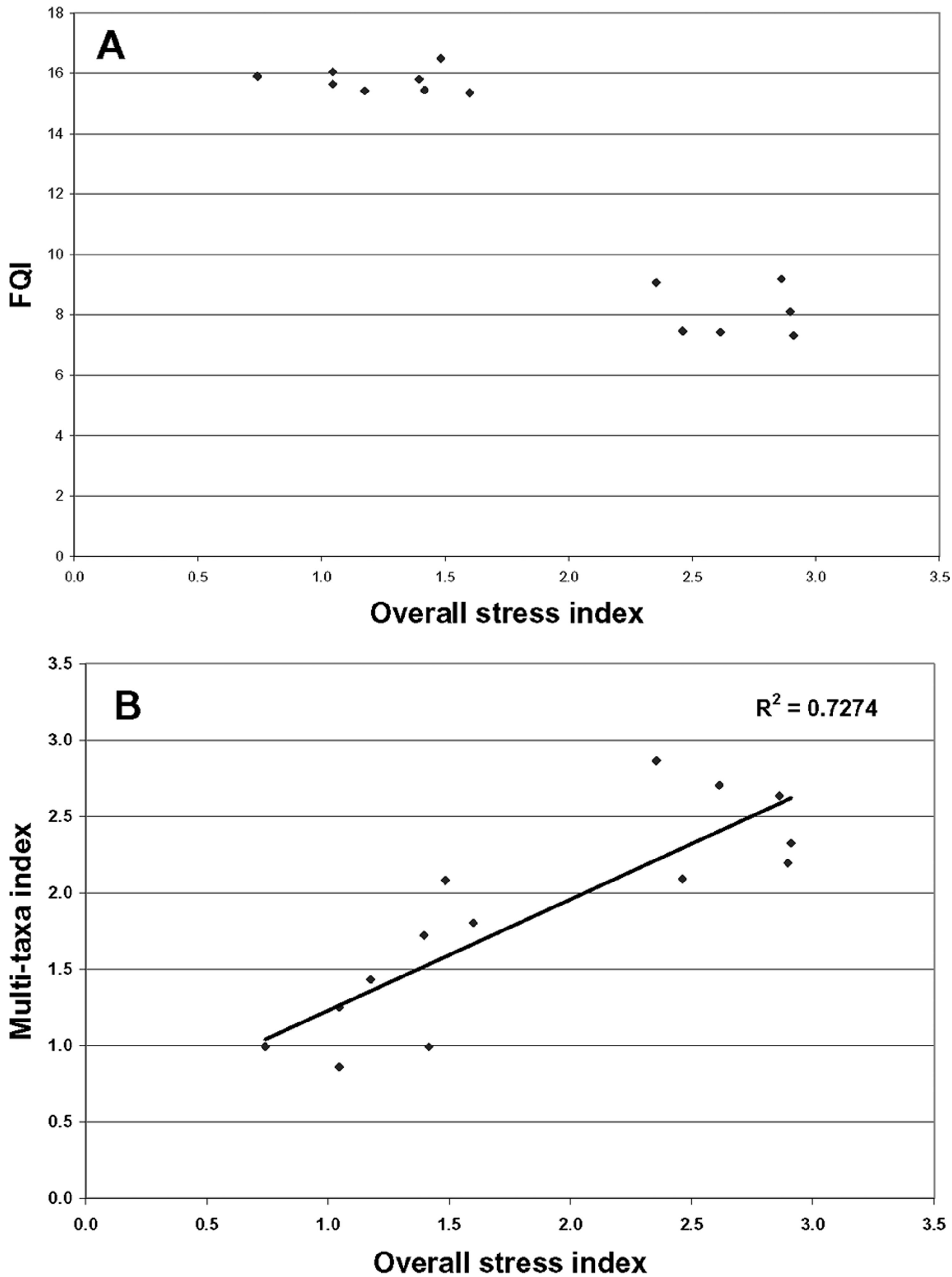

Figure 8. Comparison of two vegetation indices with the GLEI overall stress index. A. Floristic quality index (FQI). B. GLEI Lake Huron wetland vegetation multi-taxa index.

human-related stress; generally, levels of stress decrease from south to north. The primary stressors in the southern region are due to agricultural impacts (e.g. nutrients and pesticides) and human development, while the northern region has substantially less agriculture and more sparsely populated human settlements. Much of the northern region is still dominated by forests. The biological communities sampled and their ecological conditions are reflected by many indicators. For instance, the breeding bird communities in the southern regions are dominated by those species that are highly associated with agricultural and urban landscapes such as the American robin (*Turdus migratorius*), European starling (*Sturnus vulgaris*, a European exotic), mourning dove (*Sturnus vulgaris*), and brown-headed cowbird (*Molothrus ater*) (Howe et al., 2007). In contrast, the northern region has species more typical of forested situations (e.g. American redstart [*Setophaga ruticilla*] and white-throated sparrow [*Zonotrichia albicollis*]). These changes from south to north were also strongly reflected in the fish community. Exotic species such as carp and goldfish were more common in the southern regions with higher proportions of agricultural land. Diatom communities and wetland vegetation also reflected the gradient from south to north. In particular, wetland vegetation near Saginaw Bay was strongly influenced by agricultural development.

The strong contrast between the southern and northern regions of the U.S. Lake Huron coastal region is partly a reflection of the climate and physiographic differences that exist in the Great Lakes region. The region is divided into the southern Eastern Broadleaf Forest ecoprovince and the northern Laurentian Mixed Forest ecoprovince (Keys et al., 1995). Hence, there were natural, pre-human-influence differences between the two regions. The U.S. Lake Huron coastal region covers a substantial amount of the variation that exists across the Great Lakes coastal region. This is illustrated by the environmental gradients we have observed for the U.S. coastal region of all the Great Lakes (Table 2), the breeding bird communities of Lake Huron in comparison with all of the Great Lakes (Figure 4), and the diatom communities (Figure 5). The variation in each of these examples was reflected in relatively wide variation in the environmental gradients and the biotic communities sampled in the U.S. Lake Huron coastal region. For instance, the relative length of the environmental gradients for Lake Huron were highest for land cover variation and very similar to the large variation found in Lake Michigan for agriculture and the overall stress index (Table 2).

The analyses presented here for selected biotic communities illustrate that each of the sampled taxa can provide important information on the ecological condition of the U.S. Lake Huron coastal region. Hence, each could serve as an "ecological indicator" of the condition of the coastal region, and each can generally reflect the potential causes for these conditions. Clearly, more information is necessary to further test these indicators and more refinement would be necessary to link specific causes with the biotic responses observed. For instance, "agriculture" includes a wide array of potential, but specific stressors to biotic communities. These include influences from specific fertilizer applications such as nitrogen and phosphorus, specific pesticide applications, the habitat changes due to sediment input, or the conversion of habitat such as wetlands to agricultural land. Similarly, "human development" has an array of specific causes that can influence biological communities, such as land conversion or alteration, runoff of pollutants from impervious surfaces, or herbicide/pesticide applications to lawns.

Conclusions

The information shown here exemplifies the broad effects that many human activities have had and will likely have on the ecological condition of the Lake Huron coastal region in the future. The ecological indicators provided, along with the wide breadth of sampling, establish a baseline of conditions for the U.S. Lake Huron coastal region. A routine sampling framework for these indicators over time can provide a means to detect improvement or further deterioration as well as direct management resources to bring about future improvements.

Acknowledgements

Diatom identification and enumeration results were supported by N. Andresen, G. Sgro, M. Ferguson, and A. Kireta; and diatom taxonomic support was provided by J. Kingston, E. Stoermer, and J. Johansen. D. Breneman, J. Schuldt, J. D. Holland, J.P. Gathman, R. Hell, A. Ly, J. Baillargeon, and J. Wiklund provided assistance with fish and macroinvertebrate data and sampling. R. Regal provided statistical advice. Although this research has been funded wholly or in part by the U.S. EPA through cooperative agreement EPA/R-82867501 to the Great Lakes Environmental Indicators project, and through grant EPA/R-82877701 to L. Johnson, it has not been subjected to the agency's required peer and policy review and therefore does not necessarily reflect the views of the agency and no official endorsement should be inferred. This is contribution number 490 from the Center for Water and the Environment, Natural Resources Research Institute, University of Minnesota Duluth.

References

AOU, 1998. *Check-list of North American Birds, 7th Ed*. American Ornithologists' Union, Washington, D.C.

Battarbee, R. W., Jones, V. J., Flower, R. J., Cameron, N. G., Bennion, H., Carvalho, L., Juggins, S., 2001. Diatoms. In: J. P. Smol, H. J. B. Birks, W. M. Last (Eds.), *Tracking Environmental Change Using Lake Sediments Volume. 3: Terrestrial, Algal, and Siliceous Indicators,* pp. 155–202. Kluwer, Dordrecht.

Bertram, P., Stadler-Salt, N., 1998. Selection of indicators for the Great Lakes basin ecosystem health, Version 3. 1998 State of the Lakes Ecosystem Conference, U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.

Bourdaghs, M., Johnston, C. A., Regal, R. R., 2006. Properties and performance of the floristic quality index in Great Lakes coastal wetlands. Wetlands 26, 718–735.

Brady, V. J., 2007. Regional coastal indicators. A synthesis report from the EPA STAR Estuarine and Great Lakes Coastal Indicators (EaGLe) program to the EPA National Center for Environmental Research.

Brady, V. J., Ciborowski, J. J. H., Johnson, L. B., Danz, N. P., Holland, J. D., Breneman, D. H., Gathman, J. P., 2007. Optimizing fishing time: One vs. two-night fyke net sets in Great Lakes coastal systems. J. Great Lakes Res. 33, 236–245.

Brazner, J. C., Danz, N. P., Niemi, G. J., Regal, R. R., Trebitz, A. S., Howe, R. W., Hanowski, J. M., Johnson, L. B., Ciborowski, J. J. H., Johnston, C. A., Reavie, E. D., Brady, V. J., Sgro, G. V., 2007a. Evaluation of geographic, geomorphic, and human influences on Great Lakes wetland indicators: a multi-assemblage approach. Ecol Indic. 7, 610–635.

Brazner, J. C., Danz, N. P., Niemi, G. J., Regal, R. R., Hollenhorst, T., Host, G., Brown, T., Trebitz, A. S., Howe, R. W., Hanowski, J. M., Johnson, L. B., Ciborowski, J. J. H, Johnston, C., Reavie, E., Sgro, G., 2007b. Responsiveness of Great Lakes wetland indicators to human disturbances at multiple spatial scales: a multi-assemblage assessment. J. Great Lakes Res. 33, 42–66.

Danz, N. P., Regal, R. R., Niemi, G. J., Brady, V. J., Hollenhorst, T. P., Johnson, L. B., Host, G. E., Hanowski, J. M., Johnston, C. A., Brown, T. N., Kingston, J. C., Kelly, J. R., 2005. Environmentally stratified sampling design for the development of Great Lakes environmental indicators. Envir. Monit. Assess. 102, 41–65.

Danz, N. P., Niemi, G. J., Regal, R. R., Hollenhorst, T., Johnson, L. B., Hanowski, J. M., Axler, R., Ciborowski, J. J. H., Hrabik, T., Brady, V. J., Kelly, J. R., Morrice, J. A., Brazner, J. C., Howe, R. W., Johnston, C. A., Host, G. E., 2007. Integrated gradients of anthropogenic stress in the U.S. Great Lakes basin. Environ. Manage. 39, 631–647.

Environment Canada and U.S. Environmental Protection Agency, 2005. State of the Great Lakes 2005. EPA 905-R-06-001, governments of Canada and the U.S.

ESRI, 2000. Using ArcMap, ESRI Press, Redlands, CA.

Hollenhorst, T. P., Brown, T. N., Johnson, L. B., Ciborowski, J. J. H., Host, G. E., 2007. Methods for generating multi-scale watershed delineations for indicator development in Great Lake coastal ecosystems. J. Great Lakes Res. 33, 13–26.

Howe, R. W., Regal, R. R., Niemi, G. J., Danz, N. P., Hanowski, J. M., 2007. A probability-based indicator of ecological condition. Ecol. Indic. 7, 793–806.

Johnston, C. A., Bedford, B., Bourdaghs, M., Brown, T. N., Frieswyk, C. B., Tulbure, M., Vaccaro, L., Zedler, J. B., 2007. Plant species indicators of physical environment in Great Lakes coastal marshes. J. Great Lakes Res. 3, 106–124.

Johnston, C. A., Ghioca, D., Tulbure, M., Bedford, B. L., Bourdaghs, M., Frieswyk, C. B., Vaccaro, L., Zedler, J. B., 2008. Partitioning vegetation response to anthropogenic stress to develop multi-taxa wetland indicators. Ecol. Appl. 18, 983–1001.

Keys, J. E. Jr., Carpenter, C. A., Hooks, S. L., Koeneg, F. G., McNab, W. H., Russell, W. E., Smith, M. L., 1995. Ecological units of the eastern United States–first approximation. Technical Publication R8-TP 21. Map (scale 1:3,500,000). U.S. Department of Agriculture, Forest Service, Atlanta, GA.

Kireta, A. R., Reavie, E. D., Axler, R. P., Sgro, G. V., Kingston, J. C., Brown, T. N., Danz N. P., Hollenhorst, T., 2007. Coastal geomorphic variability in the Laurentian Great Lakes: implications for a diatom-based monitoring tool. J. Great Lakes Res. 33, 136–153.

Lawson, R., 2004. Coordinating coastal wetlands monitoring in the North American Great Lakes. Aquat. Ecosys. Health Manage. 7, 215–221.

Maidment, D. R., Morehouse, S., 2002. *Arc Hydro: GIS for Water Resources*. ESRI Press, Redlands, CA.

Niemi, G. J., McDonald, M., 2004. Application of ecological indicators. Annu. Rev. Ecol. Evol. S. 35, 89–111.

Niemi, G. J., Wardrop, D., Brooks, R., Anderson, S., Brady, V., Paerl, H., Rakocinski, C., Brouwer, M., Levinson, B., McDonald, M., 2004. Rationale for a new generation of ecological indicators for coastal waters. Environ. Health Persp. 112, 979–986.

Niemi, G. J., Axler, R. P., Brady, V. J., Brazner, J., Brown, T. N., Ciborowski, J. H., Danz, N. P., Hanowski, J. M., Hollenhorst, T. P., Howe, R., Johnson, L. B., Johnston, C. A., Reavie, E. D., Simcik, M., Swackhamer, D., 2006. Environmental indicators of the U.S. Great Lakes coastal region. Report NRRI/TR-2006/11 to the U.S. Environmental Protection Agency STAR Program, ver.1. Agreement R82-8675, Washington DC. Prepared by Great Lakes Environmental Indicators Collaboration, Natural Resources Research Institute, University of Minnesota Duluth.

Niemi, G. J., Kelly, J. R., Danz, N. P., 2007. Foreword. Environmental indicators for the coastal region of the North American Great Lakes: Introduction and Prospectus. J. Great Lakes. Res. 33, 1–12.

Reavie, E. D., Axler, R. P., Sgro, G. V., Danz, N. P., Kingston, J. C., Kireta, A. R., Brown, T. N., Hollenhorst, T. P., Ferguson, M. J., 2006. Diatom-based weighted-averaging transfer functions for Great Lakes coastal water quality: relationships to watershed characteristics. J. Great Lakes Res. 32, 321–347.

Ribic, C. A., Lewis, S. J., Melvin, S., Bart, J., Peterjohn, B., 1999. Proceedings of the marsh bird monitoring workshop. U.S. Fish and Wildlife Service, U.S. Geological Survey.

Seilheimer, T. S., Chow-Fraser, P., 2006. Development and use of the wetland fish index to assess the quality of coastal wetlands in the Laurentian Great Lakes. Can. J. Fish. Aquat. Sci. 63, 354–366.