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Environmental Indicators for the Coastal Region of the U.S. Great Lakes

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Environmental Indicators for the Coastal Region of the U.S. Great Lakes



9 April 2006

U.S. EPA STAR Cooperative Agreement Number: R-828675

NRRI/TR-2006/11

Version VIII

27 June 2006



FOREWORD

The Great Lakes Environmental Indicators (GLEI) collaboration was formed in response to a joint U.S. Environmental Protection Agency (EPA) and National Aeronautics and Space Administration (NASA) request for assistance (RFA) in FY 1999 to develop environmental indicators of the U.S. Great Lakes coastal region. Our response was the formation of a collaboration of 27 scientists from 10 different institutions as a cooperative agreement with U.S. EPA's Office of Research and Development and an associated grant from NASA. The original proposal was written in late 1999 and early 2000 and the 5-year effort spanned from January 2001 to January 2006. Institutional members of the collaboration included the following:

University of Minnesota Duluth
University of Minnesota Twin Cities
University of Wisconsin, Green Bay
South Dakota State University
University of Windsor, Ontario, Canada
University of Wisconsin, Madison

Cornell University
John Carroll University
University of Michigan
U.S. EPA Mid-Continent Ecology Division

In addition to the collaborators, a senior advisory committee was established to provide feedback and critical input in early stages of the project. The committee consisted of the following individuals:

- Rob Brooks, Penn State Cooperative Wetlands Center, Pennsylvania State University.
- Tom Burton, Department of Zoology, Michigan State University.
- Sushil Dixit, Department of Biology, Queen's University, Ontario.
- Bob Hughes, Dynamac Corporation, Corvallis, Oregon.
- Larry Kapustka, Ecological Planning and Toxicology, Inc., Corvallis, Oregon.
- Dan McKenney, Canadian Forest Service, Sault Ste. Marie, Ontario.
- Dan Simberloff, Department of Ecology and Evolutionary Biology, University of Tennessee.

The GLEI collaborators as a whole met 8t times during the 5-year effort as well as having conference calls at intervals of 3 weeks to 2 months (Section III). GLEI scientists also met annually with similar groups funded through U.S. EPA's STAR program – EaGLe (Estuarine and Great Lakes Indicators) program. Among the highlights of these gatherings were the organization and presentations at 5 major national/international symposia (2 at Ecological Society of America, 1 at the American Society of Limnology and Oceanography, 1 at Society of Environmental Toxicology and Chemistry, and 1 at Society of Wetland Scientists) (Section VI).

I personally want to thank everyone involved in this project for their hard work and cooperation in this effort. More than 48 undergraduate students, more than 36 graduate students, and more than 80 individuals have participated in the gathering, compilation, analysis, and writing of various parts of this effort. To date, 23 peer-reviewed publications, 20 technical reports, 2 book chapters, and 172 presentations have been completed during the project. In addition, 36 papers



are either in review or in preparation resulting from these efforts. A total of 2 undergraduate theses, 14 master's degrees (one in progress), 3 PhDs were completed (4 in progress), as well as 4 post-doctoral associates have been trained.

There are too many individuals for me to personally acknowledge, but there are several individuals who deserve special mention for their contributions and wisdom at various times over the past 5 years – John Brazner, Terry Brown, Jan Ciborowski, Nicholas Danz, Tom Hollenhorst, Lucinda Johnson, and Ronald Regal. Finally, the initiation, implementation, and completion of this project would certainly not have been possible without the coordination of Valerie Brady and persistence of U.S. EPA's project officer, Barbara Levinson – what a duo they make!

GLEI was supported by cooperative agreement R82-8675 from the U.S. Environmental Protection Agency's Science to Achieve Results (STAR) program. Although the research described in this report has been funded wholly or in part by the United States Environmental Protection Agency, it has not been subjected to the Agency's required peer review and, therefore, does not reflect the view of the Agency and no official endorsement should be inferred.

GERALD J. NIEMI, DIRECTOR
GREAT LAKES ENVIRONMENTAL INDICATORS
APRIL 2006



The recommended citation for this report is:

Niemi, G.J., R. Axler, V. Brady, J. Brazner, T. Brown, J.H. Ciborowski, N. Danz, J.M.Hanowski, T. Hollenhorst, R. Howe, L.B. Johnson, C.A. Johnston, E. Reavie, M. Simcik, D. Swackhamer. 2006. Environmental indicators of the U.S. Great Lakes coastal region. Report NRR/ITR-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, 121 pp + attachments (CD).



This report is dedicated to the memory of Dr. John Kingston – our friend and colleague.



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I. EXECUTIVE SUMMARY

A. ABSTRACT

The goal of this research collaboration was to develop indicators that both estimate environmental condition and suggest plausible causes of ecosystem degradation in the coastal region of the U.S. Great Lakes. The collaboration consisted of 8 broad components, each of which generated different types of environmental responses and characteristics of the coastal region. These indicators included biotic communities of amphibians, birds, diatoms, fish, macroinvertebrates, and wetland plants as well as indicators of polycyclic aromatic hydrocarbon (PAH) photo-induced toxicity and landscape characterization. These components are summarized below and discussed in more detailed in 5 separate reports (Section II).

Stress gradients within the U.S. Great Lakes coastal region were defined from 207 variables (e.g., agriculture, atmospheric deposition, land use/land cover, human populations, point source pollution, and shoreline modification) from 19 different data sources that were publicly available for the coastal region. Biotic communities along these gradients were sampled with a stratified, random design among representative ecosystems within the coastal zone. To achieve the sampling across this massive area, the coastal region was subdivided into 2 major ecological provinces and further subdivided into 762 segment sheds. Stress gradients were defined for the major categories of human-induced disturbance in the coastal region and an overall stress index was calculated which represented a combination of all the stress gradients.

Investigators of this collaboration have had extensive interactions with the Great Lakes community. For instance, the Lake Erie Lakewide Area Management Plan (LAMP) has adopted many of the stressor measures as integral indicators of the condition of watersheds tributary to Lake Erie. Furthermore, the conceptual approach and applications for development of a generalized stressor gradient have been incorporated into a document defining the tiered aquatic life criteria for defining biological integrity of the nation's waters.

A total of **14** indicators of the U.S. Great Lakes coastal region are presented for potential application. Each indicator is summarized with respect to its use, methodology, spatial context, and diagnosis capability. In general, the results indicate that stress related to agricultural activity and human population density/development had the largest impacts on the biotic community indicators. In contrast, the photoinduced PAH indicator was primarily related to industrial activity in the U.S. Great Lakes, and over half of the sites sampled were potentially at risk of PAH toxicity to larval fish. One of the indicators developed for land use/land change was developed from Landsat imagery for the entire U.S. Great Lakes basin and for the period from 1992 to 2001. This indicator quantified the extensive conversions of both agricultural and forest land to residential area that has occurred during a short 9 year period.

Considerable variation in the responses were manifest at different spatial scales and many at surprisingly large scales. Significant advances were made with respect to development of methods for identifying and testing environmental indicators. In addition, many indicators and concepts developed from this project are being incorporated into management plans and U.S.



EPA methods documents. Further details, downloadable documents, and updates on these indicators can be found at the GLEI website - <http://glei.nrri.umn.edu>.

B. INTRODUCTION

The Great Lakes is the largest freshwater system in the world. More than 10% of the U.S. population lives within the Great Lakes watershed, and the region is among the most heavily industrialized areas of the U.S. The coastal nearshore zone has been heavily impacted by chemicals, organic enrichment, and physical alterations, primarily from industrialization, urbanization, and agriculture (Krieger *et al.* 1992, Mackey and Goforth 2005). Coastal systems are the places with high human densities, repositories of wastes, focal points of industrial activity, centers of recreational pursuits, regions of high fish production, and areas of high primary production (Boesch *et al.* 2001, Jackson *et al.* 2001, Niemi *et al.* 2004). This region also contains some of the most pristine areas in the middle of the continent.

A substantial body of literature exists on the effects of human activities on biota of the Great Lakes basin. Among the primary human stressors in coastal ecosystems of the basin are land use and landscape change (Brazner 1997, Detenbeck *et al.* 1999), climate change (Hartmann 1990, Mortsch and Quinn 1996, Magnuson *et al.* 1997, Kunkel *et al.* 1998, Mortsch 1998, Kling *et al.* 2003), exotic species (Brazner *et al.* 1998, Brazner and Jensen 1999), point and non-point source pollution (The Nature Conservancy 1994), atmospheric deposition (Vitousek *et al.* 1997, Nichols *et al.* 1999), and various hydrological modifications (e.g., dredging, breakwaters, docks, harbors). Substantial efforts have been directed toward improving conditions in the Great Lakes, including the establishment of a process (State of the Lakes Ecosystem Conferences [SOLEC], Bertram and Stadler-Salt 1998) to measure condition and detect changes over time with environmental indicators (Environment Canada and U.S. EPA 2003).

Development of environmental indicators has received considerable attention in the Great Lakes (e.g., Maynard and Wilcox 1997, Wilcox *et al.* 2002, Simon 2003); however, there are a limited number of indicators for the coastal region (Environment Canada and U.S. EPA 2003, Lawson 2004). This document summarizes a 5-year effort to test many of the proposed indicators for the coastal region, revise some of the existing indicators, and develop new indicators for application to measure condition as well as point to potential causes of impairment within the U.S. Great Lakes coastal region.

The major question addressed was, “What environmental indicators can be developed to efficiently, economically, and effectively measure and monitor the condition, integrity, and long-term sustainability of the coastal region of the U.S. Great Lakes?”

Our specific objectives included:

- § identifying environmental indicators that are useful to define the condition, integrity, and change of the ecosystems within the coastal region;
- § testing indicators with a rigorous combination of existing data and field data to link stressors of the coastal region with environmental responses; and
- § recommending a suite of indicators to guide managers toward improved management decisions.

If implemented, the indicators can aid managers to: 1) communicate with the public on the condition and integrity of the coastal region, 2) guide development of monitoring programs to



measure change in the coastal region, 3) identify areas in need of restoration or conservation strategies, and 4) provide input for modeling efforts to forecast future conditions of the coastal region.

C. METHODS

Study Area

The Great Lakes basin encompasses more than 760,000 km² with the land area encompassing more than 515,000 km². The U.S. portion of the land area includes over 290,000 km² with a total shoreline length of over 7,800 km. The coastal region borders 8 states and the Canadian province of Ontario. A boundary in climatic and physiographic features divides the basin into 2 broad regions of nearly equal size: the Laurentian Mixed Forest (LMF) and Eastern Broadleaf Forest (EBF) provinces (Keys *et al.* 1995). General patterns of human activity and land use differ between provinces, with most agricultural activities occurring in the southern portion of the basin, while the northern portion of the basin remains largely forested. The southern portion contains deeper, more permeable, and highly buffered soils in comparison with the northern portion. Metropolitan areas are more common in the southern basin. We restricted this collaboration to the U.S. Great Lakes coastal region, primarily because of monetary and logistical limitations; however, most of the results are applicable to the entire Great Lakes ecosystem.

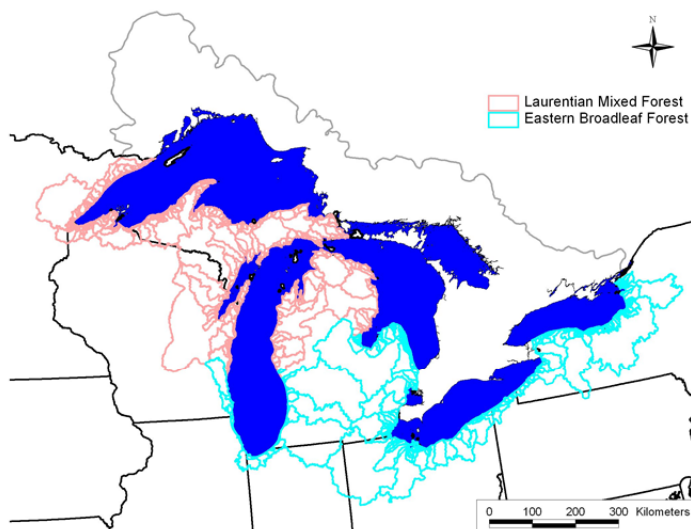


Figure 1. A total of 762 segment sheds identified for the U.S. Great Lakes Watershed.

delineated by 1) a segment of shoreline extending in both directions from the mouth of a second order or higher stream to half the distance to the adjacent streams, and 2) the associated drainage area. Segment shed area ranged widely, from 30 ha to 1.7 million ha (Figure 1). The number of segment sheds by lake is as follows: 102 in Lake Erie, 148 in Lake Huron, 157 in Lake Michigan, 90 in Lake Ontario, 12 in Lake St. Clair, and 236 in Lake Superior. An additional 17 segment sheds were found in connecting channels between the lakes.

Sample design

Our primary goal was to ensure that we distributed our sampling across the major axes of stress in the coastal region of the U.S. Great Lakes. In this way, our sampling represented a ‘natural experiment’ in which biotic communities are examined across gradients of stress. We partitioned the entire U.S. Great Lakes coastline into 762 coastal watersheds, or “segment sheds” (Danz *et al.* 2005, Johnston *et al.* 2006). Each segment shed consisted of the land area



Within each segment shed a total of 207 stress variables from 19 different data layers were compiled in a geographic information system (GIS). Each of the data layers was available from publicly available databases and in digital format. These data layers were classified into 6 major categories of stress within the Great Lakes including agricultural activity (21 variables), atmospheric deposition (11), land use/cover (23), human population and development (14), point source and non-point sources (79), and specific shoreline characteristics (6), plus 1 natural category, soil characteristics (53).

We employed a variety of multivariate statistical techniques including PCA to reduce the dimensionality in these data, and clustering techniques to identify groups of sites with similar stress profiles (Danz *et al.* 2005, Danz *et al.* in press). A random stratified sampling design was used to select segment sheds from clusters with similar stress profiles while considering provinces and individual lakes. At the segment shed level, there were many sites that could be sampled. We also employed a random selection procedure as well as assessed access to select sites of various hydro-geomorphic types within a segment shed. Hydro-geomorphic types included the following: open-coast wetlands, riverine wetlands, protected wetlands, high energy shorelines, and embayments (Keough *et al.* 1999, Host *et al.* 2005). Specific study site types were selected if they were relevant to a component. For instance, aquatic organisms were not studied in upland terrestrial areas nor were wetland plant communities studied in high energy shorelines. Final selection of study sites was also designed to maximize overlap, and thus integrate, across the different components of the study. For instance, because of the nature of the biological response, the contaminants component could sample the fewest sites, while the bird and amphibian subcomponent could sample hundreds of sites. Hence, most of the components sampled the contaminant sites and the bird and amphibian component sampled the most sites.

Analysis

Our basic approach to analysis was exploratory, in which the various environmental patterns (e.g., biological communities) were examined relative to the stress gradients. To reduce the number of potential relationships, each component identified stress gradients that were most relevant to the biota they sampled. The basic premise of these analyses was to explore whether there was a relationship between stress and biota. In most cases, each component also used a training set/test set approach in which the strength and predictability of the relationship was examined. These stress-biota response relationships were also examined over a wide variety of spatial scales to identify the appropriate scale in which the response could potentially be applied. For instance, because the stress variables were compiled in a GIS, calculations over many spatial scales were possible. The original selection of samples sites was based on stress variables calculated at the level of the segment shed, while most stress-response relationships for wetland complexes presented in the final analysis were based on stress variables calculated at the watershed level. However, we also explored stress-response relationships at various buffer distances from the specific sampling locations such as 500 m, 1000 m, or 5000 m buffers.

The stress gradients represent ‘pressure indicators’ as defined by SOLEC (Shear *et al.* 2003). These gradients can be used individually to examine ecological changes associated with such activity as agriculture, human populations, or other stressors like atmospheric deposition. We explored each of these gradients in detail, but also calculated an overall stress gradient in which all categories of stress were combined into 1 overall stress index (Danz *et al.* in press). This



stress index represents the integration of all 207 individual stress variables that were originally gathered and retains a high proportion of the variation in those original variables. We used this stress index to estimate the overall condition of the 762 segment sheds within the U.S. Great Lakes watershed (Figure 2). This stress index could be periodically evaluated to quantify the trend in condition of the U.S. Great Lakes coastal region (see Appendix A.15.). The stress index was evaluated by most of the components as a broad indicator of stress in the coastal region of the U.S. Great Lakes.

A final phase of the analysis included an integration phase in which we simultaneously analyzed

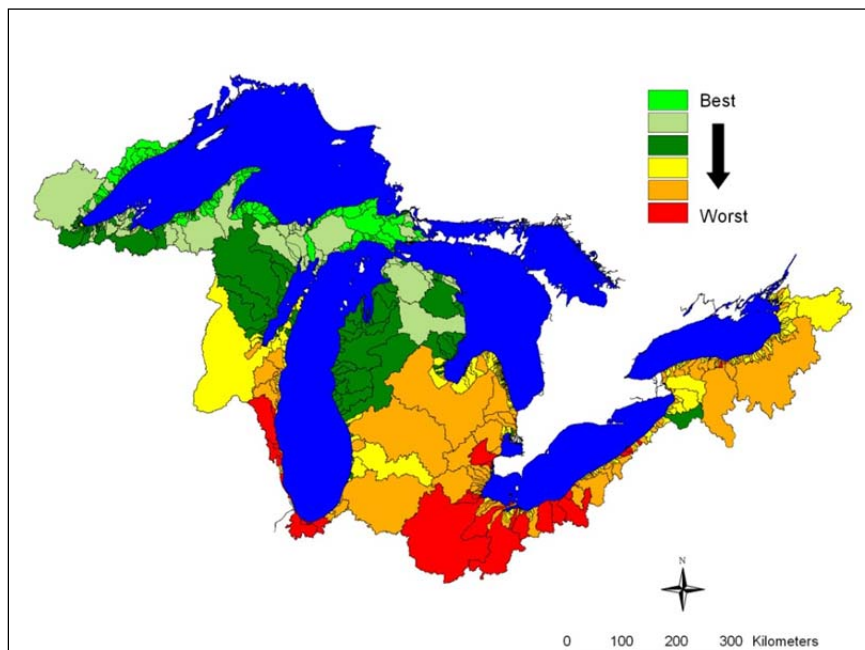


Figure 2. The overall Stress Index for the U.S. Great Lakes coastal region.

the responses of amphibians, birds, diatoms, fish (sampled by electro-fishing and fyke nets), macroinvertebrates, and wetland vegetation in relation to biogeography (lake and province), hydro-geomorphic type, and the overall stress index (Brazner *et al.* Ms. 1). These considerations are critical for actual application of state (response) indicators because, in practice, one must know where to apply an indicator and whether there is a relationship to a potential stress. We used a

hierarchical variance partitioning technique to identify the relative contribution of these major factors in an exploration of 66 individual state indicators (Brazner *et al.* Ms. 1). Furthermore, we also explored these same 66 indicators in an analysis of 3 major stressors (agriculture, human population/development, and point sources) with classification and regression trees (CART). This analysis is in a preliminary status (Brazner *et al.* Ms. 2).

D. RESULTS

A total of 341 wetland complexes, 122 high energy shorelines, 171 high energy/upland shorelines, and 26 embayments were collectively sampled across the U.S. Great Lakes coastal region (Figure 3). For wetland complexes, this represents over 30% of the wetlands that currently occur in the study area. Over 25 wetland complexes were sampled by more than 4 components of this collaboration and over 58 wetland complexes were sampled by 3 or more components. A summary of the sites visited by each of the components of the study includes the following: amphibians (214 wetland complexes), birds (224 wetland complexes, 171 high energy/upland shore areas), diatoms (98 wetland complexes, 68 high energy/near-shore areas, and 21 embayments), fish and macroinvertebrates (87 wetland complexes, 48 high energy/near-shore areas, and 20 embayments), photoinduced PAH, toxicity (48 sites), and wetland vegetation (90 wetland complexes).

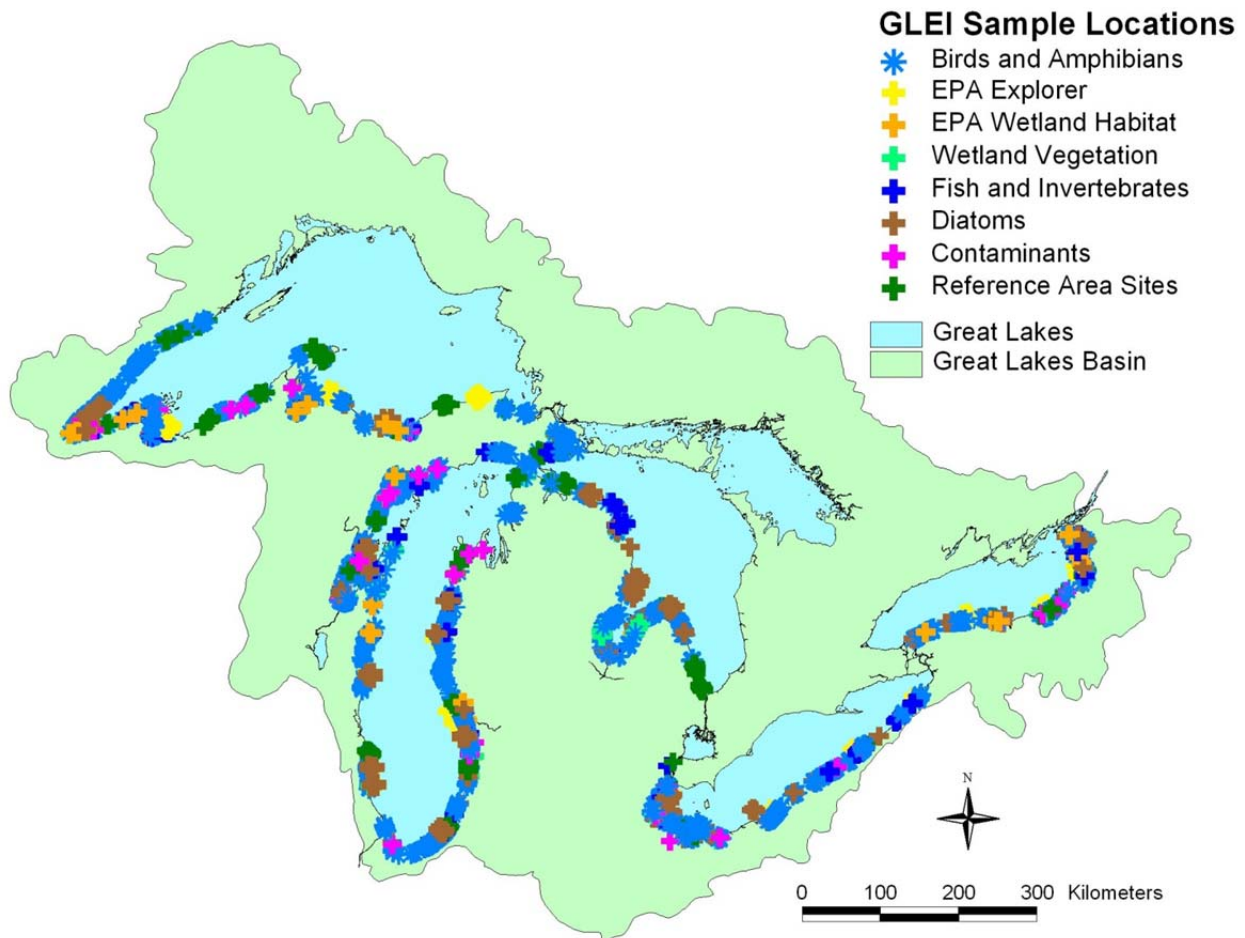


Figure 3. General locations of study sites across the U.S. Great Lakes coastal region.

D.1. Birds and Amphibians

Birds and amphibians have been used as indicators of condition of the Great Lakes, especially wetland ecosystems, for several years (Environment Canada and U.S. EPA 2003, Weeber and Vallianatos 2001). Moreover, birds have been used as ecological indicators in a variety of contexts in many parts of the U.S. and Canada (Morrison 1986, Niemi and McDonald 2004).

Our objectives were to: 1) develop a suite of scientifically robust, cost-effective indices of bird and amphibian assemblages that reflect ecological condition of the Great Lakes; 2) quantify the extent to which these indices are related to environmental pressure indicators such as land use characteristics, water quality, presence of exotic species, and hydrological modifications; 3) derive predictive models based on statistical relationships between pressure indicators and indices of bird/amphibian diversity and abundance; 4) use these models to infer ecological conditions at local and regional scales and to establish or improve the baseline for environmental monitoring programs; 5) develop a quality assurance/quality control infrastructure for future assessments of bird and amphibian communities; and, ultimately, 6) provide scientific recommendations for improving and monitoring the ecological health of the Great Lakes basin.



Experimental Approach

We evaluated both coastal wetlands and uplands within 1 km of the Great Lakes shoreline using standardized methods already in place for the Marsh Monitoring Program (coastal wetlands) or general studies of upland birds (Howe *et al.* 1997). Most sites were sampled during a single year; our approach was to include an extensive sample of many sites rather than an intensive sample of fewer sites. Approximately 10% of the sites were sampled during both years to provide some indication of annual variation, and a pilot study during 2001 explored alternative sampling approaches.

Data collected over the 2-year period provided a basis for multivariate analyses of species' associations and environmental correlates. These analyses were used to develop *probability-based indicators of ecological condition*, that explicitly incorporate species' responses to an independently-measured reference gradient of environmental stress. This approach represents an entirely new method for the development of indicators.

Bird Survey Methods

We used a standard protocol established by Ribic *et al.* (1999) to conduct wetland breeding bird surveys during June through early July of 2000, 2001, and 2002. Surveys were conducted between 0500 and 0930 CDST, and on mornings with good weather conditions. Each point was sampled 1 time with an initial 5 minute passive count, followed by a tape playback of several cryptic species, followed by an additional 5 minute passive listening. Upland birds were sampled in roadside transects within approximately 1 km of the Great Lakes shoreline. A single transect consisted of 15 points at least 500 m apart. At each point a trained observer conducted a 10 minute, unlimited-radius bird count following a standard protocol.

Amphibian Survey Methods

We followed guidelines outlined by MMP for conducting amphibian calling surveys at the same points that were sampled for wetland breeding birds (Weeber and Vallianatos 2001). Three calling surveys were conducted at each site and each survey was 3 minutes in length.

Results

Cost effectiveness

In the 2001 pilot study we tracked the labor and travel costs to complete a sample for amphibians, wetland birds and upland birds. We found that, on average, a sample of 15 upland points costs approximately 4 times as much to complete compared to a wetland bird survey and that an amphibian sample was approximately 3 times more costly than a wetland bird sample. The pilot study also indicated that 3 point samples were optimal from a cost-benefit perspective for sampling larger coastal wetlands.

Amphibians

We recorded at least 12 species of frogs and toads (anurans), 3 observed at fewer than 5 and another (Mink Frog, *Rana septentrionalis*) at 11 of the 361 point counts. The most commonly reported species was Spring Peeper (*Pseudacris crucifer*), followed by Green Frog (*Rana clamitans*), Gray Treefrog (*Hyla versicolor* and *Hyla chrysoscelis*), American Toad (*Bufo americanus*), Northern Leopard Frog (*Rana pipiens*), Chorus Frog (*Pseudacris maculata* and *P. triseriata*), Bullfrog (*Rana catesbeiana*), and Wood Frog (*Rana sylvatica*). Distributions of most



species showed clear geographic variation between the northern Laurentian Mixed Forest Ecological Province and the southern Eastern Deciduous Forest Ecological Province.

Stress-response relationships

The strongest response to the land use stress gradient was exhibited by the Spring Peeper, the only amphibian species to show a consistent relationship to the stress gradients in both the northern and southern ecological provinces. Bullfrog showed a strong negative relationship with condition in the northern ecological province, but showed little relationship in the southern province. Likewise, American Toad showed a positive relationship with the stress index in the northern province (similar to the Spring Peeper), but the opposite relationship in the southern part of the Great Lakes.

These anomalies warn against the application of anuran-based indicators across the entire Great Lakes basin. Because some species showed inconsistent responses to the stress gradients, anuran species richness is a poor indicator of environmental condition in the Great Lakes coastal zone. Based on our analysis, the abundance or frequency of Spring Peepers was the simplest and most reliable indicator for potential application across the U.S. portion of the Great Lakes coastal zone.

In a more intensive investigation of anurans in Lakes Michigan and Lake Huron, Price *et al.* (2005) found that most anuran species were most sensitive to land cover variables measured at rather large geographic scales (3 km radius). For nearly every species, human population and development (e.g., residential development, road density, etc.) showed a negative relationship with anuran frequency of occurrence.

Amphibian Indicator

The only species of frog or toad to show a geographically consistent and strong relationship with environmental stress was Spring Peeper. A simple abundance metric for this species would provide a relative index of condition, but a better measure would be to: a) estimate frequency of occurrence or probability of occurrence in the site of interest, then b) obtain parameter estimates for a standardized stress/response relationship (*species-specific sensitivity/detectability (SSD) functions*), which vary by province, and c) calculate condition (C_{obs}) iteratively to derive a standard index ranging from 0 to 10.

Wetland Birds

We sampled 371 points in 215 wetland complexes, nearly all of which also were the part of the amphibian survey. The most frequently recorded species, Red-winged Blackbird, was more than 3 times more abundant than the second most commonly recorded species (European Starling). Other common birds in the coastal wetland samples included (in decreasing order of abundance) Canada Goose, Herring Gull, Ring-billed Gull, Yellow Warbler, Common Grackle, Common Yellowthroat, Tree Swallow, and Song Sparrow. Because these species are so ubiquitous, they provide little information about the environmental condition of a given wetland. The majority of the 155 bird species recorded in coastal wetlands were much less common than these 10 abundant species. A typical 10 minute census using the standard marsh monitoring protocol (Ribic *et al.* 1999) yielded between 11-18 species, often more than 20.

We used the multivariate-derived “reference gradient” of wetland complexes to identify species



that exhibit consistent responses (positive or negative) to environmental stress. This reference gradient was established through PCA of 39 environmental variables, including previously derived PCA scores from the analysis of Danz *et al.* (2005) and proportion of land cover in 6 classes (natural non-wetland, wetland, residential, commercial/industrial, agricultural, and roads) within different radii from the center of the complex (100 m, 500 m, 1 km, and 5 km).

Given the reference gradient, we plotted frequencies of occurrence of bird species in different categories of sites (condition = 0-1, 1-2, 2-3, etc.). The SSD function results can be modeled by a 4 parameter mathematical expression describing the probability of observing the species when condition = 0, the probability of observing the species when condition = 10, the value of condition where the probability of observing the species is half-way between the minimum and maximum probabilities, and the steepness of the non-linear relationship. The SSD functions take into account both the sensitivity of the species to environmental stress as well as probability of observing the species even in optimal conditions. We used an iterative procedure in Microsoft Excel to estimate best-fit parameters for species that were observed in at least of the 10 of the 371 point counts. From 41 species that showed significant relationships with the nonlinear SSD model ($r > 0.433$, $p < 0.05$), we selected 25 wetland or open country species for calculating a site-specific indicator of ecological condition.

Using the parameter estimates for the SSD functions of 25 species, we calculated bird-derived values of ecological condition for 20 sites that had been excluded from the analysis used to calculate the SSD functions. Our new, probability-based ecological indicator (C_{obs}) can be derived from presence/absence data for the 25 target species at a given site. Rather than use the standard method of adding or multiplying weightings to produce an index, our method “works backward” from the observed data, using an approach pioneered by Hilborn and Mangel (1997). We used computer iteration to ask: “What is the value of C_{obs} , ranging from 0 to 10, that best fits the observed presence/absence data and the previously derived SSD functions?” The results have proven to be remarkably robust and useful for defining ecological condition based on combinations of the breeding bird assemblages.

Upland Birds

We identified 187 bird species in the survey of 171 coastal segments, each sampled with a route of 15 standard 10 minute point counts. To assess annual variation in species composition, 23 of the routes were sampled during both 2002 and 2003. In total, this phase of the project evaluated 2,544 separate point counts. Although we refer to the census results as upland bird assemblages, the species included birds of wetlands, forests, urban areas, and all habitat types located within approximately 1 km of the shoreline.

The most abundant species (Ring-billed Gull, European Starling, Herring Gull, American Crow, House Sparrow, American Robin) were familiar birds of urban and suburban environments in both the northern Laurentian Mixed Forest Province and the southern Eastern Deciduous Forest Province. Other species differed substantially between the 2 geographic provinces, however, warranting a separate analysis of ecological indicators for each region.

Like our analysis of coastal wetlands, we calculated “reference condition” for sites based on environmental attributes, in this case the proportional area in 6 general land cover classes within



100 m, 500 m, 1 km, 3 km, and 5 km of the 15 bird survey points. PCA was used to generate a single gradient ranging from 0 (maximally impacted by human activities) to 10 (minimally impacted by human activities).

We plotted the proportion of points (maximum = 15) at which the species was recorded against the reference condition for each route, excluding 20 routes for later validation of the model. These relationships were used to estimate the 4-parameter SSD functions (Howe *et al. in prep*). Statistically significant SSD functions ($p < 0.05$) were derived for 72 bird species in the northern (Laurentian Mixed Forest) ecological province and for 50 bird species in the southern (Eastern Deciduous Forest) ecological province.

Once parameters of SSD functions were established, the ecological condition of new sites could be calculated through iteration (Hilborn and Mangel 1997). In this case, we derived the value of condition (C_{obs}) that yielded the closest fit between observed species frequencies (among the 15 bird census points) and the predicted frequencies given the species' SSD functions. We applied this method to the 20 sites withheld from the derivation of SSD functions. Results again illustrated a close fit between reference condition and bird-based condition; however, as with the wetland bird species, we did observe many interesting and biologically meaningful deviations (Howe *et al. Ms. 1*).

Amphibian Indicator I. Ecological Condition Based on Spring Peeper Occurrence

The only species of frog or toad to show a geographically consistent and strong relationship with environmental stress was Spring Peeper. A simple abundance metric for this species would provide a relative index of condition, but a better measure would be to: a) estimate frequency of occurrence or probability of occurrence in the site of interest, then b) obtain parameter estimates for a standardized stress/response relationship (our SSD functions), which vary by ecological province, and c) calculate condition (C_{obs}) iteratively to derive a standard index ranging from 0 to 10.

Indicators involving other species are potentially useful, although geographic region must be taken into account. Our findings demonstrate clearly that species richness of amphibians is not a reliable indicator of environmental stress.

Bird Indicator I. Ecological Condition Based on Coastal Wetland Birds

Numerous bird species of coastal wetlands show strong responses to environmental stress and therefore can be used in multi species indicators of ecological condition. We have identified 25 species with consistent stress response relationships, including American Bittern, Bald Eagle, Sandhill Crane, Common Loon, Sedge Wren, Swamp Sparrow, and 6 others indicating high quality sites; and Mallard, Ring-billed Gull, Marsh Wren, Common Grackle, and Red-winged Blackbird, and 8 others indicating poorer quality sites. To combine these species into a single index ranging from 0 (maximally degraded) to 10 (minimally degraded), we recommend a probability-based approach described in detail by Howe *et al. (Ms. 2)*. Calculation of condition (C_{obs}) involves computer iteration of species occurrences or probabilities of occurrence (in multiple counts), given standardized, species-specific stress-response relationships. We provide parameters describing the stress-response relationships (Howe *et al., Ms. 2*), along with a framework for estimating and interpreting C_{obs} .



Bird Indicator II. Ecological Condition Based on Coastal Zone Birds in the Laurentian Mixed Forest Province

Birds also provide excellent indicators of the general ecological condition of the Great Lakes coastal zone. In this case, separate calculations are appropriate for the northern vs. southern portions of the Great Lakes. Our proposed indicator variable (C_{obs}) can be calculated from data on the frequency or probability of occurrence of selected species with known responses to environmental stress. In this case, samples should be acquired from multiple sites covering all or many habitats within 1 km of the Great Lakes shoreline. Multiple samples from the same area or samples from multiple sites allow the investigator to estimate probabilities of species occurrences in the area of interest. These probabilities are subsequently applied to calculate C_{obs} .

We provide parameter estimates describing stress-response relationships (SSD functions) for 25 species that show strong and predictable responses to a “reference” stress gradient. These parameters, which can be standardized across the Laurentian Mixed Forest Province, form the basis for calculating C_{obs} from field data. Calculation of C_{obs} requires computer iteration, easily performed with tools such as the solver function of Microsoft Excel. A formula for calculating C_{obs} and the accompanying theoretical framework are provided by Howe *et al.* (Ms. 1). Values of C_{obs} range from 0 (maximally degraded) to 10 (minimally degraded), permitting meaningful comparisons with results from other taxonomic groups or other geographic areas.

Species employed in the analysis include birds from a variety of habitats. Occurrences of Ovenbird, Black-throated Green Warbler, Red-eyed Vireo, American Redstart, Hermit Thrush, Winter Wren, White-throated Sparrow, and Nashville Warbler indicate high values of condition, whereas occurrences of House Sparrow, European Starling, Common Grackle, Rock Pigeon, Red-winged Blackbird, and House Finch indicate lower values of condition (i.e., a more degraded coastal zone).

Bird Indicator III. Ecological Condition Based on Coastal Zone Birds in the Eastern Deciduous Forest Ecological Province

We documented clear geographic differences not only in the distribution of bird species, but also in the responses of many species to a reference gradient of environmental stress. To account for these differences, separate indicators of ecological condition should be calculated for the northern and southern regions of the Great Lakes coastal zone. We provide an independent set of parameters describing SSD functions of birds to environmental stress in the Eastern Deciduous Forest Ecological Province. Species exhibiting a positive response to ecological condition (i.e., becoming less frequent as environmental stress increases) include Veery, Ovenbird, Red-eyed Vireo, Black-capped Chickadee, Chipping Sparrow, Red-bellied Woodpecker, American Redstart, and Canada Warbler, while species showing the opposite response (i.e., becoming more frequent as environmental stress increases) include Rock Pigeon, House Sparrow, European Starling, Common Grackle, and Ring-billed Gull.

Investigators provide field data for these species in the form of frequencies or (better) probabilities of occurrence in multiple point counts. Using the standardized SSD functions (which we have provided), a value of ecological condition (C_{obs}) ranging from 0 (maximally degraded) to 10 (minimally degraded) can be derived by computer iteration as described by Howe *et al.* (Ms. 1). This robust estimator can include additional (or fewer) species depending on



special circumstances such as local habitat availability or survey conditions. In fact, species from other taxonomic groups can easily be incorporated in the analysis, yielding estimates of C_{obs} that will be directly comparable to (but possibly more accurate) than estimates from a smaller subset of species.

D.2. Contaminants

The initial project focused on the evaluation of 2 indicators:

1. PAHs of photo-induced toxicity to fish and benthic organisms; and
2. organic chemical indicators of xenoestrogenic exposure to fishes.

However, it was not possible to develop an indicator for xenoestrogenic activity (see Section II. B).

Indicator of photoinduced toxicity of PAHs to larval fish

PAH compounds are ubiquitous in the environment and are of current concern. Our approach was to compare contaminant concentrations to a biological endpoint or condition across a gradient of non-degraded to highly degraded sites at approximately 25 locations. PAH photo-induced toxicity data were gathered in the field to test a model developed in the lab by collaborators at EPA-MED. These data included the concentrations of PAHs in sediment, larval fish, and oligochaetes; sediment photo-induced toxicity potential; and UV dose. The toxicity that was predicted from the model was compared to that measured in the lab assay.

PAH exposure is a function of partitioning of PAHs from the water column into larval fish, and usually the PAH in water is a result of partitioning from contaminated sediments to water. Because PAHs are more readily measured in sediments compared to water, we used the concept of a sediment-biota accumulation factor (BSAF). The BSAF describes the relationship between PAHs in lipids of biota and PAHs in sediment organic carbon, and is expressed as the ratio of the lipid-normalized concentration of PAHs in biota to the organic carbon normalized concentration of PAHs in sediment. We collected sediments and larval fish at each of our study sites and measured the BSAFs to test this approach.

The BSAFs for 2 compounds, fluoranthene and pyrene, were the most consistent across sites, and are incorporated into the indicator developed. It is assumed that this BSAF is representative for coastal sites throughout the Great Lakes. Thus the user of the indicator measures a suite of 9 photo-toxic PAHs and organic carbon in sediments, normalizes them to the organic carbon fraction of the sediment, multiplies their sum by our measured BSAF of 0.16 to estimate the sum of photo-toxic PAHs in fish lipid, and multiplies the value by the lipid fraction of the larval fish of interest (10% is a good default). This gives a photo-toxic PAH concentration in the fish tissue, in dry mass concentration.

Once the UV-A dose and photo-toxic PAH concentration are estimated, they can be used to calculate an LT-50, meaning the time (in hours) that it takes for 50% of the population to die. To compare the risk across sites, one needs to examine a plot of photo-toxic PAH concentration versus UV-A dose with an assumption of a given light penetration depth. This indicator can be used to prioritize sites for further investigation – where calculated LT-50s are small (<100 hrs), further investigation may be warranted; where calculated LT-50s are very large (>1000 hrs) there is minimal risk and additional investigation may not be warranted.



We calculated the LT-50s for all 25 sites that were sampled as part of our field work. The analysis assumed a constant depth of 10 cm, while the actual risk for photo-induced toxicity would depend on actual light transmission with depth. Approximately half of the sites sampled had predicted LT-50s less than 300 hrs, indicating that these sites have potential risk for photo-induced toxicity of larval fish.

Summary

The PAH indicator can be used by Great Lakes managers to estimate whether larval fish populations at a locale are potentially at risk from PAH photo-induced toxicity. Users of this indicator need to estimate PAH exposure to fish by measuring specific PAH compounds in sediment, estimate UV-A dose by measuring absorbance of water with a spectrophotometer, and measure suspended particulate matter gravimetrically. These measurements are then applied in a model that estimates the risk of photo-induced toxicity.

D.3. Diatoms

Diatoms (algal assemblages) have proven to be robust indicators of stressors such as nutrients, water clarity (Dixit and Smol 1994), and acidification (e.g., Siver *et al.* 2003), as well as a suite of other water quality problems in freshwater ecosystems (Smol 2002). Four diatom-based indicators of Great Lakes coastal quality were developed. The application of the respective diatom-based indicator is based on need and/or logistical considerations.

Indicator 1. Diatom-based inference models for water quality variables

The diatom assemblages sampled were used as training sets to relate contemporary assemblages with environmental variables of interest (e.g., total phosphorus or nitrogen, pH, chloride, suspended solids). Transfer functions for 17 site-level water quality variables (Reavie *et al.* 2006) were developed using weighted averaging regression. Diatom-inferred (DI) estimates of water quality variables for each sample were calculated by taking the optimum of each taxon to that variable, weighting it by its abundance in that sample, and calculating the average of the combined weighted taxa optima. The strength of the transfer functions were evaluated by calculating the squared correlation coefficient (r^2) and the root mean square error (RMSE) of prediction between measured values and transfer function estimates of those values for all samples.

Over 2000 diatom taxa were identified, and 352 taxa were sufficiently abundant to include in transfer function development (Reavie *et al.* 2006). Multivariate data exploration revealed strong responses of the diatom assemblages to stressor variables such as total phosphorus (TP). A diatom inference transfer function for TP provided a robust reconstructive relationship ($r^2 = 0.65$; RMSEP = 0.26 log ($\mu\text{g/L}$)).

Measured and diatom-inferred water quality data from the Great Lakes coastlines were regressed against watershed characteristics, including gradients of agriculture, atmospheric deposition and point sources (specifically industrial facilities) to determine the relative strength of measured and diatom-inferred data to identify watershed stressor influences. With the exception of pH, diatom-inferred water quality variables were better predicted with watershed characteristics than were measured water quality variables (Reavie 2006). This provides additional evidence that there is a close coupling between watershed characteristics and coastal diatom communities.



Indicator 2. Diatom-based integrative water quality model

This indicator used the same set of chemical and diatom data used to develop Diatom Indicator 1 to derive an integrated water quality (WQ) model (Reavie *et al.* 2006). Diatom Indicator 2 was created to form a comprehensive measurement of WQ and to examine how well the diatoms responded to a general water quality gradient in contrast to specific WQ variables like total phosphorus. The comprehensive WQ index was calculated from a principal components analysis of all the measured WQ variables to derive a major environmental gradient that ranged from “high” (i.e., low-nutrient, clear-water sites) to “low” (i.e., high-nutrient, high chloride, turbid sites) water quality (Reavie *et al.* 2006). Following the development of this gradient, diatom species coefficients were calculated from diatom taxa optima and tolerances from weighted-average regressions of diatom responses across the WQ gradient. As for the previous indicator, watershed land use data were examined with the Diatom Indicator 2 values using multiple linear regression.

Comparisons of observed to diatom-inferred data indicated good predictive ability for the integrated WQ model ($r^2_{\text{jackknife}} = 0.62$, RMSEP = 1.32). The relative power of these models was also illustrated by comparing measured and diatom-based data to watershed characteristics. As with the previous indicator, the diatom-based integrated indicator was better correlated with watershed characteristics than were measured WQ variables. This approach appears to better characterize diatom-environmental relationships by merging several WQ variables that simultaneously influence diatom species assemblages. One disadvantages of using a WQ index includes some loss of information for water quality managers who may be interested in specific variables, such as phosphorus. However, an integrated measure of water quality may be a useful step toward building more informative and comprehensive WQ models.

Indicator 3. Diatom-based multimetric index of disturbance

This diatom-based multimetric index was developed to link with coastline disturbance in Great Lakes coastal wetlands, embayments and high-energy sites. Unlike the previous 2 indicators, the multimetric index was derived and tested using a fundamentally different approach because of the potential for logistical constraints or limited expertise of diatom taxonomy by users (see Section II.C). This index approach provides a means to evaluate environmental quality at a locale based on the diatom assemblage and can provide an integrated picture of impacts at a site. We developed 38 diatom-based metrics from taxonomic and functional characteristics of the diatom assemblage. Among these metrics, we selected those that were primarily related with the stress gradients. The multimetric index was developed based on the sum of the selected metrics, with each metric weighted based on its strength of relationship to the stressor gradient. Fifteen candidate metrics met the criteria of our selection process. However, to create an approach that was adaptable to the limitations of a user audience, 2 variations of the multimetric index were developed: 1) A full 15-metric compilation in which the metrics included were proportions of particular genera; proportions of monoraphid taxa, biraphid taxa, and the complex of taxa comprising *Achnanthydium minutissimum*; the Shannon-Weaver index of diversity; and diatom-inferred chloride concentration (C1); and 2) A simpler, 13-metric compilation that excluded the Shannon-Weaver diversity value, and the diatom-inferred C1 value.



Indicator 4. Diatom valve deformities as indicators of pollution

We derived an indicator based on morphologically abnormal diatoms from the genus *Tabularia*. This indicator was based on *Tabularia* collected at a coastal site in Lake Erie near Cleveland, Ohio, an area with a legacy of severe environmental problems. Based on our observations, it appears that frustular abnormalities are common in diatom communities that undergo toxic stress, and *Tabularia* showed an extreme variety of atypical shapes (Stoermer and Andresen 2006). Frustules were bent, asymmetric, had irregular striae patterns, irregular margins, or combinations of these characters. Morphological abnormalities of the diatoms was not anticipated to be one of the indicators developed and, hence, we only assessed abnormalities near Cleveland. However, the presence of benthic diatoms that are atypical may offer valuable insights into toxic effects in the Great Lakes. Although the present state of knowledge does not permit firm conclusions concerning abnormalities in diatoms, investigation of benthic diatom populations in the Great Lakes is a neglected topic that deserves more attention.

Summary

The results to date strongly support the use of diatoms in Great Lakes coastal monitoring programs to track the impacts of anthropogenic stressors. There is also considerable value in these indicators for retrospective assessments. Because long-term measured water quality data can be sparse or unreliable, and pre-European settlement data are unavailable, diatom-based paleoecological studies in the Great Lakes have been valuable in describing background conditions and anthropogenic impacts. To date, most of these studies have focused on sediment cores collected from deep, open water areas, but diatoms can be extremely useful for paleoecological assessments of near-shore or wetland systems.

D.4. Fish and Macroinvertebrates

Background

Fish and macroinvertebrates have been widely used as environmental indicators in the Great Lakes (Simon 2003, Uzarski *et al.* 2006). We combined the strengths of 2 common approaches (multimetric and multivariate) to generate ecologically relevant indicators that had the greatest possible discriminatory power to distinguish degraded from least-impaired systems.

Our overall objectives were to: 1) characterize fish and macroinvertebrate communities in the coastal region, 2) summarize and quantify measures of associated aquatic habitat structure, 3) develop ecological indicators using fish and macroinvertebrate communities, 4) assess fish and macroinvertebrate responses to stress gradients, 5) identify appropriate spatial scales of responses of macroinvertebrate and fish indicators to landscape stressors, and 6) develop multivariate methods to assess coastal ecosystem condition using fish and macrobenthos communities. Here we primarily focus on objective 3; additional details of the overall study are described in Section II.D.

Methods

The sampling effort conducted from 2001 and 2003 resulted in a total of 116 sites sampled at 101 unique locations spanning over 14,000 km of the U.S. Great Lakes coastline. Fifteen sites were revisited to quantify temporal variation. In addition, 53 sites were sampled as part of a parallel study (EPA grant number R-828777) to define reference condition in nearshore coastal waters of the Great Lakes. Benthic samples were collected using sweep nets, sediment coring



tubes, and petite ponar grab samplers from which at least 226 genera or higher level macroinvertebrate taxa (exclusive of Chironomidae and Oligochaeta) were identified. Approximately 1,100 overnight fyke net sets were fished, resulting in capture, identification and release of over 100,000 fish representing 110 species. Habitat attributes and characteristics of sampling location and the surrounding landscape were recorded at more than 1,500 benthos sampling points, 800 net locations, and 3,000 additional randomly selected points. Water quality was measured at approximately 2,000 locations. Fish community composition (numbers of individuals of each species) was noted at each fyke net; the catch was standardized by net size (small vs. large) and catch per unit effort. Fish and macroinvertebrates were summarized with respect to relative abundance of each taxon per site, as well as using a variety of taxon metrics describing trophic habits, life history features, behavioral characteristics, and community composition.

Results and discussion

Community structure – zoobenthos. The extensive collection records of zoobenthos (over 4,000 samples from almost 150 distinct Great Lakes locations) have been an important source of biogeographic and taxonomic information over and above the primary use of the data to develop and test indicators of anthropogenic stress. GLEI researchers discovered 1 invertebrate species new to the Great Lakes and mapped the range expansion of a second invader (Grigorovich *et al.* 2005a, b).

Community structure - aquatic habitat. Quantifying aquatic habitat alteration stemming from anthropogenic disturbance. Anthropogenic stressors often exert their effects on biota indirectly by altering the physical structure of the habitat. We summarized the spatial variation in over 100 individual habitat-associated attributes of 133 sampling sites to yield 4 measures of habitat structure: landuse/land cover, physical structure, vegetation cover, and anthropogenic disturbance. Redundancy analysis of these measures indicated that about a third of the overall variation in habitat structure could be predicted from landscape and stressor features. Fifteen percent was uniquely attributable to stress, and 4% could also be explained by covariation with other features. Overall, anthropogenic disturbance exerted small but meaningful changes in habitat attributes that themselves influence macroinvertebrate (Foley *et al.* in preparation, Brady *et al.* in preparation) and fish community structures (see below).

Community structure – fishes. Two fish indicators indexes assess Great Lakes coastal wetland condition (see 2-page summary in Appendix A). Uzarski *et al.* (2006) proposed that because emergent plant communities adapt quickly to changing water levels, fish communities associated with plant types could be used as indices of wetland condition. They proposed a fish Index of Biotic Integrity (IBI) for wetlands dominated by cattails (*Typha*) and another IBI for those in which bulrushes (*Scirpus*) were the most common species. The fish IBI scores we calculated for these wetlands did indeed vary, but only according to specific classes of human-related stress. Fish communities in cattail-dominated wetlands became degraded as a disturbance variable that combined population density, road density and urban development in the watershed surrounding the wetland increased. In contrast, the fish communities of bulrush-dominated wetlands reflected the impacts of nutrient and chemical inputs associated with the intensity of agricultural activity in the surrounding landscape. These effects were observed in data collected over several years, during which time Great Lakes water levels varied by up to 100 cm, thus confirming the effectiveness of the indices under changing water conditions.



Developing multivariate fish and macroinvertebrate indicators using a priori classification of reference condition and degraded conditions

Indicators of environmental conditions are typically developed by defining the bounds of composition of the biological community expected within a suite of sampling sites selected to represent the reference condition. However, because such measures are unbounded, one cannot tell how degraded a non-reference community is. We defined reference conditions as the 20% of Great Lakes coastal locations exhibiting the least possible amount of anthropogenic stress, and complementary degraded conditions as sites with the greatest observable degree of urban stress or agricultural disturbance. Cluster analysis revealed that Great Lakes fish communities of reference sites formed 5 distinct assemblages, associated with ecoregions and wetland type. For each of the 5 distinct ecoregion/wetland types we used Bray-Curtis ordination to identify fish indicator species characteristic of the reference condition, and other species that dominated sites greatly affected by urban stress and agricultural disturbances.

This approach was effective for 2 reasons. First, grouping together reference sites exhibiting common species composition provided an objective, empirical strategy for determining how many different indicator measures were necessary. Secondly, the designation of both reference and degraded conditions permitted us to develop models of fish species relative abundances that can be used to evaluate the quality of sites in response to specific anthropogenic stressors.

This approach will be especially effective in developing macroinvertebrate indicators given the strong dependence of zoobenthos on local habitat characteristics (depth, substrate texture, macrophyte structure) in addition to regional stress effects.

Fish community indicators of stress. Strong patterns in fish presence/absence were observed with respect to local, landscape, and spatial variables; 46% of the total variation in the presence/absence of fish across the basin was explained by those variables, with more than half attributable to local variables and a little less than half attributed to landscape/stress. Independent of spatial location in the basin we have identified 6 species with consistent responses to stress. The Burbot is considered an indicator of low stress environments; European Carp was consistently associated with high values along the agriculture chemical gradient. Alewife, Emerald Shiner, Largemouth Bass, and Sand Shiner are all positively correlated with point sources of pollution and/or human population density/development. These species all exhibit “wedge” shaped responses with respect to stress, indicating that unmeasured variables become increasingly important in regulating abundance over a portion of the stress gradient (generally at low levels of stress).

Summary

Our results verify that IBI and multivariate scores of fish communities reflect specific classes of anthropogenic stress at Great Lakes coastal margins. The indices reflect certain types of human disturbance and are suitable for assessing wetland condition in response to agriculture or population density supplementary to generalized disturbance. These results address one of the weaknesses of the classical IBI approach to developing indicators, in that a single value representing ecological condition does not address the cause of impairment. In addition, we have developed a method to distinguish reference and degraded sites, and have identified several



basin-wide indicators of stress.

D.5. Wetland Vegetation

The objectives of this component were to: 1) identify vegetative indicators of condition of Great Lakes coastal wetlands that can be measured at a variety of scales, 2) develop relationships between environmental stressors and those vegetative indicators, and 3) make recommendations about the utility and reliability of vegetative indicators to guide managers toward long-term sustainable development.

A total of 90 wetland complexes were selected for study and classified by hydrogeomorphic type as open-coast wetlands (n=27), riverine wetlands (n=35), or protected wetlands (n=28). Sampling was done in 1 x 1-m² plots distributed along randomly-placed transects within areas of herbaceous wetland vegetation in the study sites selected (Johnston *et al.* in press). Transects were placed in areas mapped by national and state wetland inventories as emergent wetland vegetation. Within each plot all vascular plant species were identified to the lowest taxonomic division possible. Percent cover was estimated visually for each taxon according to modified Braun-Blanquet cover class ranges. Field teams were jointly trained and tested to ensure consistency of visual observations (Kercher *et al.* 2003).

Indicator development and evaluation

We evaluated 2 existing indicators that we found were not very useful (Bourdaghs *et al.* in review, Brazner *et al.* Ms. 1, Ms. 2):

Species richness

We found that species richness was suppressed by tall invasive plant species such as *Typha x glauca* and *Phragmites australis* and species richness was not in itself a good indicator of environmental condition.

Percent of all taxa that are obligate wetland plants

We expected that the proportion of obligate wetland species would decrease with increasing anthropogenic stress; however, this relationship was weak and was poorly correlated ($r^2 = 0.057$) to the overall stress index (Danz *et al.* in press).

Three existing indicators that were satisfactory included the 1) floristic quality index (FQI), 2) the mean coefficient of conservatism, and 3) the percent of all taxa that are native plants. The first 2 indices are both based on the coefficient of conservatism (C), a numerical score from 0 to 10 assigned to each plant species in a local flora that reflects the likelihood that a species is found in remnant natural habitats. Both indices were found to be acceptable ecological indicators of condition, although floristic quality indices were slightly better than the coefficient of conservatism when compared with the overall stress index (Danz *et al.* 2006). The third indicator, the percent of all taxa that are native plants was significantly related to the overall stress index (Danz *et al.* 2006) and it was particularly sensitive to the proportion of row crop area in watersheds draining to coastal wetlands (Brazner *et al.* Ms. 2).

New indicators using the wetland vegetation data (see Appendix A11-13). Each is briefly described below.



Multitaxa wetland vegetation indices

Two indices based on either a 10-taxa index or a 4-taxa index were developed. Each uses mean percent cover estimated in a series of 1 m x 1 m transects spanning a moisture gradient within emergent wetland stands. The indices were both shown to be highly correlated with the stress index that represented a variety of stressors affecting these wetland systems. The indices are relevant to the entire Great Lakes coastal system because the taxa used are all widespread throughout the region.

Maximum canopy height

This index is a relatively simple metric of plant biomass within a wetland. Maximum canopy height of wetland plants as measured during the maximum growth stage in July or August was highly correlated with the stress index. This measurement is related to several factors associated with disturbance in wetland systems, including; 1) fertilization by nutrients contributed by non-point source pollution, 2) invasive plant species that tend to be taller than non-invasive species, and 3) tall plants shade out other plants which results in reductions of plant biological diversity within the wetland. This indicator is relevant to all Great Lakes coastal wetlands and may have applications to many other wetland systems.

Species dominance index (SDI)

This index indicates ecological integrity of wetland ecosystems by identifying dominant plant species and categorizing their behavior as 1 of 7 forms of dominance. The index combines 3 related attributes of dominance in a similar fashion that is commonly used by plant ecologists for the calculation of importance values. Dominance uses 3 attributes: mean plant cover (abundance of the dominant species), mean species suppression (number of species associated with the dominant species), and tendency toward high cover (the likelihood that a species is abundant when it occurs). SDI is calculated like an importance value in which each value is standardized from 0 to 1, summed, and divided by 3. Cut-off values can be assigned for the various forms of dominance in a wetland (see Appendix A13).

E. LAND USE – LAND COVER.

The land use and land change (LULC) assessment was completed as part of the NASA portion of the overall project. We produced a 30 m LULC dataset for the U.S. portion of the Great Lakes watershed for 1992 and 2001. The primary objective was to quantify LULC composition and changes in the watershed between 1992 and 2001 (Wolter *et al.* in press).

Overall, 798,755 ha (2.5%) of the U.S. portion of the Great Lakes watershed changed from 1992 to 2001. The 2 dominant land types in 1992 were forest and agriculture, covering ~ 45% and ~37% of the watershed, respectively. By 2001, each had decreased in area by ~2.3%. Of the changes that occurred in the basin, 49.3% were transitions from undeveloped to developed land. Development (high-intensity, low-intensity, and roads) and most early successional vegetation classes (ESV) (e.g., upland grasses and brush) increased with concomitant decreases in forest and agricultural classes. For instance, low-intensity development increased by 33.5%, high-intensity development by 19.6%, roads by 7.5%, upland brush by 137.4%, upland grasses by 14.7%, and lowland brush by 3.8%, while upland and lowland forest classes all decreased between 1.1% and 2.6%, respectively. Although forest change between 1992 and 2001 was small



on a percentage basis, the area changed was very large -- specifically the decrease in upland hardwoods by ~ 215,000 ha. Low-intensity developments and roads increased in areal extent similar in magnitude to the loss of forest, but the percentage increase was much greater due to the smaller proportion of developed land in the Great Lakes basin. For example, road area increased 7.5% between 1992 and 2001, and was the 4th most dominant LULC type in the watershed, covering ~ 2 million ha.

The 3 most common transition classes of land types were agriculture to human-associated development, forest to early successional vegetation (e.g., logging), and forest to developed. Agricultural to developed conversions represented the category of greatest change (210,068 ha), forestland to early successional vegetation was the second largest transition (180,690 ha), and forest to developed land was the third (154,681 ha).

We also examined changes in the watershed within 3 buffer distances from the shoreline: 0-1 km, 1-5 km, and 5-10 km. Of the 2.5% of watershed area that changed between 1992 and 2001, 4.8% of this total occurred within 1 km of the Great Lakes shoreline. The 1-5 and 5-10 km buffer zones each contained ~ 3% of the total watershed change. LULC transitions between 1992 and 2001 within these near-shore zones of the Great Lakes largely parallel those of the overall watershed. Within the 0-1 km zone from the Great Lakes shoreline, conversions of forestland to both early successional vegetation (9,087 ha, 5.0%) and developed land (8,657 ha, 5.6%) were the largest transitions, followed by conversion of 3,935 ha (1.9%) of agricultural land to developed. For the 1-5 km zone inland from the shore, forest to developed conversion was the largest of the 3 transitions (17,049 ha, 11.0%), followed by agricultural to developed (14,279 ha, 6.8%) and forest to early successional vegetation (13,116 ha, 7.3%). Within the 5-10 km zone from shoreline, transition category dominance was most similar to the trend for the whole watershed with 16,113 ha (7.7%) of agriculture converted to developed, 14,516 ha (8.0%) of forest converted to early successional vegetation, and 14,390 ha (9.3%) of forestland being developed by 2001.

The remaining land use changes were relatively minor, but one change is especially noteworthy. A total of 15,685 ha of wetlands was converted to developed land between 1992 and 2001 within the watershed. A total of 12.8% (2,008 ha) occurred within 1 km of the Great Lakes shoreline, 14.9% (2,337 ha) within the 1-5 km range, and 10.7% (1,678 ha) within the 5-10 km zone. When the 3 buffers are combined, 38.3% (6,007 ha) of wetland conversion to developed land between 1992 and 2001 occurred within 10 km of the Great Lakes shoreline.

F. INTEGRATION SUMMARY

The analysis of 66 indicator response variables for amphibians, birds, diatoms, electro-fish, fyke net fish, macroinvertebrates, and wetland vegetation by lake, province, hydro-geomorphic type, and the stress index revealed that lake was, on average, most important in explaining variation among the variables. This reveals that many of the indicators will need to be developed on a lake-by-lake basis. A surprising result was that hydro-geomorphic type was relatively unimportant for most of the variables, except for macroinvertebrates. Province was also not very important in explaining overall variation, but that was partially because lake and province are high related by common biogeography and lake had slightly better explanatory power over province. Indicators related to birds were among the best explained by the stress index. This



indicates that birds may be among the better indicators that can be related with the stressors included in the overall stress index. In general, these results provide solid guidelines for examination of further relationships among the variables and for the refinement of indicators. These results are summarized more thoroughly in a manuscript that is submitted (Brazner *et al.* Ms. 1).

The second analysis used the same 66 indicator response variables, but focused on further evaluation of stressors and over 5 spatial scales, including 100, 500, 1000, and 5000 m buffers and at the whole watershed scale. At each of these scales, stress was calculated by the proportion of row crop to represent agricultural stress; the proportional sum of low and high intensity urban, commercial/industrial and road surface land to represent human development stress; and an index of point source and contaminant stress to represent pollution. The results indicated that the watershed scale was, in general, the best spatial scale for classifying the indicators. Row crop and human development were more related to the indicators than to the pollution variables, but we emphasize that the major contaminant responses were not included in this analysis. The biotic communities, however, were more highly related with the land use variables (agriculture and human population density/development) compared with pollution sources. These results are also summarized more thoroughly in a manuscript that is in review (Brazner *et al.* Ms. 2).

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Table 1. Environmental indicators developed for the U.S. Great Lakes coastal region. Full descriptions in Appendix A and at <http://glei.nrri.umn.edu>.

Indicator	Measurement method	Description	Appendix
Amphibians of coastal wetlands	Field surveys	Species-based indicator using the responses of amphibians, especially the Spring Peeper, to stress gradients.	A.1.
Birds of coastal wetlands	Field surveys	Species-based indicator of ecological condition using counts of wetland birds across stress gradients.	A.2.
Birds of the coastal zone	Field surveys	Species-based indicator of ecological condition using counts of birds in the coastal zone across a reference gradient.	A.3.
PAH phototoxicity to larval fish	Field, microscopy	This indicator estimates the risk of photo-induced toxicity of PAHs to larval fish populations.	A.4.
Diatom-based chemical inference models	Field, microscopy	Diatom-based models were developed to infer a suite of important coastal parameters, including nutrients, water clarity and salinity variables.	A.5.
Diatom-based water quality condition model	Field, microscopy	This diatom-based model provides an overall inference of water quality at a coastal site.	A.6.
Multimetric diatom index of coastal habitat quality	Field, microscopy	This indicator uses broad taxonomic and functional characteristics of the diatom assemblage to rank a site within the range of habitat disturbance (low to high) in U.S. Great Lakes coastlines.	A.7.
Diatom deformities reflect pollution	Field, microscopy	Developmental deformities in the cell walls of diatoms appear to be related to contamination, and so deformity assessment is proposed as a possible indicator approach for the Great Lakes.	A.8.
Fish indicator indices in <i>Typha</i> -dominated wetlands	Field surveys	<i>Typha</i> -based index of biotic integrity were calibrated against stressor gradients to provide information about sources of impairment.	A.9.
Fish indicator indices in <i>Scirpus</i> (bullrush)-dominated wetlands	Field surveys	<i>Scirpus</i> (bullrush)-based index of biotic integrity were calibrated against stressor gradients to provide information about sources of impairment.	A.10.



Table 1. Environmental indicators developed for the U.S. Great Lakes coastal region. Full descriptions in Appendix A and at <http://glei.nrrri.umn.edu>.

Indicator	Measurement method	Description	Appendix
Multitaxa wetland vegetation indices	Field plots	Indices that use a few selected plant species to evaluate wetland condition.	A.11.
Maximum canopy height	Field measurements	An index of plant biomass in which biomass increases with overall anthropogenic stress.	A.12.
Species dominance index	Field measurements	An index that indicates ecological integrity of wetlands from dominant plant species and their behavior.	A.13.
Land use/land cover change in the Great Lakes basin	Landsat sensor data/GIS	Detection of changes in land use and land cover over time in the Great Lakes basin.	A.14.



II. Project Reports

A. BIRDS AND AMPHIBIANS

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Introduction

Birds and amphibians have been used as indicators of condition of the Great Lakes, especially wetland ecosystems, for several years (Environment Canada and U.S. EPA 2003, Weeber and Vallianatos 2001). Moreover, birds have been used as ecological indicators in a variety of contexts in many parts of the U.S. and Canada (Morrison 1986, Niemi and McDonald 2004).

Our objectives were to: 1) develop a suite of scientifically robust, cost-effective indices of bird and amphibian assemblages that reflect ecological condition of the Great Lakes; 2) quantify the extent to which these indices are related to environmental pressure indicators such as land use characteristics, water quality, presence of exotic species, and hydrological modifications; 3) derive predictive models based on statistical relationship between pressure indicators and indices of bird/amphibian diversity and abundance; 4) use these models to infer ecological conditions at local and regional scales and to establish or improve the baseline for environmental monitoring programs; 5) develop a quality assurance/quality control infrastructure for future assessments of bird and amphibian communities; and, ultimately, 6) provide scientific recommendations for improving and monitoring the ecological health of the Great Lakes basin.

Experimental approach

We evaluated both coastal wetlands and uplands within 1 km of the Great Lakes shoreline using standardized methods that are already in place for the Marsh Monitoring Program (coastal wetlands) or general studies of upland birds (Howe *et al.* 1997). Most sites were sampled during only a single year; our approach was to include an extensive sample including many sites rather than an intensive sample of fewer sites. Approximately 10% of the sites were sampled during both years to provide some indication of annual variation, and a pilot study during 2001 explored alternative sampling approaches. Specifically, we sampled a larger number of points per wetland and additional sampling methods such as timed searches and tadpole traps.

Data collected over the 2-year period provided a basis for multivariate analyses of species' associations and environmental correlates. These analyses were used to develop *probability-based indicators of ecological condition*, that explicitly incorporate species' responses to an independently measured reference gradient of environmental stress. Our approach represents not only a new method for calculating ecological indicators based on birds and amphibians, but an entirely new method for the development of indicators in general.



Bird survey methods

We used a standard protocol established by Ribic *et al.* (1999) to conduct wetland breeding bird surveys during June through early July 2000, 2001, and 2002. Surveys were conducted by trained observers (Hanowski and Niemi 1995) between 0500 and 0930 CSDT, and on mornings with no precipitation and winds below 18 kph. From 1 to 3 half-circle sample points at least 200 m apart were placed in each coastal wetland depending on the area of the wetland complex. Each point was sampled 1 time with an initial 5 minute passive count, followed by a tape playback of several cryptic species, followed by an additional 5 minute passive listening.

Upland birds were sampled in roadside transects within approximately 1 km of the Great Lakes shoreline. A single transect consisted of 15 points at least 500 m apart (Figure 2). At each point, located and documented by a GPS reading, a trained observer conducted a 10 minute, unlimited-radius bird count following the standard protocol of Ralph *et al.* (1995) and Howe *et al.* (1997), a method that is straightforward and easily repeated by trained observers. All counts were conducted between approximately sunrise and 9:00 a.m.

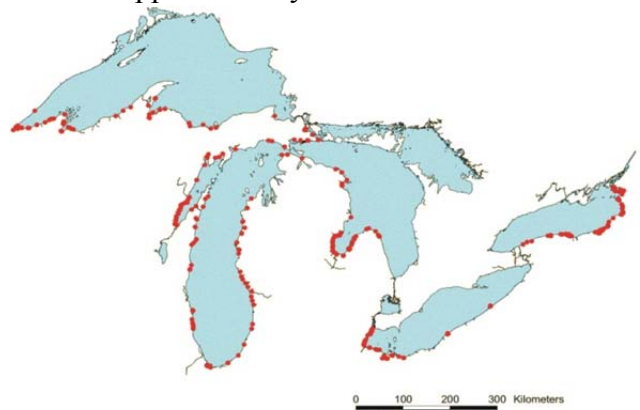


Figure 1. Locations (dots) of coastal wetland study sites for birds and amphibians.

Amphibian survey methods

We followed guidelines outlined by MMP for conducting amphibian calling surveys at the same points that were sampled for wetland breeding birds (Weeber and Vallianatos 2001). Three calling surveys were conducted at each site following MMP temperature guidelines. Surveys started 1-half hour after sunset and were completed before midnight. Each survey was 3 minutes in length and conducted in good weather conditions (light winds and no precipitation). We assigned calling level codes to the detection of each species. Data from all analyses were entered into a Microsoft Access database and then double-entered to assure accuracy.

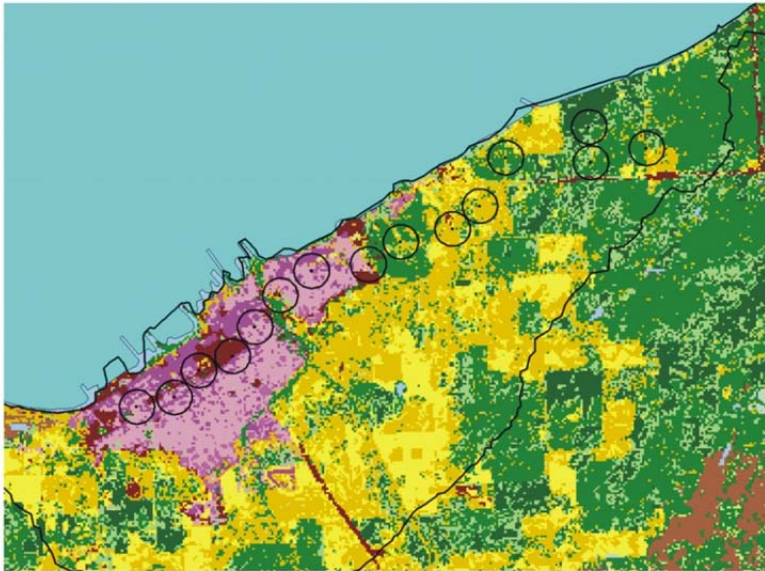


Figure 2. Upland bird survey route near Ashland, WI, consisting of 15 points at least 500 m apart. Bird survey points (black dots) are encircled by 500 m GIS buffer, within which we evaluated the proportion of land cover types. Colored pixels represent land cover classes developed by Wolter et al. (2006).

Results

The overall distribution of sites sampled for birds and amphibians spanned the entire U.S. Great Lakes coastal region (Figure 1). We sampled a total of 220 wetland complexes for amphibians from 2002 to 2003 which included a total of 331 individual points (Table I). Similarly, a total of 224 wetland complexes were sampled for birds, including 338 individual points sampled. In contrast, 171 upland coastline segments were sampled with a total of 2,544 individual points (15 points per segment). Overall, this represented a sample of approximately 1/3 of the

available segment sheds and over 30% of the wetland complexes within the U.S. Great Lakes coastal region.

Cost effectiveness

In the 2001 pilot study we tracked the labor and travel costs to complete a sample for amphibians, wetland birds and upland birds. We found that, on average, a sample of 15 upland points costs approximately 4 times as much to complete compared to a wetland bird survey, and that an amphibian sample was approximately 3 times more costly than a wetland bird sample. The pilot study also indicated that 3 point samples were optimal from a cost-benefit perspective for sampling larger coastal wetlands.

Amphibians

We recorded at least 12 species of frogs and toads, 3 of which were observed at fewer than 5 and another (Mink Frog, *Rana septentrionalis*) at only 11 of the 361 point counts (Figure 3). The most commonly reported

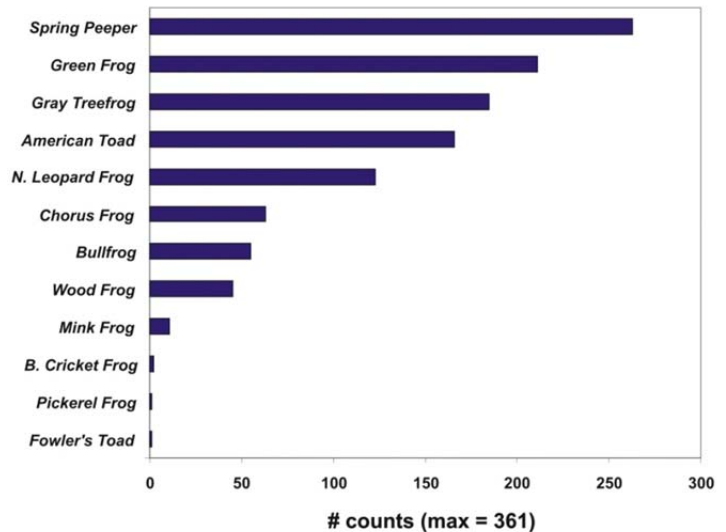


Figure 3. Amphibian species observed in coastal wetland study sites. Width of bar is proportionate to the number of points (of 361) at which the species was recorded. Copes Gray Treefrog (*Hyla chrysoscelis*) and Eastern Gray Treefrog (*Hyla versicolor*) were combined as Gray Treefrog.

Table I. Distribution of study sites among taxonomic groups and lakes during 2002-03.



Lake	Amphibians		Upland Birds		Wetland Birds	
	Segments	Points	Segments	Points	Segments	Points
Erie	24	41	33	489	24	41
Huron	47	61	22	330	47	61
Michigan	74	114	55	824	73	113
Ontario	34	61	18	254	35	61
Superior	41	54	43	647	45	62
	220	331	171	2544	224	338

species was Spring Peeper, followed by Green Frog (*Rana clamitans*), Gray Treefrog (*Hyla versicolor* and *Hyla chrysoscelis*), American Toad (*Bufo americanus*), Northern Leopard Frog (*Rana pipiens*), Chorus Frog (*Pseudacris maculata* and *P. triseriata*), Bullfrog (*Rana catesbeiana*), and Wood Frog (*Rana sylvatica*). Distributions of most species showed clear geographic variation between the northern Laurentian Mixed Forest Ecological Province and the southern Eastern Deciduous Forest Ecological Province (see below). A typical coastal wetland point yielded 3 to 5 anuran species, with somewhat higher numbers in Lakes Ontario and Huron and lower numbers in Lakes Erie and Superior (Figure 4).

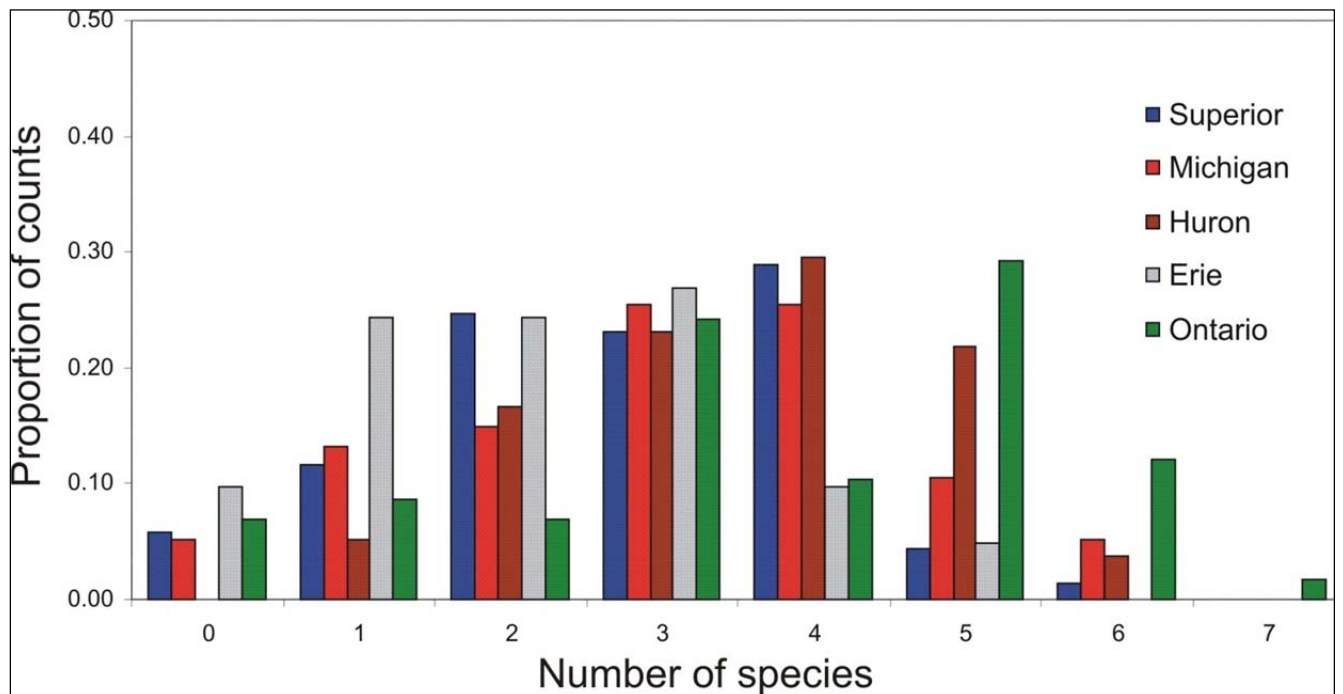


Figure 4. Distribution of species richness among amphibian point counts in different lakes. Values for each count combine all 3 survey dates.



Documented relationships between species and independent measures of environmental stress, critical for developing meaningful environmental indicators, were variable both among anuran species and among geographic areas for the same species. We used a multivariate analysis of remote-sensed land cover variables (Wolter *et al.* in press) and other measures associated with human environmental impacts (Danz *et al.* 2005) to develop an index of environmental stress or “reference condition” ranging from 0 (most degraded) to 10 (least degraded). Sites were grouped into categories of similar reference condition (e.g., 0-0.5, 0.5 – 1.0, 1.0 – 1.5, etc.), and the frequency of each anuran species was plotted against the 0 – 10 environmental gradient. Results reflected the north-south variation in abundance within species (Figure 5) as well as the sensitivity of different species to environmental stress.

Strongest (positive) response to the reference gradient was exhibited by Spring Peeper (Figure 5), that was the only species to show a consistent relationship to environmental stress in both the northern and southern ecological provinces. Bullfrog showed a strong negative relationship with condition in the northern ecological province, but showed little or perhaps a slightly positive relationship in the southern province. Likewise, American Toad showed a positive relationship with condition in the northern province (like Spring Peeper), but the opposite relationship in the southern part of the Great Lakes.

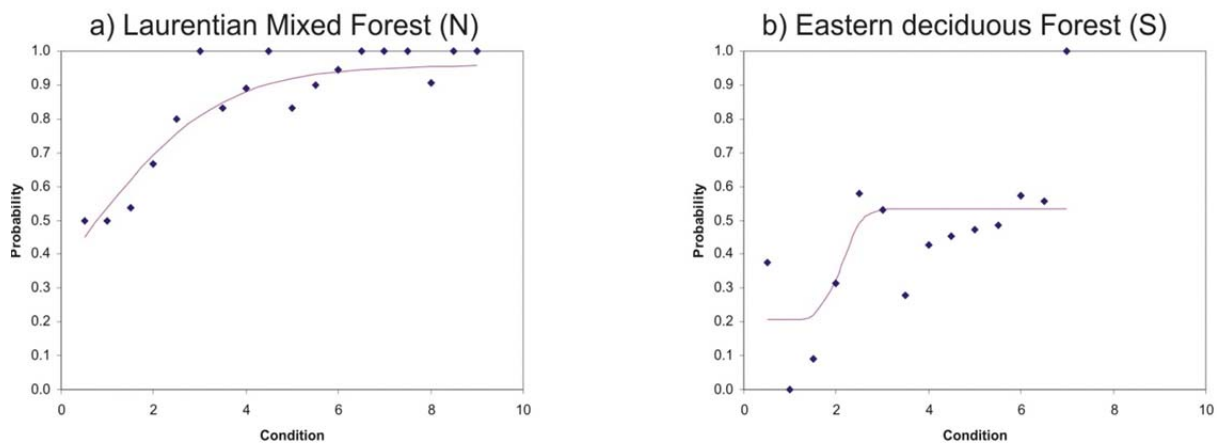


Figure 5. Relationship between frequency of occurrence (= Probability) of Spring Peeper in coastal wetlands characterized by different degrees of human impact. Sites with low values of condition, measured by multivariate analysis of land cover, pollution emissions, agricultural intensity, and other environmental impacts, are characterized by high levels of environmental stress or degradation, while sites with high values of condition are characterized by low levels of environmental stress.

These anomalies warn against the application of anuran-based indicators across the entire Great Lakes basin. The fact that some species show positive response to condition, while others show a negative response, also suggests that anuran species richness is a poor indicator of environmental condition in the Great Lakes coastal zone, at least with respect to the reference gradient used in our analysis. A direct analysis of species richness (Figure 6) confirms this advice.

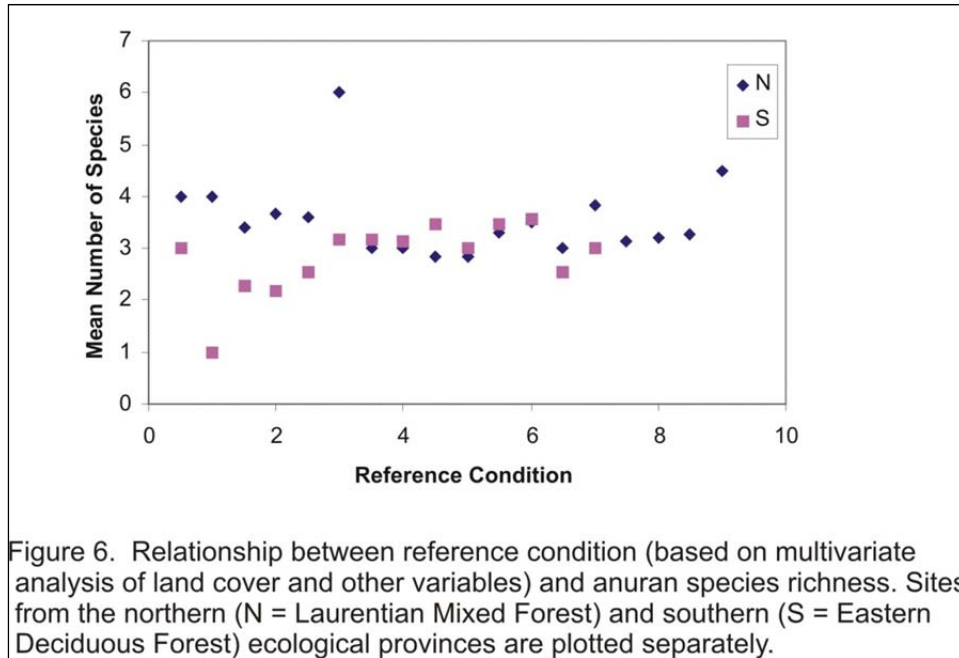


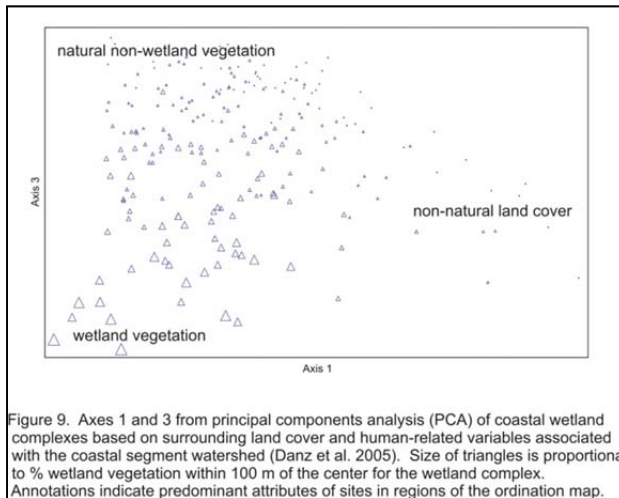
Figure 6. Relationship between reference condition (based on multivariate analysis of land cover and other variables) and anuran species richness. Sites from the northern (N = Laurentian Mixed Forest) and southern (S = Eastern Deciduous Forest) ecological provinces are plotted separately.

Application of these species/environmental stress relationships to the development of anuran-based indicators is in progress. Our general approach to indicator development is described in the section on birds of coastal wetlands. Based on the data presented here, the abundance or frequency of Spring Peepers is the simplest and most reliable indicator across the U.S. portion of the Great Lakes coastal zone.

In a more intensive investigation of anurans in Lakes Michigan and Huron, Steven Price led an evaluation of the relationships between anuran frequencies and a broader range of land cover variables, including measurements collected directly at the wetland survey points. Like our general analysis, Price's analysis (Price *et al.* 2005) also used remote sensing data from Landsat 5 and Landsat 7 imagery. We found that most (but not all) anuran species were most sensitive to land cover variables measured at rather large geographic scales (3 km radius). For nearly every species, variables associated with urbanization (residential development, road density, etc.) showed a negative relationship with anuran frequency of occurrence. These results suggest that the reference gradient used in our general analysis might include variables that have confounding effects on anuran/environment relationships.

Wetland birds

Wetland birds were sampled at 371 points in 215 wetland complexes, nearly all of which also were the part of the amphibian survey. The most frequently recorded species, Red-winged Blackbird, was more than 3 times more abundant than the second most commonly recorded species (European Starling). Other common birds in the coastal wetland samples included (in decreasing order of abundance) Canada Goose, Herring Gull, Ring-billed Gull, Yellow Warbler, Common Grackle, Common Yellowthroat, Tree Swallow, and Song Sparrow. Because these species are so ubiquitous, they provide little information about the environmental condition of a given wetland.



The majority of the 155 bird species recorded in coastal wetlands were much less common than these 10 abundant species. A typical 10 minute census using the standard marsh monitoring protocol (Ribic *et al.* 1999) yielded between 11-18 species, often more than 20. The richness and familiarity coastal wetland bird species therefore

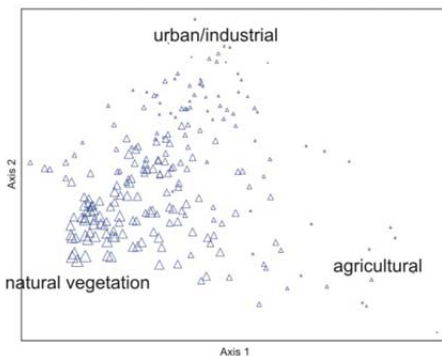


Figure 8. Axes 1 and 2 from principal components analysis (PCA) of coastal wetland complexes based on surrounding land cover and human-related variables associated with the coastal segment watershed (Danz et al. 2005). Size of triangles is proportional to % natural non-wetland vegetation within 500 m of the center for the wetland complex. Annotations (natural vegetation, agricultural, urban/industrial) indicate predominant attributes of sites in different regions of the ordination map.

et al. (2005) and proportion of land cover in 6 classes (natural non-wetland, wetland, residential, commercial/industrial, agricultural, and roads) within different radii from the center of the complex (100 m, 500 m, 1 km, and 5 km). Variables were chosen because they could be ordered on a scale from most-impacted to least-impacted by human activities or from highest proportion wetland area to lowest proportionate wetland area. Results (Figures 8 and 9) yielded 5 interpretable axes that explained 68% of the variation in the original variables. Scores on each of the axes, ordered from most-impacted by humans to least-impacted by humans (or lowest proportion wetland to highest proportion wetland), were weighted by the proportion of variance explained and combined to form a single gradient of ecological condition ranging from 0 (highly degraded non-wetland) to 10 (minimally degraded wetland).

Given the reference gradient, we plotted frequencies of occurrence of bird species in different categories of sites (condition = 0-1, 1-2, 2-3, etc.). The results, which we call *SSD functions*, can

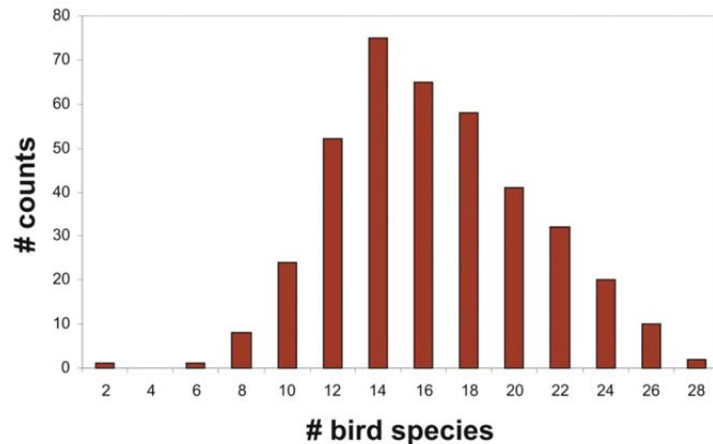


Figure 7. Numbers of bird species recorded in standard point counts in Great Lakes coastal wetlands during 2002-03. # of counts = the number of point counts (of 371) with the given number of bird species (0-2, 3-4, 5-6, 7-8, etc.).

provide outstanding opportunities for developing indicators of ecological condition in the Great Lakes coastal zone.

We again used the multivariate-derived “reference gradient” of wetland complexes to identify species that exhibit consistent responses (positive or negative) to environmental stress. This reference gradient was established through a PCA of 39 environmental variables, including previously derived PCA scores from the analysis of Danz



be modeled by a 4 parameter mathematical expression describing the probability of observing the species when condition = 0, the probability of observing the species when condition = 10, the value of condition where the probability of observing the species is halfway between the minimum and maximum probabilities, and the steepness of the non-linear relationship. The SSD functions take into account both the sensitivity of the species to environmental stress as well as probability of observing the species even in optimal conditions. We used an iterative procedure in Microsoft Excel to estimate best-fit parameters for species that were observed in at least of the 10 of the 371 point counts. From 41 species that showed significantly significant relationships with the nonlinear SSD model ($r > 0.433$, $p < 0.05$) we selected 25 wetland or open country species calculating site-specific indicator of ecological condition. We excluded forest species, colonial nesters, and most species of open upland habitats, although several birds with broad habitat preferences (e.g., American Crow, American Goldfinch) were included in the list of 25 species. Sandhill Crane, American Bittern, Sedge Wren, Common Yellowthroat, and Yellow Warbler showed strongest positive associations with the reference gradient, while Mallard, Common Grackle (Figure 10b), and European Starling showed strongest negative relationships. The shapes of the best-fit SSD functions varied according to the ecology and overall abundance of different species. Bald Eagle, for example, showed a rather low probability of occurrence even at optimal condition, whereas

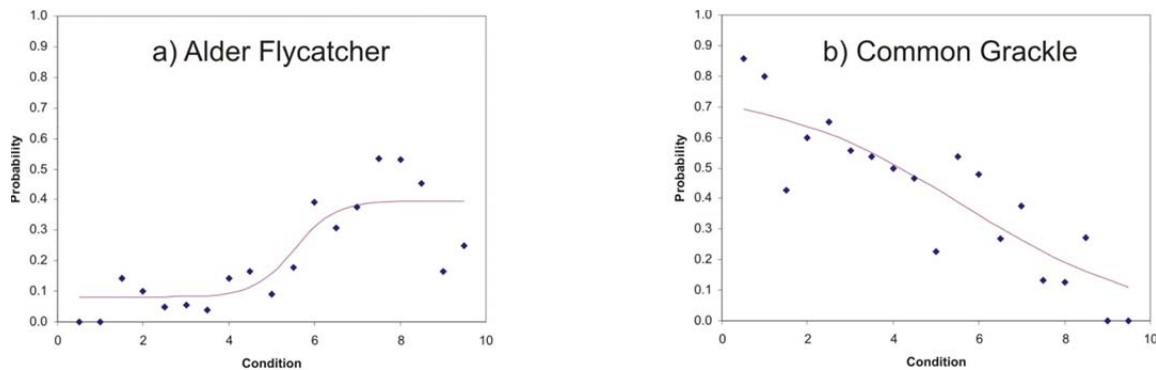


Figure 10. Species-specific sensitivity/detectability (SSD) functions for Alder Flycatcher, a sensitive species whose presence indicates high values of ecological condition and Common Grackle, a tolerant species whose absence indicates high values of condition.



the more abundant Swamp Sparrow, which also exhibited a positive relationship with reference condition, is somewhat likely to occur even in rather degraded sites. Armed with parameter estimates for the SSD functions of 25 species, we calculated bird-derived values of ecological condition for 20 sites that had been excluded from the analysis used to calculate the SSD functions. Our new, probability-based ecological indicator (C_{obs}) can be derived from presence/absence data for the 25 target species at a given site. Rather than use the standard method of adding or multiplying weightings to produce an index, however, our method “works backward” from the observed data, using an approach pioneered by Hilborn and Mangel (1997). In other words, we use computer iteration (e.g., the solver function in Microsoft Excel) to ask: “What is the value of C_{obs} , ranging from 0 to 10, that best fits the observed presence/absence data and the previously derived SSD functions?” Results have proven to be remarkably robust and provide insights beyond the information inherent in the reference gradient. A plot of reference condition (C_{ref}) calculated from environmental variables against ecological condition (C_{obs}) based on bird occurrences (Figure 11) shows that the 2 measures can be significantly different. For example, values of ecological condition (C_{obs}) for sites with moderately low environmental condition ($C_{ref} = 1-5$) generally were much lower than the corresponding values of C_{ref} , perhaps reflecting a threshold of environmental condition, below which bird species occur less frequently than expected based on environmental variables alone.

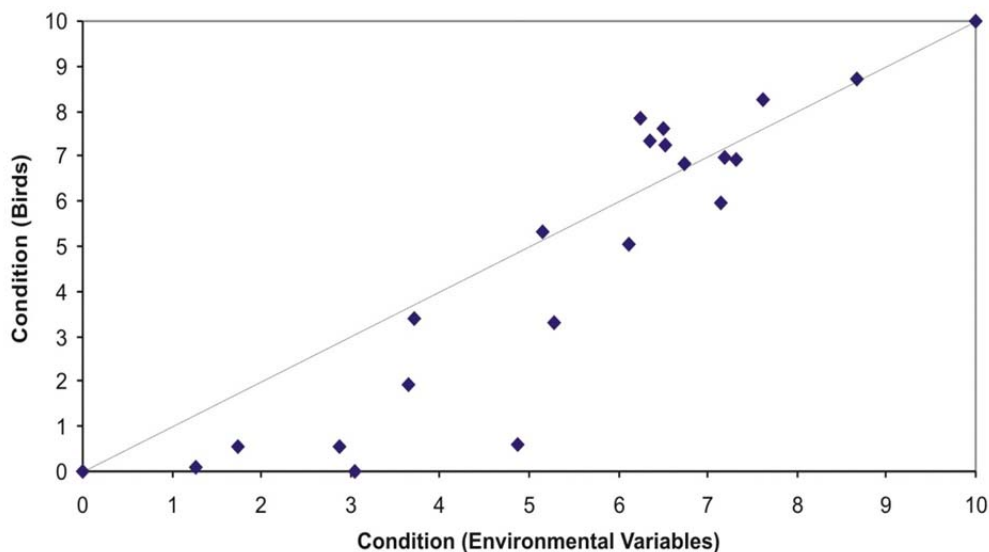


Figure 11. Comparison of reference condition (C_{ref}) based on multivariate analysis of land cover and other environmental variables with ecological condition (C_{obs}) based on presence/absence of 25 selected bird species

Upland birds

We identified 187 bird species in the survey of 171 coastal segments, each sampled with a route of 15 standard ten-minute point counts. To assess annual variation in species composition, 23 of the routes were sampled during both 2002 and 2003. In total, this phase of the project evaluated 2544 separate point counts. Although we refer to the census results as upland bird assemblages, the species included birds of wetlands, forests, urban areas, and all habitat types located within approximately 1 km of the shoreline. Like most biotic assemblages, birds of the Great Lakes coastal zone followed a log-normal distribution of relative abundance (Figure 12), with relatively few abundant species and many species with moderate to low relative abundance.

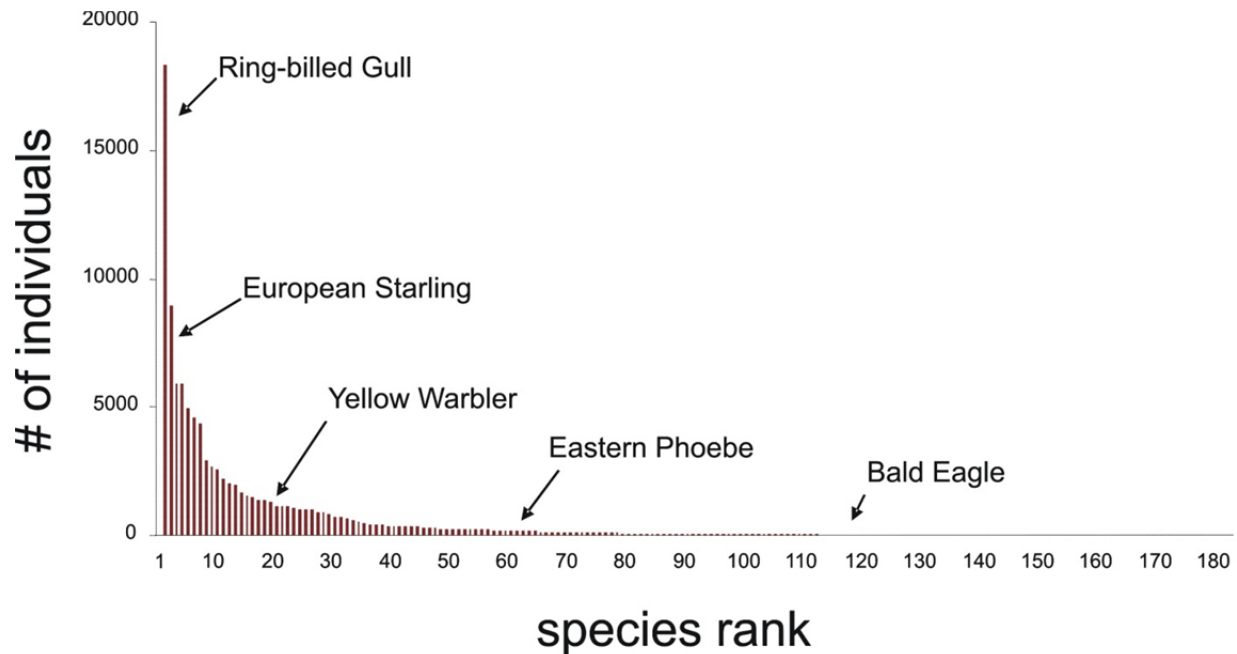


Figure12. Rank abundance diagram of bird species observed in 2544 roadside bird counts within approximately 1 km of the Great Lakes shoreline. Representative species are shown with arrows pointing toward the corresponding bar. Number of individuals refers to the total number of birds reported in all point counts combined.

The most abundant species (Ring-billed Gull, European Starling, Herring Gull, American Crow, House Sparrow, American Robin) were familiar birds of urban and suburban environments in both the northern Laurentian Mixed Forest Ecological Province and the southern Eastern Deciduous Forest Ecological Province. Other species differed substantially between the 2 geographic provinces, however (Figure 13), warranting a separate analysis of ecological indicators for each region.

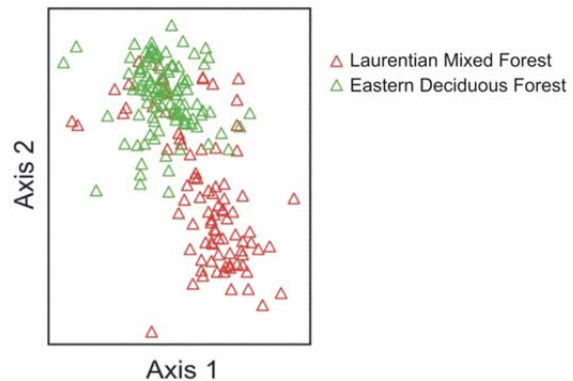


Figure13. Ordination (non-metric multidimensional scaling) of coastal segments based on bird species composition in standardized survey routes.

Like our analysis of coastal wetlands, we calculated “reference condition” for sites based on environmental attributes, in this case the proportional area in 6 general land cover classes within 100 m, 500 m, 1 km, 3 km, and 5 km of the 15 bird survey points. PCA was used to generate a single gradient ranging from 0 (maximally impacted by human activities) to 10 (minimally impacted by human activities).

We plotted the proportion of points (maximum = 15) at which the species was recorded against the reference condition for each route, excluding 20 routes for later validation of the model. These relationships (e.g., Figure 14) were used to estimate 4-parameter SSD functions (Howe *et al.* in prep). Statistically significant SSD functions ($p < 0.05$) were derived for 72 bird species in the northern (Laurentian Mixed Forest) ecological province and for 50 bird species in the



southern (Eastern Deciduous Forest) ecological province.

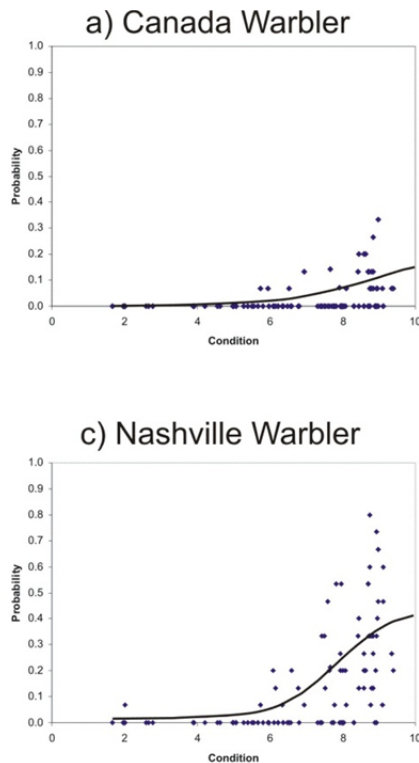


Figure 14. Species-specific Sensitivity-Detectability (SSD) c) Nashville Warbler, and d) American Robin in the Lauren illustrate the best-fit, four parameter mathematical function the proportion of points (max. = 15) at which the species v gradient based on land cover, ranging from 0 (maximally ii

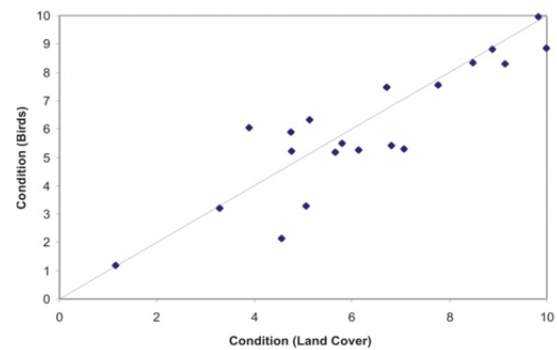


Figure 15. Correlation between ecological condition based on bird species composition (y axis) and reference condition based on land cover variables (x axis) in Great Lakes coastal segments. The 20 sites (*) were not included in calculations of Species-specific Sensitivity-Detectability (SSD) functions.

Once parameters of SSD functions were established, the ecological condition of new sites could be calculated through iteration (Hilborn and Mangel 1997). In this case, we derived the value of condition (C_{obs}) that yielded the closest fit between observed species frequencies (among the 15 bird census points) and the predicted frequencies given the species' SSD functions. We applied this method to the 20 sites withheld from the derivation of SSD functions. Results again illustrated a close fit between reference condition and bird-based condition (Figure 15), but biologically meaningful deviations were evident.

Summary and Recommendations

Our analysis provides not only robust and flexible ecological indicators for the Great Lakes coastal zone, but we propose a framework for developing biotic indicators anywhere and for any group of species. Details of our approach, including parameter estimates for applying the method to Great Lakes coastal wetlands and coastal segments, are contained in 2 manuscripts included in this report, one submitted for publication and the other soon to be submitted.

The recipe for applying this method is very simple, although the preliminary work of deriving SSD functions (which we have done for birds and amphibians) requires a large scale data set for



the region of interest. To calculate ecological condition for specific sites, a manager or researcher only needs to provide a list of species observed in 1 or more counts like the ones used to develop the SSD functions (in this case, standard point counts). If the site can be sampled multiple times (e.g., at different points or at different times), then probabilities of occurrence can be provided for each species, ideal input for the calculation of ecological condition. The solver function in Microsoft Excel can be used to derive values of condition. Eventually, we hope to provide a web-based utility that will enable any user with field data to generate estimates of condition for sites of interest. Selection of species for deriving the estimate might be expanded or limited based on the nature of the field work or the range of habitats sampled. In all cases, however, the estimates of condition will be developed in the framework of a standard scale from 0 to 10 and in the context of an explicit reference gradient.

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B. CHEMICAL INDICATORS

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Introduction

Our **overall goal** was to identify and validate effective contaminant indicators of adverse impacts on estuarine ecosystem health. Indicators were developed in the Great Lakes, but are also applicable to both marine and freshwater ecosystems. These contaminant indicators will be used to evaluate ecological condition. Specifically we focused on the evaluation of 2 indicators: 1) indicator PAHs of photo-induced toxicity to fish and benthic organisms; and 2) organic chemical indicators of xenoestrogenic exposure to fishes. Our final analysis produced an indicator for PAH photo-induced toxicity to fish.

The assessment of ecological condition in an effective manner is best accomplished using integrative indicators of condition. These indicators should be cost-effective, applicable across multiple scales, and provide useful information for environmental managers. Within the omnibus project, this contaminants subproject focused on contaminant indicators that could provide a measure of the condition of the estuarine ecosystem. These indicators also served as diagnostic indicators that will identify the primary stressors affecting the specific ecological endpoint of concern. We have focused on PAH compounds and environmental estrogens since they are ubiquitous in the environment and have existing sources, and thus are of current concern.

The **specific hypotheses** we tested were: 1) specific PAHs in combination with UV penetration are indicators of potential loss of vulnerable species within coastal fish and/or benthic communities; and 2) specific chemicals are indicators of endocrine disruption in fish via the estrogen receptor. Data collected to test these hypotheses was used to demonstrate the degree of usefulness of these 2 groups of indicator compounds as diagnostic indicators for estuarine ecosystems.

Our **overall approach** to this project is summarized as follows. For both indicators, we compared contaminant concentrations to a biological endpoint or condition across a gradient of non-degraded to highly degraded sites in approximately 25 locations that were studied by the other indicator project groups in the program. For the PAH photo-induced toxicity indicator, we collected the necessary field data to test the model developed in the lab by the collaborators at EPA MED. These data included the concentrations of PAHs in sediment, larval fish, and oligochaetes (to determine the sediment-biota accumulation factor (BSAF) and to provide the doses for the model); sediment photo-induced toxicity potential (assayed in the lab using the aquatic annelid *Lumbriculus* [lab test organism] and field sediments); and UV dose (obtained from field measurements). The toxicity that was predicted from the model was compared to that measured in the lab assay. Results were used to calibrate the model, and to provide guidance and boundaries for how this model can be applied as an indicator.

The xenoestrogen indicator was examined in an analogous manner. Our intent was to measure a suite of potential xenoestrogens in fish tissue, sediment, and/or water and compare them to vitellogenin induction in wild and caged male fish (a bioindicator of individual estrogen exposure) at the same gradient of sites. The low levels of contaminants except near point sources combined with the complexity of the biological response from xenoestrogen exposures prevented acceptable development of a simple indicator of xenoestrogen impacts.



Summary: PAH Phototoxicity

The indicator that we have developed is one that managers can use to estimate whether larval fish populations at a given site are potentially at risk from photo-induced toxicity. Photo-induced toxicity of PAHs to larval fish is a function of exposure to both PAHs and ultraviolet-A (UV-A) light (Figure 1). Users of this indicator will need to estimate PAH exposure to fish by measuring specific PAH compounds in sediment, and estimate UV-A dose by measuring absorbance of water with a spectrophotometer and measuring suspended particulate matter gravimetrically. These measurements are then put into a simple model that provides an estimate of the risk of photo-induced toxicity.

UV-A exposure depends on factors such as light intensity, dissolved organic carbon and total suspended solids. We have developed a model for measuring UV-A attenuation in the water column of the coastal Great Lakes. This model involves the measurement of spectral attenuation using a spectrophotometer (a simple piece of equipment common to most laboratories) and suspended particulate matter. Due to the ease of the measurements and incorporation of the influence of suspended particulate matter on attenuation we have created a useful tool for managers of the coastal Great Lakes. Our method can be used to evaluate the UV-A exposure setting at other sites around the Great Lakes and more importantly, predict how changes in suspended particulate matter might affect UV-A attenuation. For instance, the introduction of zebra mussels has dramatically reduced the amount of suspended particulate matter in the coastal areas and, therefore, may have a commensurate increase in UV-A exposure to larval fish in those areas (Adams 2005). Two field measurements are needed, suspended particulate matter (SPM) and the irradiance attenuation coefficient from 334 nm to 370 nm ($K_{a334-370}$). The SPM is determined by filtering 1 L of surface water through a pre-weighed 0.4 μ m polycarbonate filter,

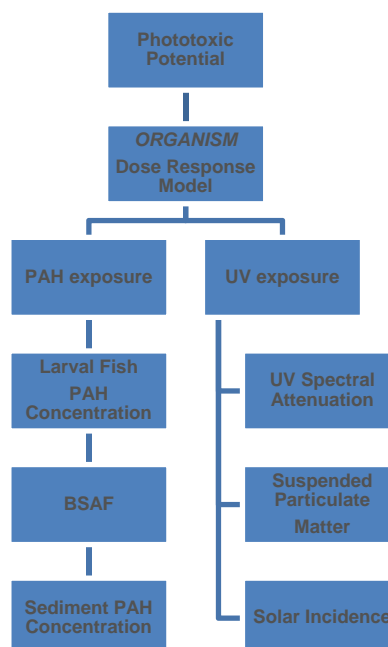


Figure 1. Overall model of indicator for photo-induced toxicity of PAHs to aquatic organisms.



drying the filter to constant weight, and dividing the dry mass of particulates by the exact volume of water filtered. $K_{a334-370}$ is determined by filtering approximately 250 mL of surface water through a 0.7 pre-combusted glass fiber filter and measuring the absorbance from 280 nm to 400 nm at 2 nm intervals, across a 1-cm pathlength, and relative to a blank containing organic-free water. The $K_{a334-370}$ is then calculated according to Adams (2005). K_d is then estimated as follows:

$$K_d = 1.55 (K_{a334-370}) + 0.204 (\text{SPM}) + 0.656$$

The UV-A dose is calculated as $(2800 \text{ uW/cm}^2 * 0.935 * 14/24 * 0.75 * T)$, where T is the fraction transmittance at 10 cm in the water column for a given UV absorbance measurement. The percent transmittance is calculated as $T = e^{(-K_d * \text{depth}/100)}$. The equation above is the product of the midday intensity * surface reflectance * hours of sun * cloud factor correction * T.

PAH exposure is a function of partitioning of PAHs from the water column into larval fish, and usually the PAH in water is a result of partitioning from contaminated sediments to water. Because PAHs are more readily measured in sediments compared to water, we are using the concept of BSAF. The BSAF describes the relationship between PAHs in lipids of biota and PAHs in sediment organic carbon, and is expressed as the ratio of the lipid-normalized concentration of PAHs in biota to the organic carbon normalized concentration of PAHs in sediment. We collected sediments and larval fish at each of our study sites and measured the BSAFs to test whether this approach would work for this indicator. The BSAFs for 2 compounds, fluoranthene and pyrene, were the most consistent across sites, and are incorporated into our indicator. It is assumed that this BSAF is representative for coastal sites throughout the Great Lakes. Thus the user of the indicator will measure a suite of 9 photo-toxic PAHs and organic carbon in sediments, normalize them to the organic carbon fraction of the sediment, multiply their sum by our measured BSAF of 0.16 to estimate the sum of photo-toxic PAHs in fish lipid, and multiply the value by the lipid fraction of the larval fish of interest (10% is a good default). This gives a photo-toxic PAH concentration in the fish tissue, in dry mass concentration. The 9 PAHs that are phototoxic are dibenzothiophene, anthracene, 4methyl dibenzothiophene, 2methylanthracene, 1methylanthracene, 9methylanthracene, 9,10dimethylanthracene, fluoranthene, pyrene, benz[a]anthracene, benzo[b]fluoranthene and benzo[a]pyrene.

Once the UV-A dose and photo-toxic PAH concentration are estimated, they can be used to calculate an LT-50, meaning the time (in hours) that it takes for 50% of the population to die. This is done by dividing the mean potency coefficient for the phototoxic PAHs (63,000; from EPA-MED) by the product of the photo-toxic PAH concentration and the UV-A dose, and to obtain a photo-toxic potency. The inverse of this value is the LT-50.

$$\text{LT-50, hrs} = 63000 / [(\text{PAH conc, ug/g dw}) * (\text{UV-A, uW/cm}^2)]$$

To provide a context and further interpretation for this LT-50, it is useful to consider 2 graphs. The first graph is a plot of the predicted LT-50 as a function of depth in the water column, for the fixed UV-A dose for that site (see Figure 2 for an example). This provides information as to how



the risk of photo-induced toxicity might vary with depth in the water column. Thus one can relate the actual depth of light penetration at the specific site to risk. This is a useful graph on a site-specific basis.

To compare the risk across sites, one can prepare a second graph that plots photo-toxic PAH concentration versus UV-A dose, assuming a given light penetration depth (we used 10 cm as a default). The isopleths on this plot are LT-50s (see Figure 3). An LT-50 greater than 300 hrs is not considered to be a risk, as the repair mechanisms are likely activated by this time and should offset the photo-toxic cell damage. One can plot the data for several sites and see if they fall above or below the isopleth for $LT-50 = 300$ hrs.

This indicator can be used to prioritize sites for further investigation – where calculated LT-50s are small (<100 hrs), further investigation may be warranted; where calculated LT-50s are very large (>1000 hrs) there is minimal risk and additional investigation may not be warranted.

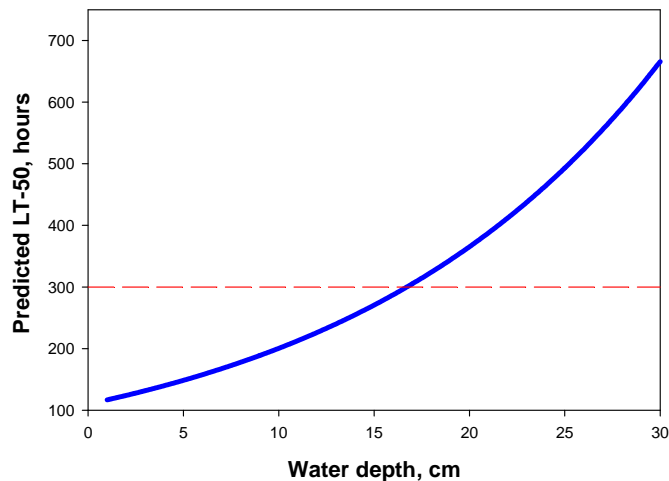


Figure 2. The effect of changing the UV-A dose (by varying the depth of light penetration) on the predicted LT-50 for a constant PAH concentration (500 ng/g) and moderate light attenuation ($K_d = 6$). A predicted LT-50 greater than 300 is indicating there

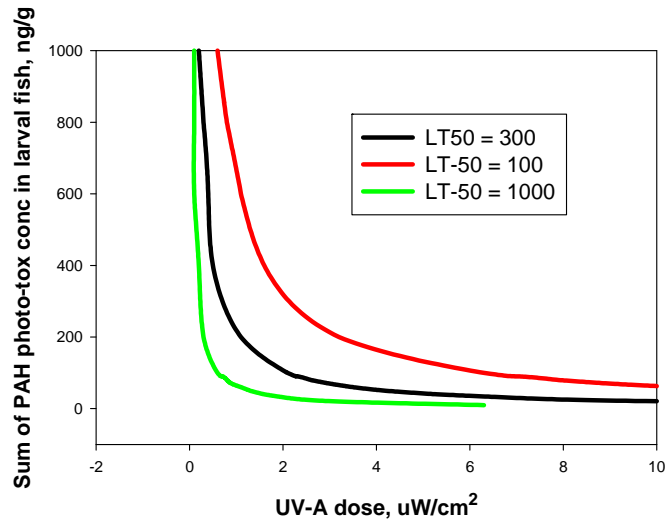


Figure 3. Relationship of varying PAH and UV-A exposures (assuming constant depth of 10 cm), with isopleths indicating predicted LT-50s of 100, 300, and 1000 hours for reference.

Validation of indicator

We have calculated the LT-50s for all the sites that were sampled as part of our field work, and the results of this are shown in Figure 4. This analysis assumed a constant depth of 10 cm, and actual risk for photo-induced toxicity would depend on actual light transmission with depth. Approximately half of our sites had predicted LT-50s less than 300 hrs, indicating that these sites have potential risk for photo-induced toxicity of larval fish.

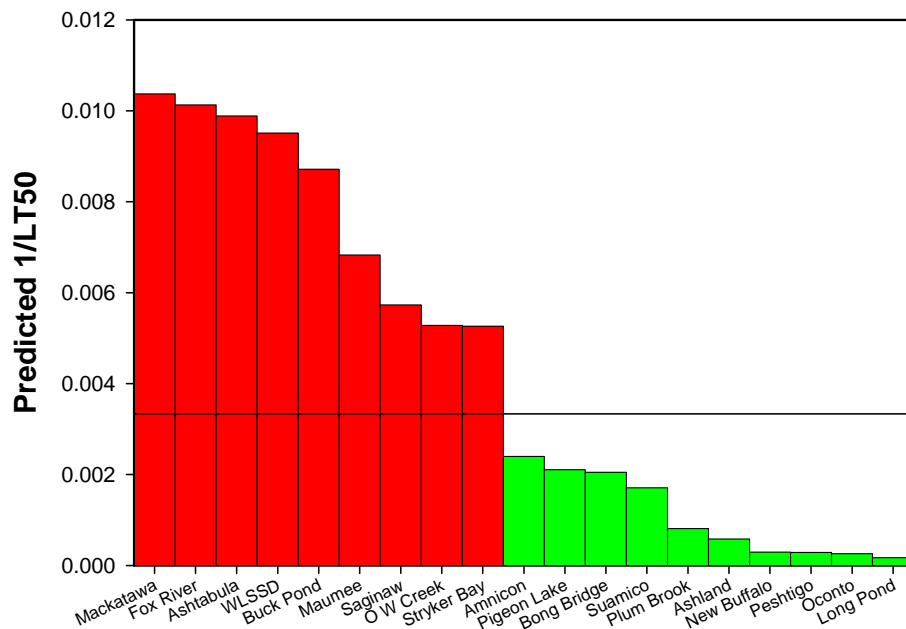


Figure 4. Calculated potency (1/LT-50) of PAHs to larval fish at sites around the Great Lakes. The red bars indicate a potential risk of photo-induced toxicity to larval fish. It was assumed that light transmission was to 10 cm.



Summary: Environmental Estrogens (EEs)

An indicator of estrogenicity was not developed. We provide an assessment of why this indicator failed to be transferred from the lab to the field. Two manuscripts from the PhD dissertation of Randy Lehr address these issues, and are summarized below.

The first manuscript provides a comprehensive review and critical assessment of the tools that have been developed to assess estrogenic exposures and response in fish, from the measurement of chemical concentrations in fish tissue to the proteomic and genomic measurements that indicate a response at the cellular or molecular level. To establish exposure-effect relationships, researchers have identified several measurement endpoints that characterize signal transduction at many intermediary steps throughout the estrogen response pathway. However, development of these assays has not followed a standardized approach and different measurement endpoints have been quantified using different analytical techniques and exposure scenarios. As a result, the sensitivity and diagnostic and predictive potential for these assay systems is different. In general, assays that characterize estrogen signal transduction at lower levels of biological organization are the most amenable to high throughput and diagnostic analysis, but the poorest predictors of potential effects at individual and population levels. Conversely, assays that characterize estrogen signal transduction at higher levels of biological organization are the best predictors of potential effects, but the least amenable to high throughput, diagnostic analysis. This complicates the linkage of exposure and effect using a single endpoint and requires the analysis of multiple endpoints to mechanistically link exposure and effect. This approach is recommended, but is not amenable to adopt as a monitoring approach for the end-users of this project. At the beginning of this project, the complexity of the estrogen response pathway was not fully appreciated, nor were these tools fully developed.

Another manuscript was directed at providing advice to environmental managers who wish to monitor for environmental estrogens (EEs). Management of chemical contaminants is highly dependent upon the establishment of exposure-effect relationships. Establishment of exposure-effect relationships for EEs is complicated by many factors and as such, the management of EEs presents several challenges. To aid the management process, researchers have developed a variety of assays to establish exposure-effect relationships and each of these assays is likely to be best suited for different aspects of the management process. Assays that quantify exposure and effect at higher levels of biological organization integrate EE exposure and are likely to be more appropriate for assessment of ecosystem condition and long-term monitoring. Assays that assess exposure and effect at lower levels of biological organization are more mechanistically diagnostic and thus, likely to be more appropriate for the identification of specific chemicals of concern and design of management interventions. The unique physical-chemical and toxicological properties of EEs also affect the design of management plans and the ability to communicate management results.

In summary, the complexity of the estrogen response pathway necessitates having indicators that can both assess exposure, and assess an integrated measure of the response elicited as a result of that exposure. The tools available do not do both of these well, and a monitoring program requires the use of multiple tools to assess exposure as well as assess specific and integrated responses to provide the link of exposure and effect. Furthermore, tools are needed to bridge the assessment of individuals to populations and communities. These tools are largely still in the



research and development phase, and few have been used effectively to assess effects of EEs to fish populations in the field.

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C. DIATOMS AND WATER QUALITY

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Introduction

Developing effective indicators of ecological condition requires that indicators be calibrated to identify their responses to important environmental stressors (Karr and Chu 1999, Seegert 2001, Niemi and McDonald 2004). The main goals of calibration are to identify environmental optima and tolerances of indicator taxa, and to define systems with similar biota that respond similarly to anthropogenic stresses (e.g., Radar and Shiozawa 2001). Calibrated bioindicators are particularly needed to monitor the impacts of human activities that increase the nutrient supply to water bodies, giving rise to cultural eutrophication, a human-driven process that has numerous adverse effects (Carpenter *et al.* 1998a, b). Phosphorus and nitrogen compounds from agricultural and urban activities are universally recognized to be the major causes of cultural eutrophication. Of the large suite of potential bioindicators, diatom algae are popular because the taxa have definable optima along gradients of environmental conditions. In addition, the diatoms are taxonomically distinct, abundant in almost all aquatic environments, respond rapidly to changing conditions, and are well preserved in sediment deposits (Hall and Smol 1999). Hence, researchers can use changes in community composition (expressed as percent abundance of each taxon) to classify and quantify long-term environmental changes that result from anthropogenic activities.

Methods

Coastal sample locations were selected, and associated segment sheds were characterized, as described in detail by Danz *et al.* (2005, 2006). Water quality sampling methods are described by Reavie *et al.* (2006) and additional variable-specific details are provided in articles that are cited therein. The sampling, preparation and assessment (identification, enumeration and statistical evaluation) of diatom materials are also presented by Reavie *et al.* (2006).

To date, 4 diatom-based indicators of Great Lakes coastal quality have been developed. With selection of an indicator based on need and/or logistic constraints, the following indicators can be used to infer past and present information about coastal habitat quality. These indicators are listed in order of decreasing complexity of application.



1. Diatom-based inference models for water quality variables

Modern datasets, also known as training sets, provide the basis for development of indicator transfer functions by relating contemporary assemblages with their corresponding environmental measurements (e.g., water quality stressors). Algal assemblages are proven robust indicators of stressors such as nutrients (e.g., Tibby 2004, Meriläinen *et al.* 2003, Ramstack *et al.* 2003), water clarity (Dixit and Smol 1994) and acidification (e.g., Siver *et al.* 2003), as well as a suite of other water quality problems in freshwater ecosystems (Smol 2002). A diatom transfer function is derived by relating diatom taxa assemblages in a training set of samples (e.g., from lakes, river reaches, coastal locales) to an environmental variable of interest (e.g., total phosphorus or nitrogen, pH, chloride, suspended solids) from a particular region (Charles 1990). The transfer function consists of taxa coefficients (environmental optima and tolerances) that can be used to infer quantitative information about the variable of interest, based on the abundance of each taxon in a sample assemblage. Transfer function evaluation and testing involves the comparison of diatom-inferred water quality to measured water quality to evaluate function robustness, that is characterized by a coefficient of determination (r^2) and an “error of prediction.” While measured water quality variables are suitable for comparison to diatom-inferred water quality, contemporary measurements are often based on single (“snapshot”) measurements from the epilimnetic environment at each site in the training set. This is not surprising because multiple time-integrated measurements can be costly and are often not logistically feasible in monitoring programs. Several studies have shown that, due to short-term fluctuations in freshwater parameters, snapshot measurements of water quality variables such as nutrients can misrepresent the prevailing water quality (e.g., Bradshaw *et al.* 2002, Detenbeck *et al.* 1996). Assemblages of algae, that are physiologically subject to water chemistry, have the potential to provide time-integrated inferences of limnological conditions.

In an effort to develop indicators for Great Lakes near-shore conditions, diatom-based transfer functions to infer water quality variables were developed from the Great Lakes coastal samples. Transfer functions for 17 site-level water quality variables (Tables 1 and 2 in Reavie *et al.* 2006) were developed using weighted averaging (WA) regression with inverse deshrinking and jackknife (leave-one-out) cross-validation for error estimation and lognormal taxa transformation. Diatom-inferred (DI) estimates of water quality variables for each sample were calculated by taking the optimum of each taxon to that variable, weighting it by its abundance in that sample, and calculating the average of the combined weighted taxa optima. The strength of the transfer functions were evaluated by calculating the squared correlation coefficient (r^2) and the root mean square error (RMSE) between measured values and transfer function estimates of those values for all samples. Jackknifing ($WA_{\text{jackknife}}$) was used in transfer function validation to provide a more realistic error estimate (RMSEP, the root mean square error of prediction) because the same data were used to both generate and test the WA transfer function.

Over 2000 diatom taxa were identified, and 352 taxa were sufficiently abundant to include in transfer function development (Table 3 in Reavie *et al.* 2006). Multivariate data exploration revealed strong responses of the diatom assemblages to stressor variables, including total phosphorus (TP). A diatom inference transfer function for TP provided a robust reconstructive relationship ($r^2 = 0.65$; RMSEP = 0.26 log ($\mu\text{g/L}$)).

Relationships between DI water quality variables and watershed characteristics, such as urban and agricultural land use, have provided an important link between bioindicators and



anthropogenic influences in the watershed (Dixit and Smol 1994). Such comparisons of diatom–inferred water quality to watershed stressors may reflect the strength of these transfer functions, particularly regarding their ability to infer more holistic stressor impacts beyond the water quality parameters that directly influence the indicator assemblages. For each modeled water quality variable, both measured and diatom–inferred values were regressed against the set of watershed–level predictors using multiple linear regression and evaluated using the coefficient of determination. The regressions tested the relationship between watershed properties and water quality in the adjacent coastal system, and were used to determine whether diatom–inferred or measured water quality is more closely related to watershed characteristics such as agricultural and urban development. Measured and diatom–inferred water quality data from the Great Lakes coastlines were regressed against watershed characteristics (including gradients of agriculture, atmospheric deposition and industrial facilities) to determine the relative strength of measured and diatom–inferred data to identify watershed stressor influences. With the exception of pH, diatom–inferred water quality variables were better predicted by watershed characteristics than were measured water quality variables (Fig. 5 in Reavie *et al.* 2006).

Because diatom communities are subject to the prevailing water quality in the Great Lakes coastal environment, it appears they can better integrate water quality information than snapshot measurements. The diatom community at a site is subject to its prevailing water quality condition, and so diatom–inferred water quality data should also reflect this condition. Diatoms are likely to integrate water quality conditions over longer temporal periods (e.g., past days to weeks) compared to water chemistry measurements (e.g., past hours).

2. Diatom-based integrative water quality model

Training sets like that described above have become the mainstay of modeling methods to calibrate diatom indicators to water quality variables of interest. The present-day distributions of diatoms (or any of several indicator organisms) are calibrated across the gradient of a selected environmental parameter. If we are to continue refining these models there is a greater need to focus on better characterization of species–environmental relationships. The transfer function approach described in the previous section deals with single water quality variables, each individually used to build a diatom-based model. These models are useful because managers are often interested in particular variables, such as phosphorus or chloride, to make water quality diagnoses. However, weaknesses in these models are associated with a loss of ecological information, resulting from the inability of a single water quality variable to account for the primary gradient of environmentally explainable variation in the diatom assemblage data.

In the comparison of observed to DI data there is a tendency for DI values to overestimate quantitative variables at the low end of the environmental gradient, and underestimate at the high end (e.g., Ryves *et al.* 2002, Yang and Duthie 1995, Leland *et al.* 2001, Reavie and Smol 2001, Werner and Smol 2005). These errors associated with model application are likely to be a result of unexplained noise in the data, that is expected when one deals with highly complex biological data such as diatom assemblages. Another likely cause of model error is that the selected variable of interest captures only a fraction of the variation in the diatom data that may be explained by other measured variables. For instance, it is well known that the measured total phosphorus gradient from a set of sites is typically correlated with nitrogen, water clarity (e.g., Secchi and color), organic compounds and suspended solids, all of which can have water quality implications. Because of inter-correlation among water quality variables, teasing out the



independent responses of the diatoms to these variables can be difficult. This second indicator approach presents an evaluation of a model based on a water quality gradient, derived by integrating a series of measured chemical variables.

This evaluation used the same set of chemical and diatom data used by Reavie *et al.* (2006) to derive an integrated WQ model. The diatom-based WQ index was created to form a comprehensive measurement to use as a general indicator of water quality, and to examine how well the diatoms responded along this gradient, versus specific variables such as TP. The first step summarized the measured chemical data into the comprehensive WQ index. A PCA of all chemical variables identified the major environmental gradient that would be considered ranging from “high” (i.e., low-nutrient, clear-water sites) to “low” (i.e., high-nutrient, high Cl, turbid sites) water quality (Fig. 1 in Reavie *et al.* 2006).

The WQ variable was used to calibrate diatom species coefficients using standard methods (Reavie *et al.* 2006), based on the diatom responses across the WQ gradient. WA calculations with jackknife cross-validation were used to provide DI WQ values. As for the previous indicator, adjacent watershed data were regressed against (A) measured and (B) DI data using multiple linear regression.

Comparisons of observed to DI data indicated good predictive ability for the WQ model ($r^2_{\text{jackknife}} = 0.62$, RMSEP = 1.32). The relative power of these models was also illustrated by comparing measured and DI data to watershed characteristics. For both models, DI parameters are better correlated to watershed characteristics than measured parameters. The combined WQ variable is better correlated to watershed characteristics than measured TP. This is likely a result of WQ being derived from several chemical parameters and, hence, should better reflect overall chemical condition than a single nutrient. Combination of these variables into a single WQ variable offers a notable advantage to characterizing watershed-measured water quality relationships, and an increase in r^2 occurs for DI-WQ over DI-TP.

Summarizing water chemistry variables into a comprehensive index of water quality appears to be suited to WA approaches, and proffers some advantages over using specific environmental variables. Mainly, this approach appears to better characterize diatom-environmental relationships by merging several variables that simultaneously influence species assemblages. Disadvantages of using a WQ index may include some loss of information for water quality managers who may be interested in specific variables, such as phosphorus. However, given that we are unlikely to see significant improvements in training set nutrient models using standard WA approaches, an integrated measure of water quality is a useful next step to building more informative models.

3. Diatom-based multimetric index of disturbance

A diatom-based multimetric index to infer coastline disturbance was developed for Great Lakes coastal wetlands, embayments and high-energy sites. Unlike the previous 2 indicators, the multimetric index was derived and tested using a fundamentally different approach. Clearly the previous 2 indicators will be of interest to managers and paleoecologists, but they have some logistic constraints (e.g., time and monetary dedication, taxonomic expertise, specialized software, and steep learning curve) that may limit their choice by managers who consider “algae” as an environmental quality indicator. Index approaches provide a means to evaluate environmental quality at a locale based on the diatom assemblage, and can be flexible enough to



suit a greater user audience. Furthermore, algal indices can simultaneously include several characteristics of the assemblage at a locale, and can potentially provide an integrated picture of impacts at a site by not being limited to inferring water quality parameters.

We developed 38 diatom-based metrics from taxonomic (e.g., proportion of a particular genus) and functional (e.g., proportion with a particular adaptive strategy, such as planktonic existence or the ability to assimilate atmospheric nitrogen) characteristics of the assemblage.

The following approach was used to identify metrics for multimetric development from the complete list of candidate metrics. (1) The suitability of each candidate metric was evaluated using stepwise regression to the stressor principal components described by Danz *et al.* (2005, 2006). In other words, metrics were compared to watershed characteristics such as agricultural intensity and urban development to identify the power of each metric to reflect anthropogenic stress. (2) Similarly, each candidate metric was related to natural gradients using stepwise regression to identify metrics that were being largely determined by natural factors. (3) Covariance among candidate metrics was investigated to identify redundancies. Within groups of co-varying candidate metrics, metrics were selected that, simultaneously, best tracked stress and least tracked natural gradients.

Many of the proposed metrics were redundant (highly correlated) or had no apparent relationship to stressors, and so were not considered further. Important and independent metrics were identified as the best candidates for inclusion in development of a multimetric index to infer environmental quality.

The multimetric index was developed based on the sum of the selected metrics, with each metric weighted based on the strength of its relationship to the stressor gradient. In this way, metrics with weak, but still significant, relationships to anthropogenic stressors would play less of a role in multimetric calculations. Fifteen candidate metrics met the criteria of our selection process. To create an approach that was adaptable to the limitations of a user audience, 2 variations of the multimetric index were developed:

(1) *The full, 15-metric compilation.* Most of the metrics included in this index are proportions of particular genera. Also included are the proportions of monoraphid taxa (taxa with a raphe structure on only 1 valve of the cell wall), biraphid taxa (taxa with a raphe on both valves), and the complex of taxa comprising *Achnantheidium minutissimum*, a common species with several forms, subspecies and varieties. The Shannon-Weaver index of diversity and diatom-inferred chloride concentration (derived using the weighted-averaging model, above) are also included.

(2) *A simpler, 13-metric compilation that excluded the Shannon-Weaver diversity value, and the diatom-inferred Cl value.* These 2 metrics require detailed taxonomic identification of the diatom assemblage at a site, and so they were removed to suit the constraints of a user group with less time, funds and/or taxonomic knowledge. As expected, this simplified metric was shown to be less robust than the full, 15-metric approach, but was still robust enough to characterize known impacted locales from less impacted ones.

4. Diatom valve deformities as indicators of pollution

The occurrence of morphological abnormalities in birds (Ludwig *et al.* 1996), fish (Smith *et al.* 1994), and invertebrates (Diggins and Stewart 1993), particularly in the coastal region of Lake Erie and its tributaries, is well known. These effects are usually attributed to toxic organic



compounds. Reports of similar effects on benthic diatoms are not as widely reported, but not unknown (Dickman 1998).

Morphologically abnormal diatoms from the genus *Tabularia* were collected at a coastal site in Lake Erie, near Cleveland, Ohio; an area with a legacy of severe environmental problems. The locality of collection is locally known as Whiskey Island, a peninsula found at the mouth of the Cuyahoga River. The island area has been an industrial site, a ship graveyard and a waste disposal area. It is currently the site of a salt mine, and has recently been developed as a large marina. The collection site is subject to numerous discharges, including industrial contaminants.

There are number of potential causes of morphological abnormalities in diatom frustules. Nonlethal mechanical damage may produce clones of cells that have structural defects. Based on our observations, it appears that frustular abnormalities are common in diatom communities that undergo toxic stress. It is probably safe to say that diatoms growing in unstable habitats are particularly susceptible to abnormal frustule formation, and the abnormalities present near Cleveland are likely related to these factors.

Observations showed an extreme variety of atypical shapes (Fig. 4 in Stoermer and Andresen 2006); frustules were bent, asymmetric, had irregular striae patterns, irregular margins, or any combination of these characters. Abnormalities in diatom valve structure have been noted and reported virtually since the group was first studied. In general, deformities have been associated with pollution or eutrophication (Antoine and Benson Evans 1986, Klee and Schmidt 1987). More specific chemical causes include silica limitation (Booth and Harrison 1979) and increased salinity in freshwater habitats (Tuchman *et al.* 1984). Of the possible causes, suggested by Barber and Carter (1981), their first category, “chemical abnormalities in the habitat” seems most likely in the populations we studied.

Presence of orphological abnormalities of the diatoms was not anticipated to be one of the GLEI indicators, and so to date we have only assessed these site-specific data near Cleveland. However, the presence of benthic diatoms that are atypical, in terms of both distribution and morphology, in the Great Lakes may offer valuable insights into toxic effects. Although the present state of knowledge does not permit firm conclusions concerning the populations described here, investigation of benthic diatom populations in the Great Lakes is a neglected topic that deserves more research attention.

Conclusions

These results to date strongly support the use of diatoms in Great Lakes coastal monitoring programs to track the impacts of anthropogenic stressors. Because the diatoms clearly respond to anthropogenic stressor influences from the watershed, integrating the diatom indicators with upland indicators (e.g., vegetation, birds) should provide a strong holistic view of overall disturbance, and a powerful management tool for Great Lakes decision makers. There is also considerable value in these indicators for retrospective assessments. Because long-term measured water quality data can be sparse or unreliable, and pre-European settlement data are unavailable, diatom-based paleoecological studies in the Great Lakes have been valuable in describing background conditions and anthropogenic impacts (Stoermer *et al.* 1993). To date, these studies have focused on sediment cores collected from deep, open water areas, and so provide integrated assessments of long-term water quality from a large coastal region or lake. The diatom-environmental relationships in this report can also provide a tool for near-shore



paleoecological studies and the assessment of more localized impacts, such as the paleolimnology of wetlands that have been impacted by cultural eutrophication.

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D. FISH AND MACROINVERTEBRATES

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Introduction

Despite the incomplete historical data record on Great Lakes habitats, there is consensus that the lakes are rapidly changing (Environment Canada [EC] and U.S. EPA 1999). No single indicator can capture the diverse information necessary to evaluate ecosystem condition. A major challenge is to select a subset of many proposed indicators that will effectively and efficiently measure the major components of ecosystem health and can diagnose causes of impaired community function. A second challenge is to link those indicators to assessment endpoints. We have combined the strengths of 2 common approaches (multimetric and multivariate) to generate derivative, ecologically relevant indicators that have the greatest possible discriminatory power to distinguish degraded systems from least-impaired systems.

Objectives

We employed a multi-tiered sampling and modeling strategy, integrating data collected at regional scales via satellite imagery, local scales, and site scales via field sampling. The goals of our project were to:

1. Evaluate the applicability of relevant SOLEC-derived and complementary indicators in the context of the ecosystem types making up the Great Lakes coastal region;
2. Rigorously evaluate a suite of indicators across the range of Great Lakes coastal habitats;
3. Recommend indicators of specific ecological conditions keyed to assessment endpoints and stressors in the Great Lakes coastal region.

Specific components of this project included:

1. Characterizing fish and macroinvertebrate communities (Grigorovich *et al.* 2005a, Grigorovich *et al.* 2005b, Kang 2004, Kang *et al.* in preparation);
2. Developing a fish index of biotic integrity (Baghat 2005), and testing *Scirpus* and *Typha*-dominated wetland indices of fish biotic integrity (Baghat *et al.*, in preparation).
3. Assessing macroinvertebrate responses to stress (Brady *et al.* in preparation); assessing fish community responses to local and landscape stressors (Johnson *et al.*, in preparation);
4. Assessing habitat changes that stem from environmental disturbances (Olker *et al.* in preparation);



5. Detecting scales of responses of macroinvertebrate and fish indicators to landscape stressors (Brazner *et al.* Ms. 1, Brazner *et al.* Ms. 2, Danz *et al.* 2006, Holland *et al.* in preparation, Brady *et al.* in preparation);
6. Developing multivariate methods to identify coastal ecosystem conditions using fish communities (Baghat 2005) and macrobenthos communities (Foley *et al.* in preparation, Ciborowski *et al.* in preparation).

Methods

Between 2001 and 2003 we sampled 116 sites at 101 unique locations across the >7,000 km U.S. Great Lakes coastal margin. Fifteen sites were revisited to quantify temporal variation. In addition, 53 sites were sampled as part of a parallel study (EPA grant # R-828777) to define reference condition at Great Lakes coastal margins. Benthic samples were collected using sweep nets, sediment coring tubes, and petite ponar grab samplers from which at least 226 genera (excluding *Chironomidae* and *Oligochaeta*) were identified. Approximately 1,100 overnight fyke net sets were fished, resulting in capture, identification and release of over 100,000 fish representing 110 species. Habitat attributes and characteristics of sampling location and the surrounding landscape were recorded at more than 1,500 benthos sampling points, 800 net locations, and 3,000 additional randomly selected points. Water quality was measured at approximately 2,000 locations. Fish community composition (numbers of individuals of each species) was noted at each fyke net; the catch was standardized by net size (small vs. large) and catch per unit effort. Fish and macroinvertebrates were summarized with respect to relative abundance of each taxon per site, as well as using a variety of taxon metrics describing trophic habits, life history features, behavioral characteristics, and community composition.

Synoptic habitat structure measurements of water depth, substrate, vegetation, hydrologic connections to the lake and landscape, and disturbances were made. Physicochemical variables were measured at each biotic sample location. Over 100 individual habitat-associated attributes of each site were summarized by PCA to yield 4 sets of eigenvectors representing landuse/land cover, physical structure, vegetation cover, and anthropogenic disturbance.

Results and Discussion

Community Structure. Zoobenthos

The extensive collection records of zoobenthos (over 4,000 samples from 143 locations) have provided important biogeographic and taxonomic information over and above the primary use of the data to develop and test indicators of anthropogenic stress. We discovered 1 invertebrate species new to the Great Lakes, mapped the range expansion of a second invader, and used the distributions and associations among several other nonindigenous invading species (NIS) together with our stressor data to test hypotheses about the mechanisms that promote establishment of new species in the Great Lakes (Grigorovich *et al.* 2005a,b).

Quantifying aquatic habitat alteration stemming from anthropogenic disturbance (Olker *et al.* in preparation). A redundancy analysis (RDA) was conducted to explain how landscape-scale features (ecoregion, hydrogeomorphic type, anthropogenic disturbance) influenced site-specific variation in local synoptic aquatic habitat attributes. In all, 33% of local aquatic habitat variation could be accounted for by the landscape and stressor features. Approximately 2/3 of this explained variation (19% of the overall variation) could be accounted for specifically by the



effects of anthropogenic stress – 15% was uniquely attributable to stress, and 4% could also be explained by covariation with spatial pattern, geomorphic type, or complex size (Figure 1 A). Overall, anthropogenic disturbance exerted small but meaningful changes in habitat attributes that themselves influence fish (Bhagat *et al.* in review, Johnson *et al.* see below), macroinvertebrate (Foley *et al.* in preparation) community structure.

Community Structure. Fishes

Two fish indicator indices assess Great Lakes coastal wetland condition (see 2-page summary in Appendix A9, A10). Scientists with the Great Lakes Coastal Wetlands Consortium had previously proposed that because submergent plant communities adapt quickly to changing water levels, perhaps the fish communities associated with plant types could be used as indices of wetland condition. They proposed a fish IBI for wetlands dominated by cattails (*Typha*) and another IBI for those in which bulrushes (*Scirpus*) were most common.

The fish IBI scores calculated for these wetlands varied predictably, but only according to specific classes of human-related stress. Fish communities in cattail-dominated wetlands became degraded as a disturbance variable that combined population density, road density and urban development in the watershed surrounding the wetland increased. In contrast, fish communities of bulrush-dominated wetlands reflected nutrient and chemical inputs associated with the degree of agriculture in the surrounding landscape. Great Lakes water levels varied by up to 100 cm over the study years, confirming the indices' effectiveness under changing water conditions. The fish IBI scores in bulrush wetlands were much lower once a threshold level of agricultural-input stress had been exceeded. In contrast, the IBI scores in cattail wetlands gradually declined with increasing population disturbance (Fig. 2). The Uzarski *et al.* (2006) IBI scores reflect specific classes of anthropogenic stress in coastal wetlands dominated by cattails and bulrushes, most notably agriculture or population density effects rather than generalized disturbance. Diagnosing causes of water quality impairment is an important component of the Great Lakes water quality agreement of the governments of Canada and the U.S., and the U.S. federal Clean Water Act. These results address one of the weaknesses of the IBI approach, in that a single value representing ecological condition does not address the cause of impairment.

Describing patterns of variation of fish communities and responses to stress. Effective environmental indicators exhibit consistent patterns of variation as a function of particular stressors and have a clearly identified scale of response (Jackson *et al.* 2000). Matching the

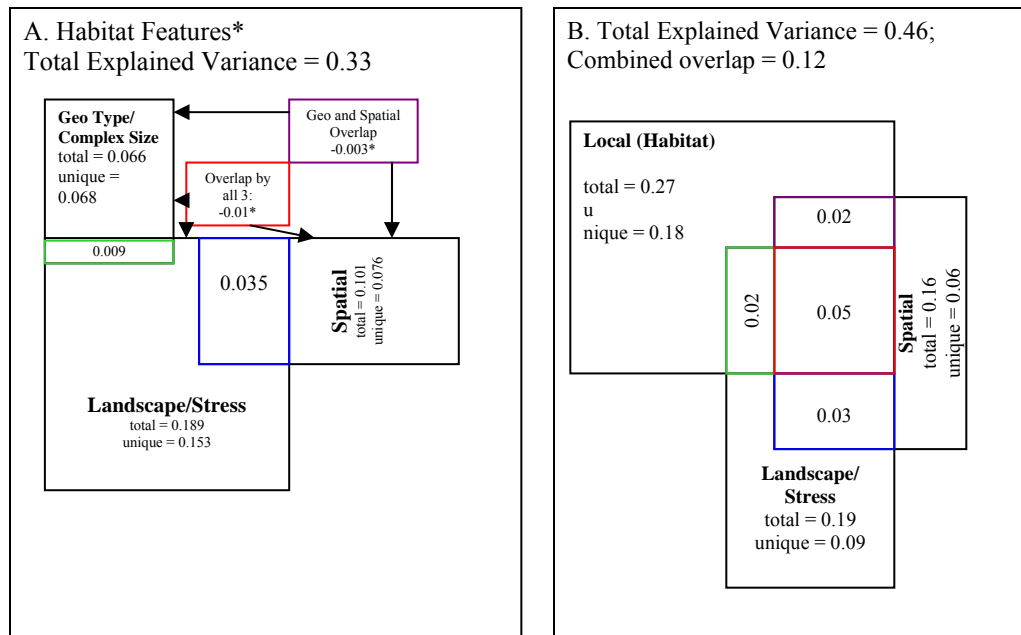


Figure 1. (A) Percent variation explained in GLEI habitat PCs by geomorphic type / complex size, landscape/stress, and spatial variables. Note that half of the variation in habitat features is associated with landscape/ stress factors. (B) Percent variation explained in GLEI fish presence/absence data (with rare species removed) by local, landscape, and spatial variables.

*Negative values due to a not strictly linear relationship between habitat PCs and environmental variables, geomorphic type, and complex type when spatial variables are held as covariates (complex relationships between predictor variables).

appropriate scale of responses to the stressors of interest is a critical step in the development of an effective indicator. We have addressed this question using several approaches to study variation pertaining to fish community responses to stress in Great Lakes coastal areas:

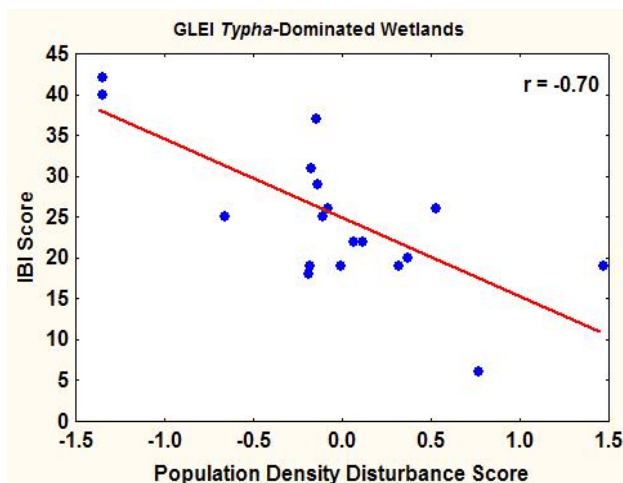


Figure 2. *Typha* IBI for fishes decreases with increasing population disturbance.

1. What are the relative influences of wetland geomorphic setting, geography, and landscape-scale stressors on the absolute and relative abundances of selected fish species and species traits?
2. What landscape-scale stressors best explain the distribution of fish species in Great Lakes coastal wetlands?
3. What is the relative influence of local habitat versus landscape stressors and spatial position on fish species across Great Lakes coastal areas?

Pronounced gradients in climate and landforms across the Great Lakes cause



strong biogeographic differences across the basin. Danz *et al.* (2006) examined the distribution of landscape stressors and selected environmental indicators and demonstrated strong geographic patterns in 5 types of anthropogenic stressors across the Great Lakes basin. Specific to fish communities, 30% of the total variation in fyke net fish catch per unit effort (CPUE) was explained by the combination of stress, geographic location, and geomorphic setting. They showed that 5 NIS, along with turbidity-tolerant species, were associated with increasing levels of those anthropogenic stressors. Danz *et al.* (2006) identified a replacement series of taxa whose relative abundance changed as the adjacent landscape ranged from natural to disturbed land covers. These analyses demonstrated that the patterns of association were confounded by species' geographic position within the basin; however, because of the coarse nature of the stressor data (i.e., derived from regional data sources and summarized at segment shed scales) the spatial scales of the stressors explaining the observed patterns could not be distinguished.

Using fish indicators that summarized species composition, native species richness, and proportional abundance values reflecting fish size, life history, behavior, feeding guild, and tolerance to turbidity, Brazner *et al.* (Ms. 1) found that the values of 6 fyke-fish indicators were best predicted by the Great Lake being sampled, whereas wetland type and amount of anthropogenic stress explained the highest amount of variance for 2 indicators each (Table II.D.2). Interaction effects between lake and wetland type were prevalent. Among these selected fyke net fish indicators bluegill, carp/goldfish, and rock bass relative abundances had the largest amount of variance accounted for by a composite measure of stress assessed at the segment shed level. This analysis revealed that both individual species and species-based composite indicators exhibited a broad range of responses to spatially-relevant features (i.e., wetland geomorphic type, Great Lake, and ecoregion) as well as to an overall measure of stress.

Analyses by Brazner *et al.* (Ms. 2) left open the question – what is the specific spatial scale of responses to individual stressors and geographic factors? This question was addressed using classification and regression trees (CART) to predict responses of fish indicators to geographic (i.e., ecoregion, lake) variation, and to stressors characterized at differing spatial extents around coastal wetlands, ranging from 100 m to full watersheds draining into coastal wetlands (Brazner *et al.* Ms. 2). An indicator of **turbidity intolerance** had the largest amount of variation explained of all the fyke net fish variables. The model predicted 54% of the total variance in fish relative abundance. Watershed area, % development at the 500 m buffer extent, and % rowcrop within the watershed were the best explanatory variables for this index. **Percent of nest-guarding spawners** was the next-best indicator, with 46% of the variance explained exclusively by physical variables, including wetland area and type, watershed area, and lake.

Two individual fish species *Lepomis macrochirus* (bluegill sunfish) and *Ambloplites rupestris* (northern rock bass) and a species group including the European carp and goldfish proved to be responsive as potential indicators. Bluegill occurrence was best predicted by the ecoregion, % development and % rowcrop agriculture. Interestingly, development was either positively or negatively correlated with this species, depending on the spatial extent. At small spatial extents (100 m and 500 m buffers), development was positively correlated with bluegill abundance. At the 5,000 m extent and the watershed, the bluegill was negatively correlated with both development and rowcrop agriculture. This suggests a potential stimulation or fertilization effect of development at the local scale.



The northern rock bass exhibited a more spatially consistent response to disturbance (with 44% variance explained). Occurrence was negatively associated with development at the watershed scale. This model also included lake and wetland area. In a separate analysis examining the spatial scale of responses to land use, the northern rock bass was found to correlate negatively with increasing development at very large scales, with the strongest negative correlation found at a 50-km² extent (Holland *et al.* in preparation).

The goldfish/European carp species group was positively correlated with rowcrop agriculture at the 500 m extent, but negatively associated with rowcrop at the 5,000 m scale (35% of variation explained). Johnson *et al.* (in preparation) found that the frequency of occurrence of both species increased with amount of rowcrop agriculture at the scale of entire watersheds.

The analyses by Brazner *et al.* (Ms. 1), effectively partitioned variation due to the spatial extent of stressors and geographic position; however, this study was limited to coastal wetlands and did not address the potential impact of local habitat features on the fish community. We studied variation in fish community composition to address the question, ‘what are the dominant environmental and geographic factors structuring the fish community in Great Lakes coastal areas, including high energy zones, embayments, and wetlands?’ In contrast findings of Danz *et al.* (2006) and Brazner *et al.* (Ms. 1), landscape and stressor data were summarized for watersheds delineated for each sample site. Fish community composition was analyzed for 143 sites, including 41 high energy, 19 embayments, and 83 coastal wetlands. Canonical Correspondence Analysis (CCA) was used to examine species-environment relationships, implementing variance apportioning procedures (Cushman and McGarigal 2002) to separate unique and shared variation among environmental predictors. Eigenvalues for 4 distinct classes of habitat variables were used as local-scale predictors along with geomorphic type and size.

Variance decomposition. Very strong (and identical) patterns in fish presence/absence were observed with respect to local, landscape/stress and spatial variables whether analyses were conducted on fish species presence/absence or relative abundance. Forty six percent of the total variation in fish species presence/absence was explained by the 3 sets of variables. Of that variation, more than half (27%) was attributable to local variables (geomorphic type and size, surrounding land use, physical habitat structure and water quality, and vegetation), and a little less than half (19%) was attributed to landscape/stress. Landscape/stress variables and spatial location shared 10% of their variation in common. Thus, 50% of the variation in spatial position was also explained by the landscape/stressor variables (Figure 1B).

Of the local-scale variation, geomorphic type accounted for 35% of the variance, land use accounted for 43%, aquatic habitat accounted for 32%, physical characteristics and unit size accounted for 28%, and anthropogenic activities (local disturbance) accounted for 13%. There was considerable overlap in the explained variation in local scale variables.

Fish community responses. Three primary fish associations were identified to have stable responses to local and landscape/stress variables independent of spatial location. These groups have characteristic thermal and habitat preferences, as well as consistent relative tolerance to disturbance. Many species exhibit a “wedge” distribution relative to intensity of stress - variation



increases (or decreases) along the stress gradient. This indicates that unmeasured variables are limiting the distribution (Cade and Noon 2003). Further analyses will be conducted to characterize this response envelope.

Potential indicators. Several species exhibit consistent response patterns to stress across geomorphic types and the basin. These include the non-native carp/goldfish and white perch; yellow perch and native species emerald shiner, northern pike, burbot, and bluegill. By quantifying the relative influence of each of these 3 factors we have been able to identify species responses to the local habitat as well as to landscape stressors, independent of the influence of geography. This has enabled us to identify species that have consistent responses to stress independently of their spatial location in the basin (Figure 3).

Developing Multivariate Fish and Macroinvertebrate Indicators Using a priori Classification of Reference Condition and Degraded Condition Sites

Effective indicators of environmental condition should be scored against accepted standards. The standard used to assess the integrity of a community is whether or not the numbers and kinds of species are similar to the community found in an environmentally similar area. Such sites are said to represent the “reference condition,” (Baghat *et al.* in prep).

Multivariate indicators of environmental condition are typically developed by defining the bounds of composition of the biological community expected within a suite of sampling sites selected to represent the reference condition. A test site is classed as ‘nonreference’ if its community falls outside that range, expressed as a probability. However, because such measures are unbounded, one cannot tell how degraded a nonreference community is. We identified classes of sites representing the 2 extremes of anthropogenic stress in Great Lakes coastal wetlands. Stress at a site was the relative maximum (relmax) intensity of road density, residential/commercial land use, agricultural land use, human population density, and distance to point sources in the contributing watershed. The 20% of wetlands with the lowest relmax scores (Host *et al.* 2005) were classified as reference condition sites.

To identify fish community indicators of reference and degraded conditions, we used the relative abundances of each fish species at 133 locations. Cluster analysis of fish community composition at 46 reference condition sites only identified 5 unique assemblages. Discriminant function analysis was then used to find the suites of environmental variables that best characterized the sites supporting each of the assemblages. Seven environmental variables, summarizing primarily

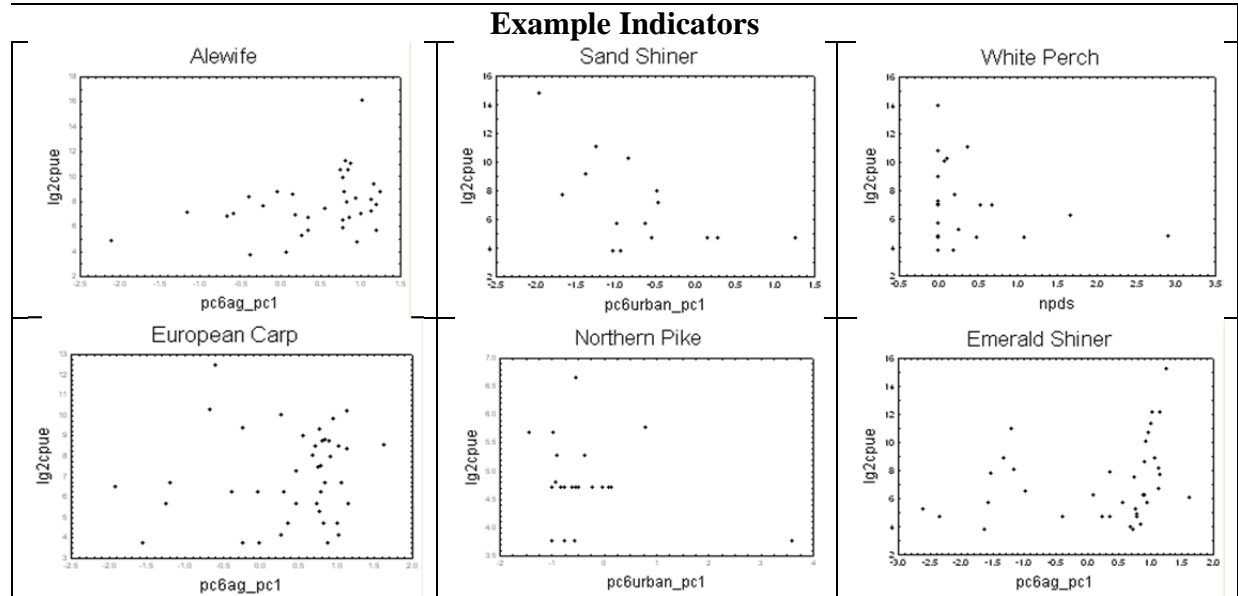


Figure 3. Examples of fish species responses to stressors summarized for watersheds contributing to coastal high energy, embayment or wetland sites. The most common response is a “wedge,” indicating that unmeasured factors are limiting at either end of the stress gradient (Cade and Noon 2003). The response envelope will be characterized for individual species and species traits at a later date.

ecoregion attributes and wetland type were able to correctly classify all but 1 of the reference condition sites. The derived discriminant functions were then used to assign the 87 other locations to 1 of the 5 unique assemblages. The assignment represented the fish assemblage expected at an ‘other’ location if that location was equivalent to reference.

We developed PCA-derived composite estimates of urban disturbance and of agricultural disturbance for each of the 133 sampling locations using the data of Danz *et al.* (2005). To identify the indicator species characteristic of reference conditions and of sites degraded by urban development and agricultural activity, respectively, we performed Bray-Curtis ordinations on the fish community data on an assemblage-by-assemblage basis. We first designated the sites with the lowest agricultural disturbance score and the highest agricultural disturbance score as the 2 end points of a ‘fish condition index of agricultural stress.’ The Bray-Curtis analysis then ordinated the sites within the assemblage along this index. The fish species whose relative abundances correlated most highly with changes in the index score were designated ‘indicator species.’ The process was then repeated using endpoints for urban disturbance scores for the assemblage. In all, 10 ordinations were performed - 2 per fish assemblage.

There was considerable variation in our ability to statistically define indicator species representative of the reference and degraded ends of the disturbance gradients. There were marked differences within assemblages of 3 clusters (correlations ranging from 0.6 to 0.7, $p < 0.05$). Furthermore, taxa indicative of reference condition sites in 1 assemblage (e.g. spottail shiners in cluster 1) were sometimes representative of disturbed conditions in another assemblage (spottail shiners in cluster 3, Table D.1). This reflects the broad correlation between latitude and productivity characteristic of areas minimally affected by humans across the Great Lakes.



The multivariate approach to identifying biological indicators of environmental condition is unique in that faunal data are used to group together reference sites that have similar species composition, thus providing an objective strategy for assessing habitat quality based on species assemblages. **We were able to develop models of fish species relative abundances that can be used to evaluate the quality of sites in response to specific anthropogenic stressors.**

Identifying macroinvertebrate indicators. We have concentrated on developing indicators for Great Lakes wetlands because wetlands exhibit less variation in depth than other Great Lakes margin habitats, and hence less compositional variability. Indicator development to date has focused on D-frame dip net samples, collected at depths of 0.5 – 1 m along transects set perpendicular to shore throughout each wetland. Most taxa were identified to genus. Chironomidae and Oligochaeta were identified to family.

Table D.1. Proposed reference and non-reference indicator species based on Bray-Curtis ordinations of species relative abundances against urban and agricultural-related disturbance indices within suites of sites derived from cluster analysis of reference site fish assemblages and DFA classification. Reference species were negatively correlated with stressors, other species were positively correlated with stress.

Cluster number (# sites)	Reference species	Disturbed (urban)	Disturbed (agriculture)
1 (n = 12)	Northern rockbass Banded killifish Yellow perch Spottail shiner Longnose dace	Alewife Spottail shiner	European carp Pumpkinseed sunfish Green sunfish White perch
2 (n = 9)	Sand shiner Bluntnose minnow	European carp Yellow perch	Bluegill sunfish Pumpkinseed sunfish Northern pike Banded killifish Bowfin
3 (n = 5)	White sucker Burbot Longnose dace	Northern rockbass Largemouth bass Spottail shiner	Alewife Smallmouth bass Spottail shiner
4 (n = 5)	Slimy sculpin Burbot	Northern rock bass White sucker Eurasian ruffe	None
5 (n = 11)	Brown bullhead Bowfin Bluegill sunfish	Emerald shiner Spottail shiner Northern rockbass	Spotfin shiner White sucker Northern rock bass Smallmouth bass



Nonmetric multidimensional scaling analysis indicated that macroinvertebrate assemblages in northern wetlands (Laurentian Mixed Forest; Keys *et al.* 1995, n=42) were highly significantly different from those in the southern Great Lakes (Eastern Broadleaf Forest; n=41, $p < 0.0001$). Furthermore, the assemblages of Lake Erie wetlands differed from those of Lake Ontario ($p < 0.0001$), and assemblages varied significantly and consistently among wetland types (riverine, protected, or open lacustrine) in the northern wetlands (LMF) ($p < 0.0001$). Potential macroinvertebrate indicator metrics were less variable, but still differed markedly between the northern and southern wetlands ($p < 0.0001$). Thus, wetland macroinvertebrate assemblages were diverse and distinct from one another when assessed solely on where wetlands occurred and on their hydrogeomorphic type. Brazner *et al.* (Ms. 1) observed similar trends in 8 zoobenthic indicator taxa by noting highly significant Great Lake by wetland-type interactions.

Several of the 24 potential macroinvertebrate indicator metrics assessed thus far show promise. In particular, relative abundance of the common mayfly genus *Caenis* may be a useful indicator for Lake Erie wetlands. The proportion of *Caenis* mayflies in dip net samples was negatively correlated with the amount of unvegetated area in the 14 Lake Erie wetlands sampled ($r = 0.47$), the amount of riprapped shoreline ($r = 0.45$), larger watershed sizes for wetlands ($r = 0.65$), amount of row crop agriculture in the watershed (0.74), our watershed urbanization PC-1 (0.67), and positively correlated with the amount of emergent wetlands and deciduous forest in the watershed ($r = 0.79$ and 0.65 , respectively) (Fig. 4). The negative correlation between the proportion of *Caenis* mayflies and wetland watershed size appears to result from the increasing likelihood of larger watersheds being more developed and hence subject to greater disturbance, particularly in the southern Great Lakes. Overall, the proportion of a sample comprised of mayflies (all genera combined) was negatively correlated with watershed size in the southern ecological province, 222 ($r = 0.52$).

Other promising metrics include:

- For Lake Erie wetlands, the proportion of a sample comprised of all Ephemeroptera, Trichoptera, Odonata and Sphaeriidae (proportion ETSO);
- For wetlands in the Northern Great Lakes ecological region (Keys *et al.* 1995):
 - Proportion of *Caenis* mayflies
 - Proportion Ephemeroptera
- For the Southern Superior Uplands ecological region (Keys *et al.* 1995):
 - Proportion *Caenis* mayflies
 - Proportion *Coenagrion* and *Enallagma* damselflies
 - Proportion Trichoptera
 - Taxonomic richness at the family or genus level

Several metrics with potential have not borne out. In particular, measures of community evenness have proven to be less useful than Shannon-Weaver diversity and richness measures.

Macroinvertebrates were also collected in wetlands using cores and petite ponars, and indicators developed based on these methods will be compared to those based on the dip net collection method. We also collected macroinvertebrates from wave-swept beaches and shoreline areas along embayments.



Zoobenthic community composition is strongly regulated by hydrological features such as exposure to waves and currents. Water depth (which ranged from 0.5 to 10 m in our sampling protocols) is expected to exert as strong an influence on community composition as many landscape and biogeographic features. Consequently, we anticipate that the application of our multivariate analytical approach described in detail for fish indicator development (see Bhagat *et al.* below) will be especially useful in accounting for this covariation.

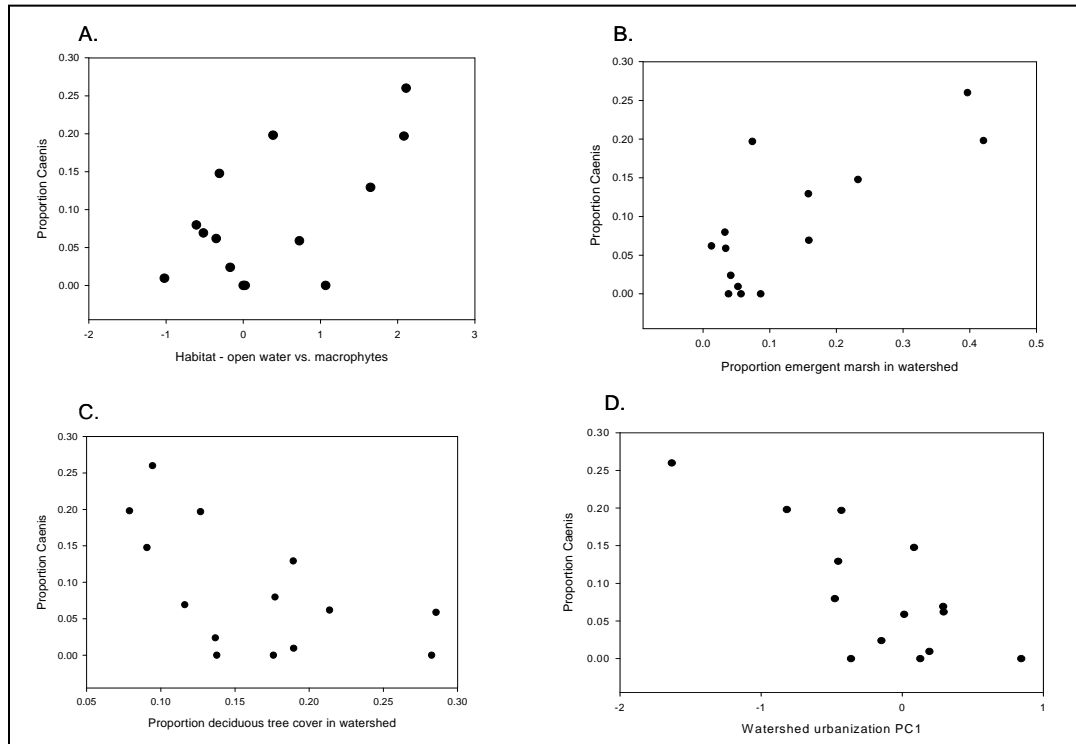


Figure 4. Variation in *Caenis* mayflies relative to habitat and watershed characteristics for Lake Erie wetlands (n=14). A. The proportion of *Caenis* mayflies was higher in wetlands with less open water ($r=0.47$). B. The proportion of *Caenis* mayflies was higher in wetlands with higher amounts of emergent marsh in their watersheds ($r=0.79$). C. *Caenis* mayfly proportions were higher in wetlands with more deciduous tree cover in the watershed ($r=0.65$). D. *Caenis* proportions were lower in wetlands with more watershed urbanization ($r=0.67$).

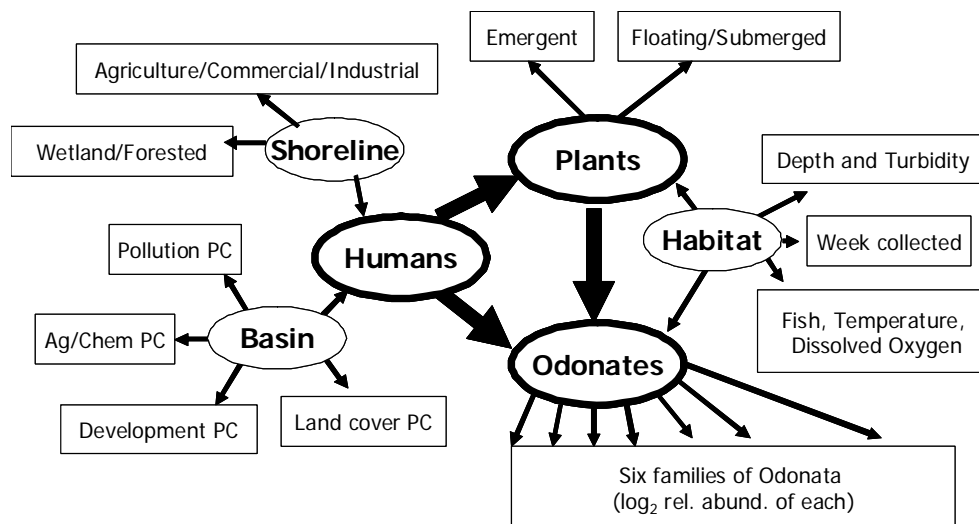


Figure 5. Structured Equation Model relating direct and indirect effects (humans to plants).

Direct and indirect impacts of human activities on larval Odonata – A structured equation modelling approach. Honors undergraduate thesis student Carolyn Foley used structural equation modelling to quantitatively determine whether anthropogenic activities along the edges of wetlands in the Great Lakes affected organisms directly or indirectly through alteration of habitat (Foley *et al.* in preparation). Structural equation models were developed to test the effect of human activities at the shoreline (Olker *et al.* in preparation) on nymphal Odonata and on the structural habitat provided for them by aquatic macrophytes at the 0-0.5 m and 0.5-1 m depths in coastal, riverine, and protected wetlands. Each model contained 4 latent variables: “human activities,” “abiotic habitat,” “plants,” and “odonates” (Fig. 5). We used 244 sampling points in the 0-0.5 m model, and 233 sampling points in the 0.5-1 m model. Structural equation models were compiled and analyzed using the SEPATH module in Statistica™ version 7.1 (Statsoft Inc., 2005). The maximum likelihood estimation was used to estimate path coefficients based on the covariance matrix of the variables, with the root-mean-square error of approximation (RMSEA) used as a goodness of fit index. The adjusted population gamma index was also examined for goodness of fit.

Overall, the models indicate that human activity in the Great Lakes wetlands sampled tended to increase the density of macrophytes (likely through eutrophication effects), that reduces the condition of the larval odonate community. The indirect effects are likely more important than direct (e.g., toxic discharge) effects of human activity on odonate communities. These patterns are broadly consistent with findings of Brady *et al.* (in preparation, see above), who reported that the proportion of damselflies in samples tended to decrease as a function of increasing generalized environmental disturbance.

Additional Applications

GLEI and the Lake Erie Lakewide Area Management Plan (LAMP)

Active interactions between GLEI PIs Jan Ciborowski and Lucinda Johnson and the Lake Erie LAMP’s technical workgroup have resulted in a strong integration of glei concepts and



approaches into various aspects of the Lake Erie implementation and indicators strategies. The Lake Erie LAMP has recognized the strong link between land-based stress and both coastal and basinwide ecosystem processes. Accordingly, they are adopting the stressor measures developed by Danz *et al.* (2005) as integral indicators of the condition of watersheds tributary to Lake Erie. The Lake Erie LAMP has allocated funding to Johnson and Ciborowski to compile and crosswalk Canadian-based GIS stressor information and develop conversion factors that will permit the entire Lake Erie basin to be assessed according to 5 classes of anthropogenic stress (Danz *et al.* 2005). Negotiations are also underway to incorporate information on Canadian portions of the other Great Lakes as opportunities arise. Once compilation is complete we will have contributed greatly to the mandate of SOLEC to provide indicators that can report on basinwide measures of biological integrity. Because our fish and invertebrate indicators are calibrated against the Danz *et al.* (2005) measures of anthropogenic stress, our derivative biological measure of ecosystem condition will also be applicable to the entire Great Lakes basin.

GLEI and Tiered Assessment of Aquatic Life Uses (U.S. EPA Office of Water)

The U.S. EPA Office of Water has been engaged in a 4-year study to develop biologically-based criteria (condition of algae, macroinvertebrates, fishes, etc.) to assess the quality of wadeable streams throughout the continental U.S. (U.S. EPA 2005). Its goal is to develop a classification strategy by which regional agency scientists can assign the biota characteristics of their region of jurisdiction into tiers representing 5 classes of biological integrity reflecting environmental condition ranging from equivalent-to-reference to strongly degraded. Co-PIs Lucinda Johnson and Jan Ciborowski have participated in adapting the conceptual approaches and applications achieved by the GLEI project (Danz *et al.* 2005) and companion Reference Condition project (Host *et al.* 2005) for definition of a human disturbance gradient (HDG) against which the biological tiers can be calibrated. GLEI provided a method for the quantification and summary of multiple stressors into a smaller number of independent stress classes (Danz *et al.* 2005) that can be related to biological endpoints (Danz *et al.* 2006), and a methodology for summarizing the classes to define the bounds of a reference condition (Host *et al.* 2005, Ciborowski *et al.* in preparation). These ideas have been incorporated into a draft document (U.S. EPA 2005) and are being presented by the Office of Water as guidelines at numerous regional development workshops. The assessment criteria that are ultimately derived from these workshops is expected to increasingly guide water use designation in waterways across the U.S. over the next decade.

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Table II.D.2. Summary of fish species and fish species trait responses to stressors and environmental variables from 5 different analyses that summarized similar stressors for different spatial extents (see notes below). Cells in blue reflect consistent responses to urbanization (including point sources or population density/development); cells in green reflect responses to agriculture or pasture. Potential indicator species are designated by an asterisk.

Species / Indicator	Danz <i>et al.</i> in revision ¹	Brazner <i>et al.</i> in review ²	Brazner <i>et al.</i> in prep ³	Johnson <i>et al.</i> in prep ⁴	Baghat <i>et al.</i> in prep ⁵
* alewife	pt source (+)	n/a	n/a	motorized recreation (+); population/develop (+); road density (+);	urban (+) agriculture (+)
* bluegill	pt source (+)	stressor	development wshed scale (+)	shoreline develop (+); population/develop (+)	agriculture (+)
bluntnose minnow	pt source (-)	n/a	n/a	population/develop (+); pt sources (+); ag (+)	
bowfin	agriculture (-)	n/a	n/a	shoreline develop (+); road density (-);	agriculture (+)
brown bullhead	urban (+)	lake	wetland type (-)	road density (-); pt sources (-)	
* burbot	population/ develop (-)	n/a	n/a	motorized recreation (+); population/develop (-); ag (-)	
* carp&goldfish	agriculture (+)	stressors	row crop 500m (+)	agriculture (+); population/develop (+)	urban (+) agriculture (+)
* emerald shiner	pasture (-)	n/a	n/a	road density (+); agriculture (+)	urban (+)
Eurasian ruffe	n/a	n/a	n/a	agriculture (-)	urban (+)
golden shiner	population/ develop (+)	wetland type	development wshed scale (-)	road density (-)	n/a
green sunfish	pasture(-)	n/a	n/a	agriculture (+)	agriculture (+)
killifish	urban (+)	n/a	n/a		agriculture (+)
* largemouth bass	urban (+)	n/a	n/a	shoreline develop (+); road density (-);	urban (+)



Species / Indicator	Danz <i>et al.</i> in revision ¹	Brazner <i>et al.</i> in review ²	Brazner <i>et al.</i> in prep ³	Johnson <i>et al.</i> in prep ⁴	Baghat <i>et al.</i> in prep ⁵
longnose dace	agriculture (-)	n/a	n/a	population/develop (+)	
northern pike	neutral	lake	agriculture wshed scale (-)	shoreline develop (+)	agriculture
pumpkinseed	urban (+)	n/a	n/a	shoreline develop (+)	agriculture
rockbass	urban (+)	stressors	development wshed scale (-)		urban (+) agriculture (+)
* sand shiner	pt source (-)	n/a	n/a	population/develop (-)	
* slimy sculpin	population/ develop (-)	n/a	n/a	agriculture (-)	urban (-)
smallmouth bass	agriculture (-)	n/a	n/a	population/develop (-); pt sources (+)	agriculture (+)
spottail shiner	neutral	n/a	n/a	population/develop (+)	urban (+) agriculture (-)
white perch	pasture (-)	n/a	n/a	agriculture (-); pt sources (-)	agriculture (+)
white sucker	population/ develop (+)	n/a	n/a	motorized recreation (+)	urban (+) (-) agriculture (+)
yellow perch	urban (+)	n/a	n/a	population/develop (+); pt sources (+); agriculture (+)	urban (+) (-)

1 Danz *et al.*, in revision: five stressors were summarized for 762 segment sheds across the basin.

2 Brazner *et al.*, in review: stressor is a single composite measure encompassing 5 different stressor types.

3 Brazner *et al.*, in preparation: three stressors (agriculture, urban, point sources) were summarized at increasing distances from the wetland (from 100 m to the full watershed).

4. Johnson *et al.*, in preparation: stressors (from Danz *et al.* in review) were summarized at the scale of individual watersheds and in the local vicinity at the site scale.

5. Baghat *et al.*, in preparation: stressors represent composite indices describing agricultural impacts versus those related to urbanization, summarized at segment shed scales.



E. WETLAND VEGETATION

Investigators: Carol A. Johnston¹, Barbara L. Bedford², Joy B. Zedler³

Cooperators: John Kelly⁴

Institutions: ¹South Dakota State University; ²Cornell University; ³University of Wisconsin, Madison; ⁴U.S. EPA Mid-Continent Ecology Division, Duluth MN

Introduction

Specific objectives of this component were to: 1) identify vegetative indicators of condition of Great Lakes coastal wetlands that can be measured at a variety of scales, 2) develop relationships between environmental stressors and those vegetative indicators, and 3) make recommendations about the utility and reliability of vegetative indicators to guide managers toward long-term sustainable development.

Methods

Wetland study sites were selected using an objective, stratified random statistical design spanning anthropogenic stressor gradients representing the entire geographic range of the U.S. Great Lakes coast (Danz *et al.* 2005, Danz *et al.* 2006). The 90 wetlands selected for study were distributed from the western end of Lake Superior to the eastern end of Lake Ontario. Sites were classified by hydrogeomorphic type as open-coast wetlands (n=27), riverine wetlands (n=35), or protected wetlands (n=28). Sampling took place from 2001 to 2003 and was restricted to the months of July and August to ensure that most of the vegetation could be identified and peak annual growth was observed.

Sampling was done in 1 x 1-m² plots distributed along randomly placed transects within areas of herbaceous wetland vegetation in the study sites selected. Transects were established with GIS prior to field campaigns, using a program called Sample (<http://www.quantdec.com/sample>) to randomize transect placement (Johnston *et al.* in press). Transects were placed in areas mapped by national and state wetland inventories as emergent wetland vegetation. Each transect intersected a randomly selected point generated by the Sample program, and was oriented to be perpendicular to the perceived water depth gradient, extending from open water to the upland boundary (or to a shrub-dominated wetland zone, if present). Transect length and target number of sample plots were determined in proportion to the size of the wetland to be sampled (20 plots/60 ha, minimum transect length = 40 m, minimum plots/site = 8). Transect coordinates were uploaded into a handheld GPS for use by field crews.

Plot locations were established in the field by dividing each transect into 20 m segments and randomly locating a plot in each segment using a random number table. Within each plot all vascular plant species were identified to the lowest taxonomic division possible. Large, identifiable non-vascular plants, such as *Chara vulgaris* L. and *Sphagnum* spp., were also given cover estimations. If a plant species could not be identified in the field, it was collected, pressed, and identified in the lab, but voucher specimens were not routinely collected. 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%, or 75 to 100%. Prior to data analyses, cover classes were converted to the midpoint percent cover of each class using the algebraic midpoints of the 6 cover class ranges (0.5, 3.0, 37.5, 62.5, 87.5). Field teams were jointly trained and tested to ensure consistency of visual observations (Kercher *et al.* 2003).

Indicator evaluation and development

Research was conducted to evaluate existing indicators and develop new indicators. We identified indicators that were not useful as indicators (see Bourdaghs in review, Brazner *et al.* Ms. 1, Ms. 2).

Species richness. We listed species richness (i.e., number of species per unit area) as a candidate indicator in our original proposal, and expected that increased stress would decrease species richness. We found that species richness was suppressed by tall invasive plant species such as *Typha x glauca* and *Phragmites australis* (Figure 1), but that species richness was not in itself a good indicator of condition. Bourdaghs *et al.* (in review) found species richness to be a much poorer indicator than either the floristic quality index or mean coefficient of conservatism.

Percent of all taxa that are obligate wetland plants.

We expected that the proportion of obligate wetland species would decrease with increasing anthropogenic stress. The relationship was weak, however, because the vast majority of the plants we encountered were obligate wetland species, regardless of the environmental condition of the wetlands sampled. This metric was poorly related ($r^2 = 0.057$) to the overall stress index developed by Danz *et al.* (2006).

Presence of endangered or threatened species. We encountered state-listed species in several wetlands in Michigan, Ohio, Pennsylvania, and New York, but our sampling methodology was not designed to seek out endangered or threatened species, so we could not test its utility as an indicator of environmental condition.

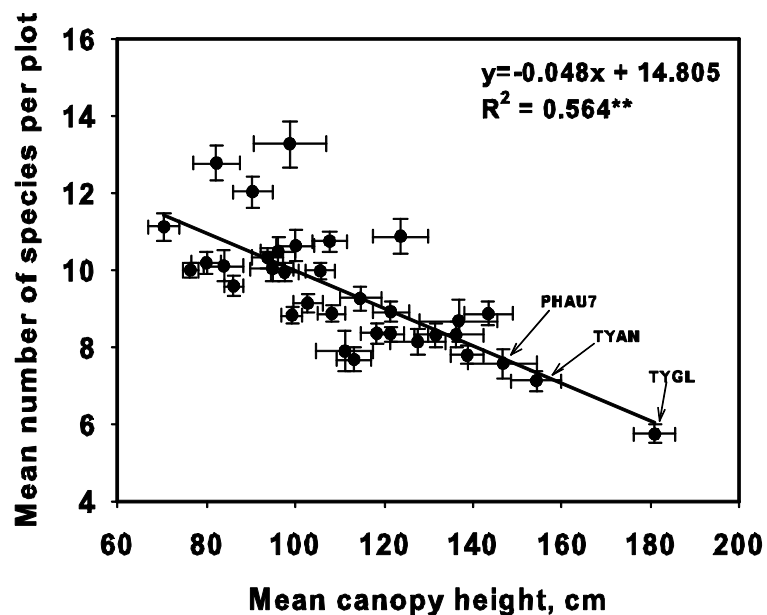


Figure 1. The three tallest plant species, invasive cattails and *Phragmites*, shade out other plant species in their plots.



Existing indicators that were effective indicators

(evaluation in Bourdaghs *et al.* in review, Brazner *et al.* Ms. 1, Ms. 2).

FQI and mean coefficient of conservatism. These existing indices are both based on the coefficient of conservatism (*C*), which is a numerical score from 0 to 10 assigned to each plant species in a local flora that reflects the likelihood that a species is found in remnant natural habitats. Such lists are compiled by state, and currently exist for 4 of the states in which we sampled coastal wetlands: Wisconsin, Michigan, Ohio, and Illinois. FQI is computed by multiplying the mean coefficient of conservatism by the square root of species richness for an observational unit. FQI and mean *C* were better at discriminating differences between sites, independent of a condition gradient, than species richness alone, but neither index type outperformed the other. Both types of indices were also found to be acceptable ecological indicators of condition, although floristic quality indices consistently outperformed coefficient of conservatism indices in this capacity. FQI had an $r^2 = 0.56$ with the stress index developed by Danz *et al.* (in press).

Percent of all taxa that are native plants. This indicator was significantly related ($r^2 = 0.326$) to the stress index developed by Danz *et al.* (2006), and it was particularly sensitive to the proportion of row crop area in watersheds draining to coastal wetlands (Brazner Ms. 2).

New indicators of environmental condition

We developed several new indicators using the wetland vegetation data (see Appendix A12-14). Each is briefly described below.

Multitaxa wetland vegetation indices. Two indices based on either a 10-taxa index or a 4-taxa index were developed. Each uses mean percent cover estimated in a series of 1 m x 1 m transects spanning a moisture gradient within emergent wetland stands. The indices were both shown to be highly correlated with the stress index that represented a variety of stressors affecting these wetland systems. The indices are relevant to the entire Great Lakes coastal system because the taxa used are all widespread throughout the region.

Maximum canopy height. This index is a relatively simple metric of plant biomass within a wetland. Maximum canopy height of wetland plants as measured during the maximum growth stage in July or August was highly correlated with the stress index. This measurement is related to several factors associated with disturbance in wetland systems including 1) fertilization by nutrients contributed by non-point source pollution, 2) invasive plant species that tend to be taller than non-invasive species, and 3) tall plants shade out other plants which results in reductions of plant biological diversity within the wetland. This indicator is relevant to all Great Lakes coastal wetlands and may have applications to many other wetland systems.

Species dominance index (SDI). This index indicates ecological integrity of wetland ecosystems by identifying dominant plant species and categorizing their behavior as 1 of 7 forms of dominance. The index combines 3 related attributes of dominance in a similar fashion that is



commonly used by plant ecologists for the calculation of importance values. Dominance uses 3 attributes: mean plant cover (abundance of the dominant species), mean species suppression (number of species associated with the dominant species), and tendency toward high cover (the likelihood that a species is abundant when it occurs). SDI is calculated like an importance value in which each value is standardized from 0 to 1, summed, and divided by 3. Cut-off values can be assigned for the various forms of dominance in a wetland (see Appendix A14).

The index is useful because a dominant plant species may control its habitat and the presence and performance of other species in the wetland community. The concept is transferable to any wetland. It has been examined for use in restoration efforts at the University of Wisconsin, in microcosms, and in both natural and restored salt marshes in southern California.

Zedler has initiated a new series of "Arboretum Leaflets" that are posted at a link from the UW Arboretum website (<http://www.botany.wisc.edu/zedler/leaflets.html>). These documents summarize the Species Dominance Index as well as other relevant material on wetland ecosystems.

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III. GLEI RESEARCH MEETINGS

2001

March 8-9	First GLEI All-Hands Meeting, Duluth MN
April 19-20	GLEI Advisory Board Meeting, Duluth MN
September 9-14	Field Pilot Sampling Meeting, Green Bay WI
October 28-30	Second GLEI All-Hands Meeting, Duluth MN
December 3-4	Eagle Annual Meeting, Morehead City NC

2002

January 24-25	GLEI Advisory Board Meeting, Duluth MN
March 13, April 29	Site Selection Meeting
June 7-10	Diatom Water Quality Workshop, Lake Michigan
October 27-28	Third GLEI All-Hands meeting, Duluth MN
December 4-6	EaGLE Annual Meeting, Edgewater MD

2003

June 2-6	GLEI Fish-Macroinvertebrate Training, Green Bay WI
June 5-7	GLEI Vegetation Training, Madison WI
November 3-4	Fourth GLEI All-Hands Meeting, Duluth MN
December 3-4	EaGLE Annual Meeting, Bodega Bay CA

2004

September 13-14	Fifth GLEI Annual Meeting (Data), Duluth MN
September 30-Oct 1	EaGLE Annual Meeting, Duluth MN

2005

March 31 – April 1	Sixth GLEI All-Hands Meeting, Duluth MN
June 2-3	Seventh GLEI Annual Meeting (Data), Duluth MN

2006

January 17-18	Eighth GLEI All-Hands Meeting, Duluth MN
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IV. THESES AND DISSERTATIONS

All fully or partially funded by GLEI.

UNDERGRADUATE THESES STUDENTS

Foley, Carolyn. 2004. The associations between larval Odonata and habitat structure as indicators of anthropogenic stress in Great Lakes coastal margin wetlands. Hon BS thesis, University of Windsor. (Current position: master's student, Purdue University).

Ladwig, Laura. 2004. *Typha x glauca* and *Phragmites australis* expansion in Peter's Marsh, Wisconsin. Senior thesis. Department of Botany, University of Wisconsin-Madison.

MASTER'S THESES STUDENTS

Adams, Andrew. 2005. Photo-enhanced toxicity of polycyclic aromatic hydrocarbons to larval fish in the coastal Great Lakes. MS thesis. Environmental Health Sciences, University of Minnesota. Current position: environmental consultant with W & M Environmental Group Inc., Dallas TX.

Bhagat, Yukata. 2005. Fish indicators of anthropogenic stress at Great Lakes coastal margins: multimetric and multivariate approaches. MS thesis. University of Windsor. 120 p. Current position: PhD student, Trent University. PDF.

Bourdaghs, Michael. 2004. Properties and performance of the floristic quality index in Great Lakes coastal wetlands. MS thesis. Current position: wetlands specialist, Minnesota Pollution Control Agency. PDF.

Ferguson, M. In progress. Analysis of the benthic diatom flora in variable habitat regions of the Laurentian Great Lakes. MS thesis. John Carroll University, Cleveland, Ohio.

Grandmaison, David. 2005. Landscape factors affecting productivity of breeding birds in Great Lakes coastal wetlands. MS thesis. University of Minnesota Duluth. Current position: wildlife biologist, Game and Fish Department, Tucson, AZ.

Johnson, Charlene. 2003. Predicting the vegetational composition of a wetland created from dredged material in Duluth-Superior Harbor. MS thesis. University of Minnesota Duluth. Current position: Superior WI Division of Public Works Wastewater Treatment.

Kang, MiSun. 2004. The invasibility of stressed sites by exotic benthic macroinvertebrates in the Great Lakes: a test of hypotheses using *Echinogammarus ischnus*. MS thesis. University of Windsor, Ontario, CA. Current position: PhD student, University of Windsor. PDF.



Lehr, Randy A. 2004. Use of estrogen equivalents to explain vitellogenin induction in fathead minnows (*Pimephales promelas*) exposed to a complex wastewater effluent. MS thesis, Water Resources Science, University of Minnesota. Current position: assistant professor at Grays Harbor College, Aberdeen WA.

Marks, D. 2003. Habitat and landscape associations of breeding birds in Great Lakes coastal wetlands. MS thesis. University of Wisconsin-Green Bay. 123 pp. Current position: U.S. Department of Agriculture, APHIS-Wildlife Services.

Miller, Christy. 2003. Effects of anthropogenic development on breeding bird abundance and communities. MS thesis. University of Minnesota Duluth. Current position: laboratory coordinator, Metropolitan State Community College, Minneapolis MN.

Pengra, Bruce. 2005. Remote sensing of *Phragmites australis* with the EO-1 Hyperion Sensor. MS thesis. South Dakota State University. 103 pp. Current position: United Nations Environmenta Programme, Eros Data Center, Sioux Falls, SD. PDF.

Peterson, Anna. 2005. Evaluation of the Ohio Rapid Assessment Method for wetlands in the western Great Lakes: an analysis using bird assemblages. MS thesis. University of Minnesota Duluth. Current position: education coordinator, HawkWatch International, Salt Lake City, UT. PDF.

Price, Steven. 2003. Anuran-habitat associations in coastal wetlands of the western Great Lakes. MS thesis. University of Wisconsin-Green Bay. 2003. 85 pp. Current position: research coordinator, Davidson College Herpetology Lab Dept. of Biology Davidson College Davidson NC.

Vaccaro, Lynn. 2005. Patterns, mechanisms, and ecological implications of cattail (*Typha* spp.) dominance in Great Lakes wetlands. MS thesis. Cornell University. 125 pp. PDF.

Yanko, K. 2002. An analysis of the benthic diatom flora of the Laurentian Great Lakes, and their use as indicators of water quality. MS thesis. John Carroll University, Ohio, 156 pp.

PHD DISSERTATIONS

Boers, Aaron M. 2006. The effects of stabilized water levels on invasion by hybrid Cattail (*Typha x glauca*). PhD dissertation. Department of Botany, University of Wisconsin-Madison.

Danz, Nicholas. University of Minnesota, St. Paul. In progress.

Frieswyk, C. 2005. Evaluating resilience: The implications of invasive species and natural water-level fluctuation on Great Lakes coastal wetlands. PhD dissertation. University of Wisconsin-Madison.



Kang, MiSun. The influence of entry sequence on invasion success and the importance of scale for biotic resistance to biological invasion. PhD thesis, University of Windsor. In progress.

Lehr, Randy A. 2005. Assessment and management of environmental estrogens. PhD thesis, Water Resources Science, University of Minnesota. 175 pp. Current position: assistant professor at Grays Harbor College, Aberdeen WA.

Tulbure, Mirela. Invasion of Great Lakes coastal wetlands by non-native genotypes of *Phragmites australis*. PhD dissertation. South Dakota State University. In progress.

Wolter, Peter. University of Wisconsin, Madison. In progress.

POSTDOCTORAL FELLOWS

Chang, J. 2004-2005. Great Lakes environmental indicators – vegetation responses to anthropogenic stress. South Dakota State University. Current position: post-doctoral fellow, Department of Plant Science, SDSU.

Grigorovich, I. 2003. Great Lakes environmental indicators - distribution and implications of nonindigenous invading species at Great Lakes coastal margins.

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Holland, J. 2003-2004. Great Lakes environmental indicators - role of scale in indicator sensitivity.



V. PUBLICATIONS

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- Boers, A.M., Rachel, L.D. Veltman, J.B. Zedler. *Typha x glauca* dominance and extended hydroperiod constrain restoration of wetland diversity. *Ecological Engineering*. In press.
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- Host, G.E., J. Schuldt, J.J.H. Ciborowski, L.B. Johnson, T. Hollenhorst, C. Richards. 2005. Use of GIS and remotely sensed data for *a priori* identification of reference areas for Great Lakes coastal ecosystems. *International Journal of Remote Sensing* 26(23):5325-5342. PDF.
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- Foley, C., *et al.* The associations between larval Odonata and habitat structure as indicators of anthropogenic stress in Great Lakes coastal margin wetlands: a structural equation evaluation. Possible submission to *Ecological Applications or Wetlands*. In preparation.
- Frieswyk, C.B., C.A. Johnston, J.B. Zedler. Measuring dominance among co-occurring plants. *Diversity and Distributions*. In review.
- Frieswyk, C.B., J.B. Zedler. Do seed banks confer resilience to coastal wetlands invaded by *Typha x glauca*? *Canadian Journal of Botany*. In review.
- Frieswyk, C.B., J.B. Zedler. Vegetation change in Great Lakes coastal wetlands: deviation from the historical cycle. *Journal of Great Lakes Research*. In review.
- Hanowski, J., R. Howe, R. Regal, G. Niemi, N. Danz. Quantifying sources of variability in wetland breeding bird surveys effects on sampling design. In preparation.
- Holland, J., *et al.* Determining the spatial scale at which Great Lakes nearshore fishes respond to anthropogenic stress. In preparation.



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- Host, G., *et al.* Predicting coastal margin habitat using landscape variables (ref condition vs GLEI). In preparation.
- Howe, R.W., R. R. Regal, G.J. Niemi, N.P. Danz, J.M. Hanowski. A probability-based indicator of ecological condition. *Ecology Indicators*. Submitted.
- Johnson, L., V. Brady, *et al.* Contrasting fish and invertebrate coastal margin habitat between reference and non-reference areas. In preparation.
- Johnson, L., V. Brady, *et al.* Relationships between coastal margin fish and invertebrate habitat and landscape stressors. In preparation.
- Johnston, C.A., *et al.* Plant species indicators of physical environment in Great Lakes Coastal wetlands. *Wetlands* In revision.
- Kang, M., J.J.H. Ciborowski, L. Johnson, T. Hrabik, C. Richards, J. Schuldt. The invasibility of stressed sites by exotic benthic macroinvertebrates in the Great Lakes: a test of hypotheses using *Echinogammarus ischnus*. For submission to *Oecologia*. In preparation.
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- Kireta, A., E.D. Reavie, R.P. Axler, J.C. Kingston, G.V. Sgro. Importance of geomorphic characteristics and lake in developing diatom models in the coastal Great Lakes. *Journal of Great Lakes Research* (special issue). In preparation.
- Lehr, R.A., A. Adams, M. Simcik, G. Ankley, D.L. Swackhamer. 2006. Effects of carrier solvent selection on the Vitellogenin (Vtg) mRNA response in male fathead minnows (*Pimephales promelas*). In preparation.
- Lehr, R.A., A. Adams, M. Simcik, G. Ankley, D.L. Swackhamer. 2006. Linking exposure and effect for environmental estrogens: the exposure-effect paradox. In preparation.
- Lehr, R.A., A. Adams, M. Simcik, G. Ankley, D.L. Swackhamer. 2006. Managing environmental estrogens in aquatic ecosystems. In preparation.
- Miller, C.M., G.J. Niemi, J.M. Hanowski, R.R. Regal. Effects of anthropogenic development on breeding bird abundance and communities. In preparation.
- Morrice, J., N.P. Danz, R.R. Regal, J. Kelly, R. Axler, E. Reavie, *et al.* Landscape characteristics as predictors of water quality in Great Lakes coastal wetlands. In preparation.
- Pengra, B.W., C.A. Johnston, T.R. Loveland. Remote sensing of *Phragmites australis* with the EO-1 Hyperion Sensor. *Remote Sensing of Environment*. In review.
- Reavie, E.D. 2006. Diatom indicator solutions for any budget. *Ecohealth*. In review.
- Reavie, E.D., R.P. Axler, G.V. Sgro, N.P. Danz, J.C. Kingston, A.R. Kireta, T.N. Brown, T.P. Hollenhorst 2006. Diatom-based multimetric index of disturbance for Great Lakes coastlines. *Environmental Bioindicators*. In preparation.



Reavie, E.D. A diatom-based integrative water quality model for Great Lakes coastlines. *Journal of Great Lakes Research* (special issue). In preparation.

Sgro, G.V., E.D. Reavie, J.C. Kingston, A.R. Kireta, M.J. Ferguson, N.P. Danz, J.R. Johansen.
Development of a habitat quality index from a diatom-based tp inference model. In preparation.



VI. PRESENTATIONS

- Adams, A.D. *et al.* Photo-induced polycyclic aromatic hydrocarbon toxic potentials of coastal Great Lakes sites. International Association for Great Lakes Research, Chicago IL. Scientific. 25-Jun-03.
- Adams, A.D., R.A. Lehr, M.F. Simcik, D.L. Swackhamer, S.A. Diamond, D.R. Mount. Photo-induced polycyclic aromatic hydrocarbon toxic potentials of larval fish habitat. Midwest Society of Toxicology and Chemistry, Rhinelander WI. Scientific (100). 29-30 Jan 03.
- Adams, A.D., R.A. Lehr, M.F. Simcik, D.L. Swackhamer, S.A. Diamond, D.R. Mount. Photo-induced toxicity of polycyclic aromatic hydrocarbons and indicator development. Joint Meeting of the Midwest and Ozark Prairie Chapters of the Society of Environmental Toxicology and Chemistry, Lacrosse WI. 4-5 Mar 04.
- Adams, A.D., R.A. Lehr, M.F. Simcik, D.L. Swackhamer, S.A. Diamond, D.R. Mount. Photo-induced toxicity in larval fish from the coastal Great Lakes. International Association for Great Lakes Research, Waterloo ON. 24-28 May 04.
- Bhagat, Y., J.J.H. Ciborowski, T.R. Hrabik, L.B. Johnson, C. Richards, J.A. Schuldt. The use of fish communities to assess water quality along the U.S. Great Lakes coastline: a comparison of multimetric and multivariate approaches. International Association for Great Lakes Research, Waterloo ON. 24-28 May 04.
- Bhagat, Y., J.J.H. Ciborowski, T.R. Hrabik, J.A. Schuldt, L.B. Johnson, C. Richards. Developing environmental indicators of stress at Great Lakes coastal margins. Canadian Conference for Freshwater Fisheries Research, Windsor ON. 5-Jan-06.
- Bhagat, Y., J.J.H. Ciborowski, T.R. Hrabik, L.B. Johnson, C. Richards, J.A. Schuldt. The use of fish communities to assess water quality along the U.S. Great Lakes coastline: a comparison of multimetric and multivariate approaches. International Association for Great Lakes Research, Waterloo ON. 24-28 May 04.
- Bhagat, Y., J.J.H. Ciborowski, V.J. Brady, L.B. Johnson, D.H. Breneman, J.A. Schuldt, T.R. Hrabik, C. Richards. Testing a fish index of biotic integrity for Great Lakes coastal wetlands: Stratification by plant zones. Canadian Section, American Fisheries Society, Collingwood ON. 5-Mar-06.
- Bhagat, Y., J.J.H. Ciborowski, T.R. Hrabik, J.A. Schuldt, L.B. Johnson, C. Richards. Developing fish indicators of stress for the Great Lakes coastal margins using multivariate techniques. International Association for Great Lakes Research, Ann Arbor MI. Scientific (100). 5-May-06.
- Boers, A.M., C.A. Johnston. Assessing the Great Lakes I and II. International Association for Great Lakes Research, Waterloo ON. 24-28 May 04.
- Bourdagh, M. The relationship between sampling area, species richness, and the floristic quality assessment index. Society for the Conservation of Biology, Duluth MN. Scientific. 28 Jun -2 Jul 03.
- Bourdagh, M., C.A. Johnston. The relationship between sampling area, species richness, and the Floristic Quality Assessment Index. EPA All-EaGLes Meeting, Bodega Bay CA. Scientific. 3-6 Dec 03.
- Brady, V.J., Y. Bhagat, J.J.H. Ciborowski, L.B. Johnson, T.P. Hollenhorst, G.E. Host, N.P. Danz, J.C. Brazner. A comparison of coastal fish and macroinvertebrate assemblages between Lake Michigan and the other Great Lakes. State of Lake Michigan Annual Conference, Madison WI. 5-Sep-06.
- Brady, V.J., L.B. Johnson, T.H. Breneman, J.J.H. Ciborowski, J.P. Gathman. Relative influence of landscape, habitat, and anthropogenic stress on macroinvertebrate communities of Great Lakes coastal wetlands. North American Benthological Society, Vancouver BC. 4-Jun-06.
- Brady, V.J., L.B. Johnson, D.H. Breneman, J.J.H. Ciborowski, T.R. Hrabik, C. Richards, J.A. Schuldt. Relative influence of landscape characteristics and anthropogenic stress on fish communities in Great Lakes coastal wetlands. International Association for Great Lakes Research, Chicago IL. Scientific. 23-Jun-03.
- Brady, V.J., L.B. Johnson, D.H. Breneman, J.J.H. Ciborowski, C. Richards. Relative influence of landscape, habitat, and anthropogenic stress on macroinvertebrate communities of Great Lakes coastal wetlands. North American Benthological Society, New Orleans LA. 5-Jun-06.
- Brady, V.J., G.J. Niemi, L.B. Johnson. Great Lakes environmental indicators project. Great Lakes Wetlands Consortium, Kellogg Biological Station, Lansing MI. Scientific (75). 1-Mar-06.
- Brady, V.J., J.A. Schuldt, L.B. Johnson, J.J.H. Ciborowski, G.E. Host, T.P. Hollenhorst, C. Richards, D.H. Breneman, J.P. Gathman. Identification of reference Great Lakes coastal wetlands and comparison of fish communities between reference and non-reference systems. Environmental Monitoring and Assessment Program Symposium, Newport RI. 3-May-04.



- Brazner, J.C. *et al.* Fish assemblages as indicators of Lake Superior coastal wetland condition. International Association for Great Lakes Research, Chicago IL. Scientific. 23-Jun-03.
- Brazner, J.C., N.P. Danz, G.J. Niemi, J.M. Hanowski, C.A. Johnston, L.B. Johnson. Evaluating geographic and geomorphic influences on indicators of Great Lakes coastal wetland condition across multiple taxonomic groups. Ecological Society of America, Montréal QC. Scientific. 9-Aug-05.
- Breneman, D.H. Developing environmental indicators for Great Lakes coastal margins. Great Lakes Fisheries Commission, Upper Lakes Common Session, Milwaukee WI. Scientists/ Fed, State Managers (50). 17-18 Mar 03.
- Breneman, D.H. V.J. Brady, J.J.H. Ciborowski, T.R. Hrabik, C. Richards, J.A. Schuldt, L.B. Johnson. Developing Great Lakes environmental indicators using wetland fish communities. North American Benthological Society, Athens GA. Scientific. 27-31 May 03.
- Chang, J., C.A. Johnston. Object-oriented classification of high-resolution coastal wetland imagery. 16th William T. Pecora Memorial Symposium: Global Priorities in Land Remote Sensing, Sioux Falls SD. 23-27 Oct 05.
- Chang, J., C.A. Johnston, G.J. Niemi, P.T. Wolter. Classification of high-resolution coastal wetland imagery using object-oriented segmentation method (poster). South Dakota/North Dakota EPSCoR (National Science Foundation, Brookings SD. 8-9 Sep 05.
- Ciborowski, J.J.H. Overview of Great Lakes environmental indicators project. Lake Erie Lamp Workgroup (Quarterly Meeting of Lake Erie Technical Workgroup), Dunkirk NY. Scientific/ Federal, State Managers (30). 7-Dec-01.
- Ciborowski, J.J.H. Integrating reference conditions and multiple stressors with ecosystem objectives and SOLEC indicators. Lake Erie Millennium Plan Planning Meeting for Habitat Research Workshops, Windsor ON. Scientific/Federal, State Managers (30). 15-16 May 02.
- Ciborowski, J.J.H. Overview of Great Lakes environmental indicators project. Lake Erie Lamp Workgroup, Lake Ontario Interdisciplinary Science Conference, Great Lakes Research Consortium, Syracuse NY. Scientists/Federal, State Managers (80). 13-Mar-03.
- Ciborowski, J.J.H. The Great Lakes environmental indicators project. Lake Ontario Interdisciplinary Science and Management Conference, Great Lakes Research Consortium, Syracuse NY. 13-Mar-03.
- Ciborowski, J.J.H. Staying on target: A regional workshop for establishing restoration targets for Great Lakes areas of concern. Invited seminar, Great Lakes Commission, Romulus MI. 6-7 Jun 03.
- Ciborowski, J.J.H. Great Lakes and great challenges - a cooperative approach to understanding and addressing the questions. Keynote address - Public Forum of the 2003 Biennial Meeting of the International Joint Commission, Ann Arbor MI. 20-Sep-03.
- Ciborowski, J.J.H. Environmental indicators: measuring and linking physical, chemical and biological integrity in the Great Lakes. Workshop: Chemical Integrity. Invited presentation: International Joint Commission, Kingston ON. 6-8 Jun 05.
- Ciborowski, J.J.H. Invertebrate metric development based on mouthpart deformities and chromosomal effects in larval chironomids. Great Lakes Wetlands Consortium, Kellogg Biological Station, Lansing MI. Scientific (75). 1-Mar-06.
- Ciborowski, J.J.H. Developing, evaluating, and integrating biological indicators of environmental conditions at Great Lakes coastal margins. Invited seminar: University of Manitoba, Winnipeg MB. 6-Mar-06.
- Ciborowski, J.J.H. Developing, evaluating, and integrating biological indicators of environmental conditions at Great Lakes coastal margins. Invited seminar: State University of New York, Brockport NY. 5-Apr-06.
- Ciborowski, J.J.H. Developing, evaluating, and integrating biological indicators of environmental conditions at Great Lakes coastal margins. Invited seminar: F.T. Stone Lab of Ohio State University, Catawba OH. 5-Jun-06.
- Ciborowski, J.J.H., L.B. Johnson. External review of the SOLEC indicators. Review panel, Detroit MI. 4-Jan-04.
- Ciborowski, J.J.H., L.B. Johnson, J.P. Gathman, V.J. Brady, J.D. Holland, T.P. Hollenhorst, J.A. Schuldt, G.E. Host, C. Richards, T.R. Hrabik. Integrating indicators of environmental condition at Great Lakes coastal margins: mapping results of standardized multivariate analyses. North American Benthological Society, Vancouver BC. 4-Jun-06.



- Ciborowski, J.J.H., L.B. Johnson, G.E. Host, T.P. Hollenhorst, J.A. Schuldt, C. Richards. Identifying reference areas at Great Lakes coastal margins. Invited seminar webcast to members of the Human Disturbance Gradient development team from EPA, TetraTech, Inc., and others. 4-Jun-04.
- Ciborowski, J.J.H., J.A. Schuldt, L.B. Johnson, G.E. Host, T.P. Hollenhorst, and C. Richards. Reference conditions, degraded areas, Stressors, and impaired beneficial uses: conceptual integration of approaches to evaluating human-related environmental pressures. Aquatic Toxicity Workshop, Ottawa ON. 29 Sep-2 Oct 03.
- Ciborowski, J.J.H., J.A. Schuldt, L.B. Johnson, G.E. Host, C. Richards, T.P. Hollenhorst. Reference conditions, degraded areas, stressors, and impaired beneficial uses: conceptual integration of approaches to evaluating human-related environmental pressures. International Association for Great Lakes Research, Chicago IL. Scientific. 23-Jun-03.
- Ciborowski, J.J.H., J.A. Schuldt, L.B. Johnson, G.E. Host, C. Richards, T.P. Hollenhorst. reference conditions, degraded areas, stressors, and impaired beneficial uses: conceptual integration of approaches to evaluating human-related environment pressures. Environmental Monitoring and Assessment Program Symposium, Newport RI. 3-May-04.
- Danz, N.P., L.B. Johnson, G.J. Niemi, R.R. Regal, J.A. Schuldt, V.J. Brady, J.C. Brazner, M. Bourdaghs, C.A. Johnston, T.N. Brown, J.M. Hanowski. Integrating a fish, bird, and plant wetland indicator using regional ecological normalization. Society for Conservation Biology, Duluth MN. Scientific. 28 Jun 2-2 Jul 03.
- Danz, N.P., G.J. Niemi, R.R. Regal, L.B. Johnson, T.P. Hollenhorst, T.N. Brown, V.J. Brady. Sampling along human pressure gradients in the coastal Great Lakes. Environmental Monitoring and Assessment Program Symposium, Newport RI. 3-May-04.
- Danz, N.P., R.R. Regal, G.J. Niemi, T.P. Hollenhorst, V.J. Brady. Using multiple anthropogenic stressors to characterize Great Lakes coastal ecosystems. International Association for Great Lakes Research, Chicago IL. Scientific. 23-Jun-03.
- Foley, C., D.H. Breneman, J.J.H. Ciborowski, J.D. Gathman, V.J. Brady, L.B. Johnson, C. Richards. The associations between larval Odonata and habitat structure as indicators of anthropogenic stress in Great Lakes coastal margin wetlands. International Association for Great Lakes Research, Waterloo ON. 24-28 May 04.
- Frieswyk, C.B., A.M. Boers, C.A. Johnston, J.B. Zedler. Cattail dominance as an indicator. International Association for Great Lakes Research, Waterloo ON. 24-28 May 04.
- Frieswyk, C.B., C.A. Johnston, J.B. Zedler. Forms of dominance in wetland plants: a potential indicator of integrity. University of Wisconsin Arboretum Science Day, Madison WI. 17-May-04.
- Frieswyk, C.B., C.A. Johnston, J.B. Zedler. Measuring dominance among co-occurring plants. Coastal Society, Newport RI. 23-26 May 04.
- Frieswyk, C.B., C.A. Johnston, J.B. Zedler. Quantifying and qualifying dominance in vegetation. 89th Annual Meeting of the Ecological Society of America, Portland OR. 1-6 Aug 04.
- Frieswyk, C.B., A. Vargas. Wetland indicators for the National Coastal Management Performance Measurement System. Discussion leaders, Great Lakes Regional Meeting of Coastal Management Programs, Milwaukee WI. 13-15 Sep 04.
- Frieswyk, C.B., J.B. Zedler. Do seed banks confer resilience to coastal wetlands invaded by cattail? Wisconsin Wetland Association 10th Annual Wetland Science Forum, Green Bay WI. 26-Jan-05.
- Frieswyk, C.B., J.B. Zedler. Many types of dominance. Society for the Conservation of Biology, Duluth MN. Scientific. 28 Jun -2 Jul 03.
- Grandmaison, D. Landscape indicators of nest predation in Great Lakes coastal wetlands. International Association for Great Lakes Research, Chicago IL. Scientific. 23-Jun-03.
- Hanowski, J.M. Breeding birds and amphibians: are they useful in defining condition of Great Lakes coastal wetlands? Department of Biology, University of MN, Duluth. Scientific. 5-Nov-06.
- Hanowski, J., R. Howe, C.R. Smith, D. Marks, S. Price. What can birds and amphibians indicate about the ecological condition of coastal ecosystems? Ecological Society of America, Savannah GA. Scientific. 7-Aug-03.
- Hanowski J.M., R.W. Howe, C.R. Smith, D. Marks, S. Price. Breeding birds and amphibians: are they useful in defining condition of Great Lakes coastal wetlands? Society of Wetland Scientists, Seattle WA. 19-23 Jul 04.
- Hanowski J.M., R.W. Howe, C.R. Smith, G.J. Niemi. can nationally standardized wetland breeding bird and amphibian monitoring data be used to assess the condition of Great Lakes coastal wetlands? Environmental Monitoring and Assessment Program Symposium, Newport RI. 3-May-04.



- Hanowski, J.M., R.W. Howe, C.R. Smith, G.J. Niemi. Comparison of wetland breeding bird and amphibian communities as integrative indicators of human impacts on Great Lakes coastal zones. Ecological Society of America, Montréal QC. Scientific. 9-Aug-05.
- Holland, J.D., V.J. Brady, J.J.H. Ciborowski, T.P. Hollenhorst, L.B. Johnson. The spatial scale at which indicator species indicate. International Association for Great Lakes Research, Waterloo ON. 24-28 May 04.
- Holland, J.D., J.J.H. Ciborowski, L.B. Johnson, J.C. Brazner. Biotic homogenization of macroinvertebrate assemblages along an anthropogenic stress gradients. Ecological Society of America, Montréal QC. Scientific. 9-Aug-05.
- Hollenhorst, T.P., N.P. Danz, G.J. Niemi, R.R. Regal, V.J. Brady. A method for selecting wetland study sites along a human disturbance gradient: a case study developing ecological indicators for the Great Lakes coastal margin. Society of Wetland Scientists, Seattle WA. 19-23 Jul 04.
- Host, G.E., T.P. Hollenhorst, L.B. Johnson, J.A. Schuldt, J.J.H. Ciborowski, C. Richards. Use of GIS and remotely-sensed data for *a priori* identification of reference areas for Great Lakes coastal ecosystems. Association of American Geographers, New Orleans LA. Scientific. 4-7 Mar 03.
- Howe, R.W. Monitoring the ecological health of North America's Great Lakes. Inaugural Lecture of UW-Green Bay Downtown Lecture Series, Green Bay WI. 23-Mar-04.
- Howe, R.W., J.M. Hanowski, C.R. Smith, G.J. Niemi. Birds and amphibians as ecological indicators in Great Lakes watersheds. International Association for Great Lakes Research, Waterloo ON. 24-28 May 04.
- Howe, R.W., M.T. Jones, N.P. Danz, J.M. Hanowski, G.J. Niemi, D. Ewert, J. Davis. A GIS framework for bird conservation and monitoring in western Great Lakes forests. Society for Conservation Biology, Duluth MN. Scientific. 28 Jun-2 Jul 03.
- Howe, R., J. Karr, A. Wolf. Historical and recent approaches to the assessment of ecological condition. Ecological Society of America, Savannah GA. Scientific. 7-Aug-03.
- Howe, R.W., R.R. Regal, G.J. Niemi, J.M. Hanowski, N.P. Danz. A new approach for developing indicators of ecological condition in Great Lakes coastal wetlands. Wisconsin Wetland Association 10th Annual Wetland Science Forum, Green Bay WI. 26-Jan-05.
- Hrabik, T.R., L.B. Johnson, V.J. Brady, D.H. Breneman, J.J.H. Ciborowski, C. Richards. Quantifying the influence of landscape characteristics on fish communities in coastal riverine wetlands for use as indicators. Eagle Symposium, American Society of Limnologists and Oceanographers, Salt Lake City UT. Scientific (40). 9-14 Feb 03.
- Johnson, L.B. Testing indicators of coastal ecosystem integrity using fish and macroinvertebrates. Great Lakes Fisheries Commission, Duluth MN. Scientific. 25-Feb-02.
- Johnson, L.B. Overview of Great Lakes environmental indicators project. Lake Erie Millennium Plan Planning Meeting for Habitat Research Workshops, Windsor ON. Scientific/ Federal, State Managers (30). 15-16 May 02.
- Johnson, L.B. Quantifying stressors across shorelines of the Great Lakes: the Great Lakes environmental indicators project. Minnesota Department of Natural Resources Fisheries Research Staff, Duluth MN. Scientific. 17-Jul-02.
- Johnson, L.B. Lake Superior canaries: Directing ecological change. Sea Grant: Superior Science for You, held at EPA Mid-Continent Ecology Division, Duluth MN. Public. 15-Jan-03.
- Johnson, L.B. Lake Superior canaries: Detecting ecological change. Sea Grant: Superior Science for You, Grand Portage MN. Public. 16-Jan-03.
- Johnson, L.B. Development of environmental indicators of condition, integrity, and sustainability in the Great Lakes basin (GLEI). Invited seminar, Wetland Studies Center, Ohio State University, Columbus OH. 22-Jan-04.
- Johnson, L.B., D.H. Breneman, V.J. Brady, J.J.H. Ciborowski, Y. Bhagat. Indicators of water quantity and quality issues: examples from Great Lakes coastal areas. Invited seminar: Sustainable Water Resources Roundtable, Ann Arbor MI. 5-Apr-06.
- Johnson, L.B., D.H. Breneman, J.J.H. Ciborowski, V.J. Brady, G.E. Host, J.A. Schuldt, T.R. Hrabik, C. Richards. Identifying reference areas and fish communities in highly disturbed coastal Great Lakes regions. North American Benthological Society, New Orleans LA. 5-Jun-06.



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- Johnson, L.B., J.J.H. Ciborowski, V.J. Brady, T.P. Hollenhorst, J.A. Schuldt, G.E. Host, J.D. Holland, J.P. Gathman, C. Richards, T.R. Hrabik. Developing indicators of coastal ecosystem condition. Seminar for the Office of Wetlands, Oceans, and Watersheds, U.S. EPA, Washington D.C. 4-Dec-04.
- Johnson, L.B., J.J.H. Ciborowski, V.J. Brady, T.P. Hollenhorst, J.A. Schuldt, G.E. Host, C. Richards, T.R. Hrabik. Development of environmental indicators of condition, integrity, and sustainability in the Great Lakes basin. Invited seminar at EPA Region 5, STAR Science Colloquium, Chicago IL. 4-Jul-04.
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- Kingston, J.C. Great Lakes environmental indicators: diatom-based assessment tools in coastal wetlands. International Association of Great Lakes Research, Winnipeg MB. Scientific (50). 2-6 Jun 02.
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- Kireta, A.R., E.D. Reavie, R.P. Axler, J.C. Kingston, G.V. Sgro Diatom-based nutrient models for the Great Lakes: spatial and geomorphic considerations. North American Benthological Society, Anchorage AK. Scientific (100). 6-Jun-06.
- Kireta, A.R., E.D. Reavie, R.P. Axler, J.C. Kingston, G.V. Sgro Importance of geomorphic characteristics and lake in developing diatom models in the near-shore Great Lakes. North American Diatom Symposium, Mobile AL. Scientific (80). 5-Nov-06.
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- Miller, C., K. Stroom, C. Richards, G.J. Niemi, J.M. Hanowski. Negative response of bird and aquatic macroinvertebrates to urban development in western Lake Superior. International Association for Great Lakes Research, Chicago IL. Scientific. 23-Jun-03.
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- Niemi, G.J. The quest for indicators of the U.S. Great Lakes freshwater coast. Invited: Dept of Biology Seminar, Duluth MN. Scientific (80). 13-Dec-02.
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- Niemi, G.J., L.B. Johnson, N.P. Danz, J.C. Brazner, V.J. Brady, J.R. Kelly. Local, landscape, and regional influences on biotic indicators in Great Lakes coastal zones. Ecological Society of America, Montréal QC. Scientific (50). 9-Aug-05.
- Niemi, G.J. H. Paerl, B. Levinson Organized Oral Session 17: Coastal indicators of ecological condition: integration of spatial scales. Ecological Society of America, Montréal QC. Scientific (50). 9-Aug-05.
- Pengra, B., J. Chang, C.A. Johnston. Influence of coastal geology on wetland abundance in the Great Lakes. Rushmore Regional Conference on Biocomplexity, Sioux Falls SD. 11-12 Aug 04.
- Radix, C. Effects of environmental stresses on zoobenthos of nearshore zones across the Great Lakes. Graduate Seminar Series, University of Windsor, Windsor ON. Scientific. 19-Mar-02.
- Reavie, E.D. Algal tools for Great Lakes coastlines: recommendations for monitoring and paleoecology. Dept. Biology, seminar series, University of Minnesota Duluth, Duluth MN. Scientific (60). 6-Feb-06.



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- Schuldt, J.A. *et al.* Identifying reference areas at Great Lakes coastal margins: application of an *a priori* classification system derived from spatial data on anthropogenic stressors. International Association for Great Lakes Research, Chicago IL. Scientific. 23-Jun-03.
- Sgro, G.V., E.D. Reavie, A.R. Kireta, J.C. Kingston, R.P. Axler, M.J. Ferguson, E.F. Stoermer. Comparison of benthic diatom indices of habitat quality in the Laurentian Great Lakes. International Association for Great Lakes Research, Ann Arbor MI. Scientific (100). 5-May-06.
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- Stoermer, E.F. Importance of physical factors in determining diatom occurrence and distribution in large lakes. International Diatom Symposium, Mięzyzd PL. 2-7 Sep 04.
- Swackhamer, D.L. Great Lakes environmental indicators project. Science Advisory Board of the International Joint Commission of the U.S. and Canada, Windsor ON. Scientific (25). 28-Nov-01.
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- Thompson, J.A., J.A. Morrice, S.L. Batterman, A.M. Cotter, G.S. Peterson, N.P. Danz. Wetland morphologic and biogeographic influences on algal responses to nutrient loading in Great Lakes coastal wetlands. North American Benthological Society, Athens GA. Scientific. 27-31 May 03.
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- Tulbure, M., D.L. Auger, C.A. Johnston. A rapid expansion of *Phragmites australis* in a Great Lakes coastal wetland. Ecological Society of America, Montréal QC. Scientific. 9-Aug-05.
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- Vaccaro, L.E., C.A. Johnston, B.L. Bedford. Understanding a biotic indicator: Scaling down from regional patterns to local mechanisms of cattail dominance and plant species density. Ecological Society of America, Montréal QC. Scientific. 9-Aug-05.
- Wolter, P.T., G.J. Niemi, C.A. Johnston. Development of environmental indicators for the U.S. Great Lakes basin using remote sensing technology. EPA All-EaGLes Meeting, Bodega Bay CA. Scientific. 3-6 Dec 03.
- Yurista, P.M., J.R. Kelly, S.E. Miller. Zooplankton size-spectra as an indicator in Great Lakes coastal waters. Eagle Symposium, American Society of Limnologists and Oceanographers, Salt Lake City UT. Scientific. 9-14 Feb 03.
- Yurista, P.M. *et al.* Zooplankton size-spectra in Great Lakes coastal waters. International Association for Great Lakes Research, Chicago, IL. Scientific. 23-Jun-03.
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- Zedler, J.B., J. Verhoeven. Restoring wetland biodiversity: why, where and how? The International Association for Ecology, Utrecht NL. 25-30 Jul 04.



APPENDIX A. INDICATOR SUMMARIES



A.1. AMPHIBIANS OF COASTAL WETLANDS

Project Summary

Amphibians are often recognized as important indicators of environmental health or ecological condition due to their dependence on both water quality and wetland habitat. During 2002-2003, researchers from the University of Wisconsin-Green Bay, University of Minnesota Duluth's Natural Resources Research Institute, and Cornell University completed an extensive field survey of breeding frogs and toads (anurans) at 331 points in 220 coastal segments in the U.S. portion of the Great Lakes coastal zone. Methods followed guidelines outlined by MMP for conducting amphibian calling surveys (Weeber and Vallianatos 2001). Three calling surveys were conducted at each site during early spring (when night-time temperatures reached 5°C), mid-spring (when over-night temperatures reached 10°C), and early summer (when temperatures reached 17°C). Calling level codes were assigned to each species, although this analysis explores simply the presence or absence of a species among all 3 counts.

Field data were complemented by GIS analysis of land cover data and other environmental variables such as human population density, pollution emissions, and agricultural impacts. Multivariate analysis of these variables yielded a gradient of "reference condition" ranging from 0 (maximally impacted by humans) to 10 (minimally impacted by humans). Wetland sites with similar reference condition were grouped into categories, and the proportion of sites where the species was recorded at least once was used as the probability of finding the species in that category. Separate analyses were conducted for the northern Laurentian Mixed Forest Ecological Province and the southern Eastern Deciduous Forest Ecological Province. More detailed, local scale variables were collected for a subset of sites by Steven Price as part of his master's thesis work at the University of Wisconsin-Green Bay.

Results

Observers recorded 13 species of frogs and toads, 4 of which were too rare to warrant quantitative analysis. Responses of each anuran species to the reference gradient (Figure 1) were plotted and evaluated in the context of a new, probability-based indicator method developed by scientists in the GLEI project (Howe *et al.*, in review). In general, frog and toad species did not show as close relationships with the reference gradient as did birds, although one species, Spring Peeper, was consistently sensitive to reference condition in both the northern (Figure 1a) and southern ecological provinces. Several species (e.g., Gray Treefrog) showed little or no relationship with reference condition in one ecological province (Figure 1b) but a stronger or opposite relationship in the other ecological province (Figure 1c).

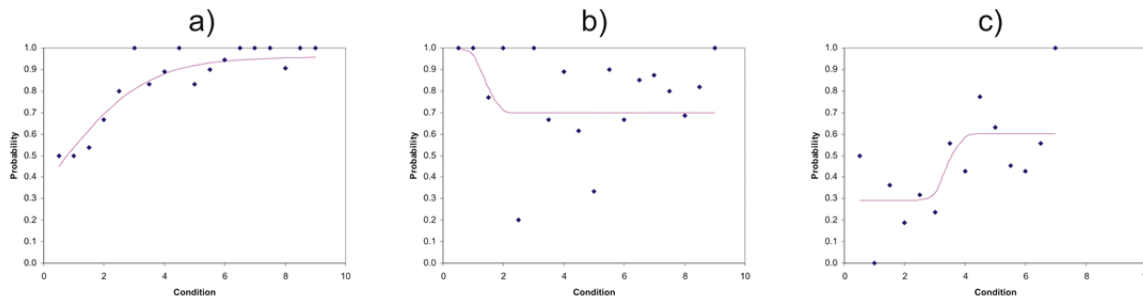


Figure 1. Relationship of species occurrence and reference condition for: a) Spring Peeper (*Pseudachris crucifer*) in the Laurentian Mixed Forest Ecological Province, b) Gray Treefrog (*Hyla versicolor*) in the Laurentian Mixed Forest, and c) Gray Treefrog in the Eastern Deciduous Forest Ecological Province.

An Amphibian-based Indicator of Ecological Condition

Our findings suggest that the occurrence of just a single anuran species, Spring Peeper, is the most defensible and robust indicator of ecological condition with respect to our reference gradient. A method for applying this method follows these steps:

1. Using a protocol similar to MMP methods, estimate the probability of recording Spring Peepers in an area of interest. For example, use relative frequency of occurrence from multiple points as the probability or use simply 1 = present and 0 = absent.
2. The SSD function for Spring Peeper (e.g., Fig. 1a) will give a value or range of condition values that best “fits” the observed probability.

In Fig. 1a, a relative frequency of 0.6 will indicate a condition of approximately 1.5 in the Laurentian Mixed Forest Ecological Province. A relative frequency of 0.9 will indicate a condition between 6 and 10. This method is most useful when combined with simultaneous condition estimates from other species such as wetland birds. In other words, information from Spring Peepers can contribute to an estimate of condition based on information from multiple species, as described by Howe *et al.* (in review). Our findings suggest that this procedure should be applied separately for the 2 ecological provinces in the Great Lakes coastal zone. The inconsistent stress-response relationships of other species of frogs and toads (anurans) suggest that species richness of anurans in Great Lakes coastal wetlands clearly is not a reliable indicator of ecological condition.

For further information contact Robert Howe (email: hower@uwgb.edu) regarding this indicator. For questions related to the greater GLEI project please contact Gerald Niemi (email: gniemi@d.umn.edu).



A.2. BIRDS OF COASTAL WETLANDS

Project Summary

During 2002-2003, researchers from the University of Wisconsin-Green Bay, University of Minnesota Duluth's Natural Resources Research Institute, and Cornell University completed perhaps the most extensive field survey of breeding birds ever conducted in the Great Lakes coastal zone. More than 22 trained observers sampled 371 points in 215 wetland complexes, ranging from the western edge of Lake Superior in Minnesota to the eastern edge of Lake Ontario in New York State. Methods followed a standardized protocol used today by the Marsh Monitoring Program (Weeber and Vallianatos 2000).

Objectives of this project were to 1) develop a suite of scientifically robust, cost-effective indicators of ecological condition for the Great Lakes; 2) quantify the extent to which these indices are related to environmental pressure indicators such as land use characteristics; 3) use the results to improve the scientific framework for environmental monitoring programs in the Great Lakes basin.

Results

Observers recorded 155 bird species, approximately 54 of which are characteristic of wetland habitats. To assess the response of these species to environmental stress, a reference gradient was established based on a large number of environmental variables describing land cover, agriculture, human population density, roads, pollution emissions, and other human impacts. Multivariate statistical analysis was used to align the study sites along a single gradient ranging from 0 (maximally impacted by humans) to 10 (minimally impacted by humans). Responses of each bird species to the reference gradient (Figure 1) were plotted and described by a mathematical function illustrating the probability of finding the species in maximally degraded sites, the probability of finding the species in minimally degraded sites, the value along the reference gradient where the probability of finding the species is halfway between the maximum and minimum probabilities, and the overall steepness of the relationship. These SSD functions contain information about the response of each species to human impacts as well as the overall probability of finding the species in the study area. Once they have been derived, the SSD functions form the basis of a robust and highly flexible method for estimating ecological condition.

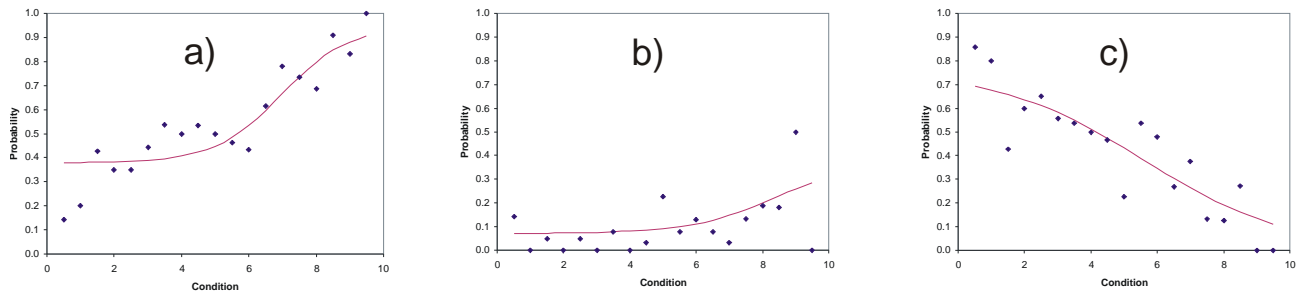


Figure 1. Examples of SSD functions for a) Swamp Sparrow, b) Bald Eagle, and c) Common Grackle. Horizontal axis is an environmental reference gradient based on human impact. Vertical axis is the probability of occurrence or frequency of the species among sample sites.

Probability-based Ecological Indicators

Ecological condition (C) for new sites can be derived through an ingenious method described by Hilborn and Mangel (1997). Rather than calculate C directly, one asks “what is the value of C that best reflects the SSD functions of the observed species?” Presence of sensitive bird species like those in Figure 1a and 1b, for example, indicates that the condition of a site must be high. An iterative process for calculating C can be implemented with the help of familiar computer software like Microsoft Excel. Eventually, a web-based utility might calculate C given any combination of species (not just birds) for which SSD functions are available. This project provides preliminary SSD functions that can be used today by environmental monitoring programs. All a user needs to do is apply results from standard bird counts, such as those from the Marsh Monitoring Program.

Computer iteration will yield a value of C ranging from 0 to 10, grounded in (but not simply mirroring) the reference gradient of human impact.

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- Weeber, R. C., M. Vallianatos. 2000. *The Marsh Monitoring Program 1995-1999. Monitoring Great Lakes wetlands and their amphibians and bird inhabitants*. Published by Bird Studies Canada in cooperation with Environment Canada and U.S. Environmental Protection Agency.

For further information contact Robert Howe (email: hower@uwgb.edu) regarding this indicator. For questions related to the greater GLEI project please contact Gerald Niemi (email: gniemi@d.umn.edu).



A.3. BIRDS OF THE COASTAL ZONE

Ecological Condition (C_{obs}) Based on Coastal Zone Birds in the Eastern Deciduous Forest Province

Project Summary

Coastal regions of the Laurentian Great Lakes reflect conditions in the surrounding watershed and exert an important influence on the lakes themselves. Indicators of ecological health or integrity in the coastal zone therefore provide valuable information about the effects of human activities on the Great Lakes ecosystem. As part of the GLEI project, researchers from the University of Wisconsin-Green Bay, University of Minnesota Duluth's Natural Resources Research Institute, and Cornell University conducted an extensive survey of birds in the U.S. portion of the Great Lakes coastal zone, defined as the area within 1 km of the shoreline. Data were collected at 171 randomly selected coastal segments (from 762 total) stratified across a multivariate gradient of environmental stressors (Danz *et al.* 2005), 76 of which were located in the Eastern Deciduous Forest Ecological Province. For each segment, we conducted transect surveys consisting of standard 10 min bird counts at 15 roadside sampling points, each separated by at least 500 m. Selected sites were sampled twice, yielding a combined sample size of 2544 point counts at 194 bird census routes. The primary objective of this work was to develop multispecies indicators of ecological condition that can be applied at both local and basin-wide scales.

Results

We encountered 187 bird species during the 2-year (2002-03) field effort. The numbers of species per transect in the Eastern Deciduous Forest Ecological Province (mean = 43.7 species, s.d. = 8.7) were remarkably similar to those in the Laurentian Mixed Forest Ecological Province

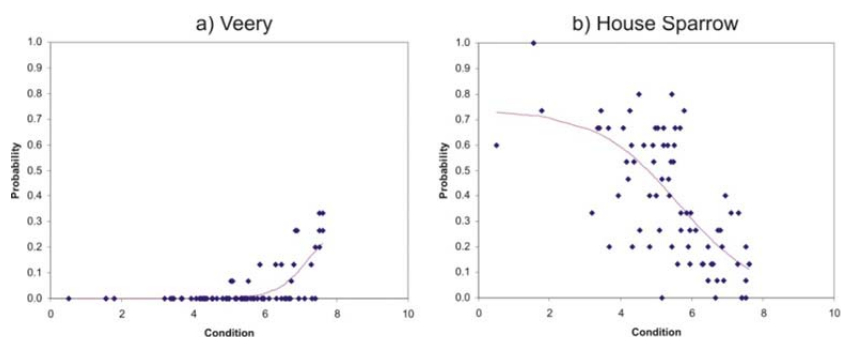


Figure 1. Species-specific sensitivity/detectability (SSD) functions (solid lines) for Veery (positively associated with condition) and House Sparrow (negatively associated with condition). Presence of Veery and absence of House Sparrow indicate high values of condition, whereas absence of Veery and presence of House Sparrow indicate low values of condition.

(mean = 43.6 species, s.d. = 9.6), but species composition differed significantly between the 2 regions. Human impacts associated with the bird survey transects were assessed by GIS/remote sensing analysis of Landsat 5 and Landsat 7 satellite images. Proportions of cover in 5 general land use

categories (natural vegetation, residential, commercial/industrial, agricultural, and roads) were evaluated at different distances (100 m, 500 m, 1 km, 3 km, 5 km) from the 15 bird survey points. Multivariate analysis was used to generate a formula for calculating “reference condition” based on land cover, ranging from 0 (maximally impacted by humans) to 10 (minimally



impacted by humans). The frequency of each species among the 15 point counts was used as the probability of encountering the species in the coastal segment. Probabilities were plotted against the reference condition to describe the species' response to environmental stress. A simple, 4 parameter mathematical function was used to describe each relationship (Figure 1). These *SSD functions* contain information about the response of each species to human impacts as well as the overall probability of finding the species in the study area. Our results demonstrate that these relationships might vary by geographic region. Once derived, the SSD functions can be used to calculate the ecological condition of new sites.

Calculating Ecological Condition

The method for calculating ecological condition (C) follows an iterative or computerized “trial-and-error” process described by Hilborn and Mangel (1997). The first step is to derive parameters of SSD functions for species of interest. This is done through expert opinion or preliminary work like ours. We have derived statistically significant functions for 50 species in the Eastern Deciduous Forest Ecological Province, but robust multivariate indicators can be derived using a smaller number of species. We recommend a list of 25 species showing the strongest SSD functions and representing a range of habitat preferences. Important species on this list include Veery, Ovenbird, Red-eyed Vireo, Black-capped Chickadee, Chipping Sparrow, Red-bellied Woodpecker, American Redstart, and Canada Warbler (positively associated with condition) and Rock Pigeon, House Sparrow, European Starling, Common Grackle, and Ring-billed Gull (negatively associated with condition). Given data on frequencies or presence/absence of the selected species, the next step is to compute (through iteration) the value of C that best “fits” the observed occurrence data. Absence of a species can be as important as presence, so surveys need to be complete (i.e., comparable to the method used for deriving the SSD functions) for the target species. The iterative process for calculating C can be implemented with the help of familiar computer software like Microsoft Excel.

For further information contact Robert Howe (email: hower@uwgb.edu) regarding this indicator. For questions related to the greater GLEI project please contact Gerald Niemi (email: gniemi@d.umn.edu).



Ecological Condition (Cobs) Based on Coastal Zone Birds in the Laurentian Mixed Forest Province

Project Summary

Coastal regions of the Laurentian Great Lakes reflect conditions in the surrounding watershed and exert an important influence on the lakes themselves. Indicators of ecological health or integrity in the coastal zone therefore provide valuable information about the effects of human activities on the Great Lakes ecosystem. As part of the GLEI project, researchers from the University of Wisconsin-Green Bay, University of Minnesota Duluth's Natural Resources Research Institute, and Cornell University conducted an extensive survey of birds in the U.S. portion of the Great Lakes coastal zone, defined as the area within 1 km of the shoreline. Data were collected at 171 randomly selected coastal segments (from 762 total) stratified across a multivariate gradient of environmental stressors (Danz *et al.* 2005), 95 of which were located in the Laurentian Mixed Forest Ecological Province. For each segment, we conducted transect surveys consisting of standard 10 min bird counts at 15 roadside sampling points, each separated by at least 500 m. Selected sites were sampled twice, yielding a combined sample size of 2544 point counts at 194 bird census routes. The primary objective of this work was to develop multispecies indicators of ecological condition that can be applied at both local and basin-wide scales.

Results

We encountered 187 bird species during the 2-year (2002-03) field effort. The numbers of species per transect in the Laurentian Mixed Forest Ecological Province (mean = 43.6 species, s.d. = 9.6) were remarkably similar to those in the Eastern Deciduous Forest Ecological Province (mean = 43.7 species, s.d. = 8.7), but species composition differed significantly between the 2 regions. Human impacts associated with the bird survey transects were assessed by GIS/remote sensing analysis of Landsat 5 and Landsat 7 satellite images. Proportions of cover in 5 general land use categories (natural vegetation, residential, commercial/industrial, agricultural, and roads) were evaluated at different distances (100 m, 500 m, 1 km, 3 km, 5 km)

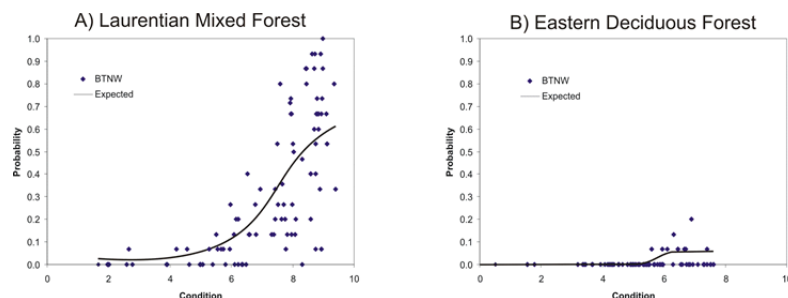


Figure 1. Species-specific sensitivity/detectability (SSD) functions (solid lines) for Black-throated Green Warbler (*Dendroica virens*) in A) the northern Laurentian Mixed Forest Ecological Province and B) the southern Eastern Deciduous Forest Ecological Province of the Great Lakes coastal zone.

from the 15 bird survey points. Multivariate analysis was used to generate a formula for calculating “reference condition” based on land cover, ranging from 0 (maximally impacted by humans) to 10 (minimally impacted by humans). The frequency of each species among the 15 point counts was used as the probability of encountering the species in the coastal segment. Probabilities were plotted against the reference condition to describe the species’ response to



environmental stress. A simple, 4 parameter mathematical function was used to describe each relationship (Figure 1). These SSD functions contain information about the response of each species to human impacts as well as the overall probability of finding the species in the study area. Our results (e.g., Figure 1) demonstrate that these relationships might vary by geographic region. Once derived, the SSD functions can be used to calculate the ecological condition of new sites.

Calculating Ecological Condition

The method for calculating ecological condition (C) follows an iterative or computerized “trial-and-error” process described by Hilborn and Mangel (1997). The first step is to derive parameters of SSD functions for species of interest. This is done through expert opinion or preliminary work like ours. We have derived statistically significant functions for 72 species in the Laurentian Mixed Forest Ecological Province, but robust multivariate indicators can be derived using a smaller number of species. We recommend a list of 25 species showing the strongest SSD functions and representing a range of habitat preferences. Important species on this list include Ovenbird, Black-throated Green Warbler, Red-eyed Vireo, American Redstart, Hermit Thrush, Winter Wren, White-throated Sparrow, and Nashville Warbler (positively associated with condition) and House Sparrow, European Starling, Common Grackle, Rock Pigeon, Red-winged Blackbird, and House Finch (negatively associated with condition). Given data on frequencies or presence/absence of the selected species, the next step is to compute (through iteration) the value of C that best “fits” the observed occurrence data. Absence of a species can be as important as presence, so surveys need to be complete (i.e., comparable to the method used for deriving the SSD functions) for the target species. The iterative process for calculating C can be implemented with the help of familiar computer software like Microsoft Excel.

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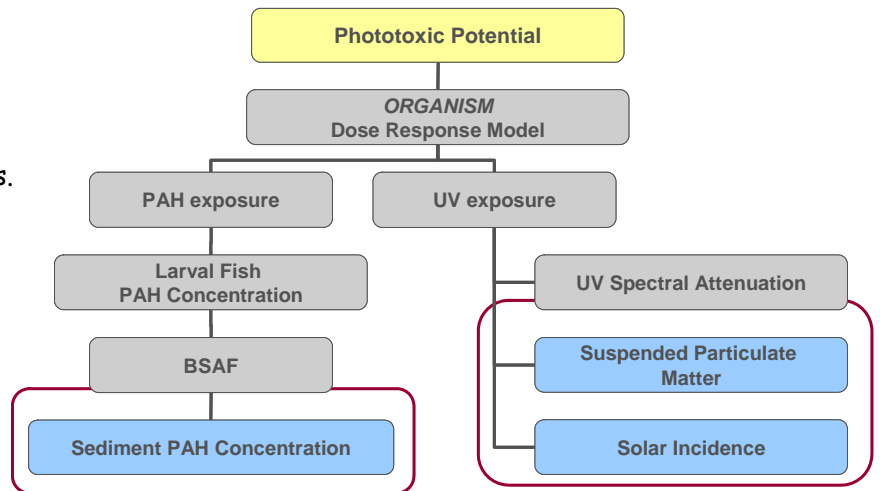
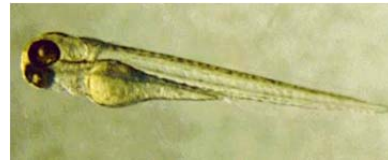


A.4. PAH PHOTOTOXICITY TO LARVAL FISH

Indicator

The time for 50% of larval fish to die is the LT50, in hours, and is a function of both PAH exposure (phototoxic PAH concentration in larval fish) and UV-A exposure.

The concentration of phototoxic PAHs¹ in fish is estimated from sediment PAHs. The UV dose is calculated from incident solar radiation and attenuation in the water column as estimated from a measurement of suspended particulate matter and spectral attenuation in surface water.

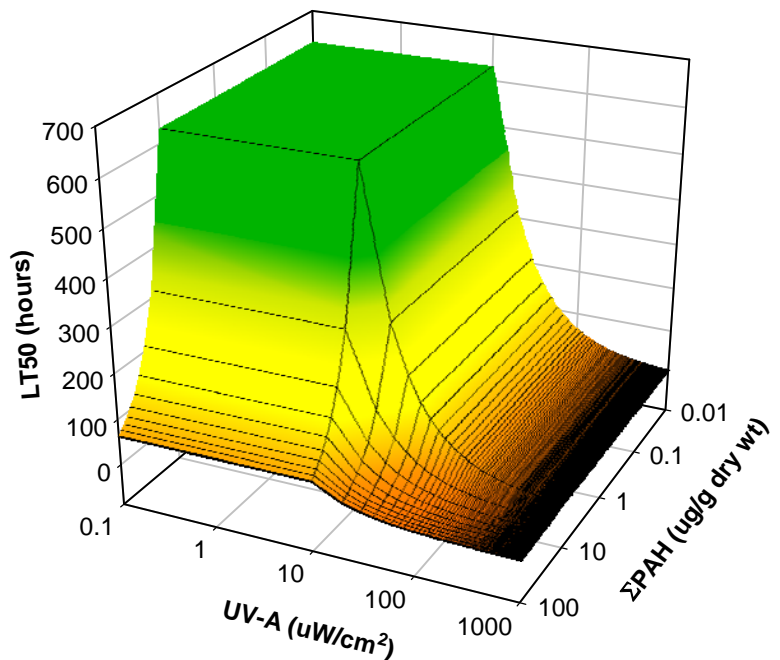


Output

The result of PAH and UV-A exposure as estimated above can be incorporated into an equation for the LT50:

$$LT50 = \frac{(PAH) \times (UV - A)}{63000}$$

The output from this equation is a three-dimensional depiction of LT50 (shown right) The green section is a combination of PAH and UV-A exposure that does not present concern. As the color shifts from yellow to red, the ecological relevance of phototoxicity increases.

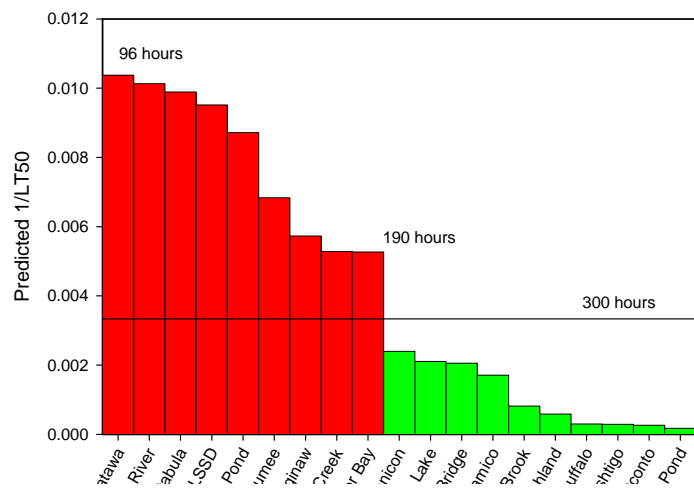


where T is the fraction transmittance at 10 (

The percent transmittance is calculated as $T = \exp\left(-K_d \times depth / 100\right)$.

Lakes sites was investigated using this indicator and the results are presented to the right. The reciprocal of the LT50 is plotted against the

ne, 2mehtylantracene, 1methylanthracene, 9methylanthracene, ntrhacene, benzo[b,j,k]fluoranthenes and benzo[a]pyrene





A.5. DIATOM-INFERENCE MODELS

We strove to devise and test a new diatom-based model for water quality variables in the coastal Great Lakes. Diatoms (e.g., Fig. 1), the siliceous yellow-brown algae, have been used extensively as indicators of water quality conditions. They are well-accepted as indicators by the U.S. EPA and other agencies, and have been used to evaluate aquatic stressors worldwide, including Europe and several areas of North America (including the Great Lakes). Diatom species respond with great fidelity to stressors associated with major “pressure” indicators in the Great Lakes (e.g., nutrient and salinity loading, siltation, and factors affecting water transparency, including exotic species). Diatom remains preserve well in sediment, so they also provide opportunities to reconstruct historical information at a site (paleolimnology). Several other features make diatoms robust environmental indicators:

- ubiquitous; occur in virtually any aquatic environment
- diverse; can provide a fine-grained assessment of environmental conditions
- versatile; sensitive to a variety of stressors, particularly water chemistry
- short turnover rate; respond rapidly to changing conditions
- more time-integrative than “snapshot” environmental measurements
- narrow tolerances and specific optima to environmental conditions

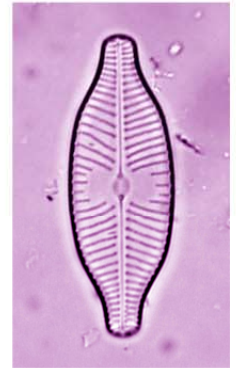


Figure 1. *Navicula*, a common diatom genus in the Great Lakes.

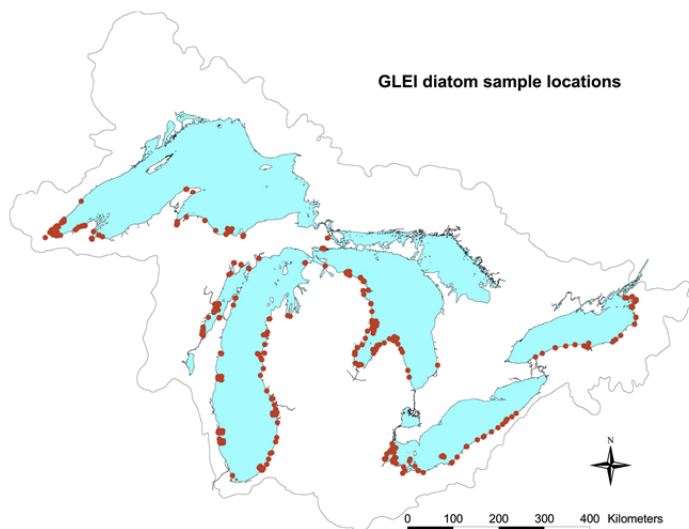


Figure 2. Diatom and chemical sample locations in the Great Lakes coastlines.

Sampling Design

Diatom and chemical samples were collected from 237 coastal sites (Fig. 2). At each site, a suite of important water quality parameters was collected, including chemical (e.g., nutrients) and physical (e.g., turbidity) variables. Diatom assemblages from each site were counted and identified to the most specific taxonomic level possible using light microscopy. Diatom data were compiled for comparison to corresponding environmental data and development of indicator models.

Indicator Application

We developed a diatom-based model to infer total phosphorus concentration (a water quality parameter typically related to augmented nutrient load and cultural eutrophication). Over 300 taxa were identified as comprising the majority of the coastal diatom population in the Great Lakes, and their environmental optima and



tolerances were identified (Fig. 3). Model testing (weighted average regression and calibration)

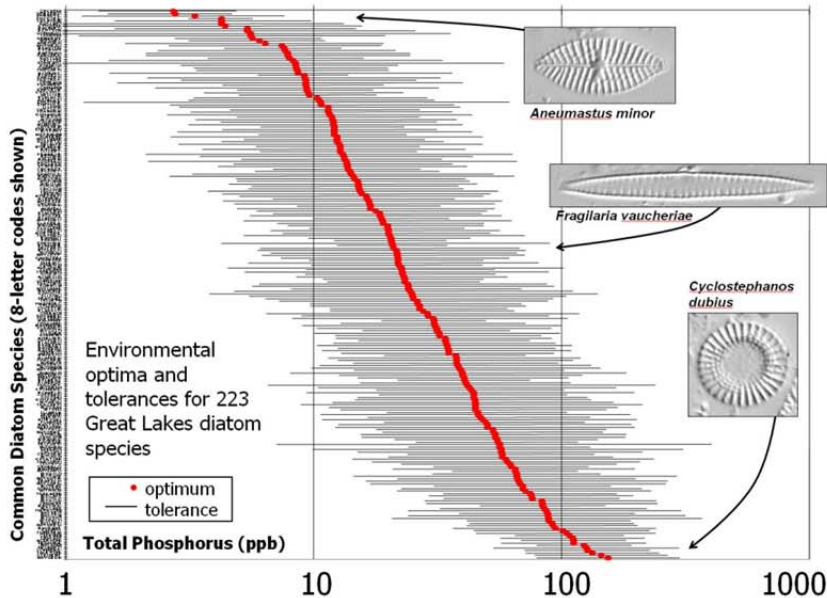
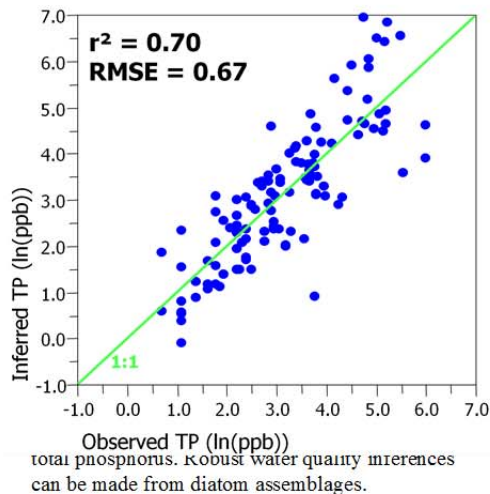


Fig. 3. Diatom species relationships to total phosphorus concentration for 223 common taxa.

has confirmed that the environmental characteristics of the diatoms provide a robust means to infer phosphorus concentrations for a study site (Fig. 4). In the future, the evaluation of diatoms in coastal ecosystems will provide cost-effective management advantages over traditional chemical measurements; the diatom assemblages are a direct measure of the health of the primary producer community, and diatom-inferred data integrate conditions than can be overlooked with

instantaneous sampling of chemical parameters. For instance, the diatom assemblage in a periphytic sample provides a time-integrated assessment at a site that is subject to erratic pulses of nutrient contamination. Indeed, it was clearly recognized that diatom-based reconstructions better predicted water quality than snapshot measurements from Great Lakes coastlines!





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A.6. DIATOM-BASED INTEGRATIVE WATER QUALITY MODEL

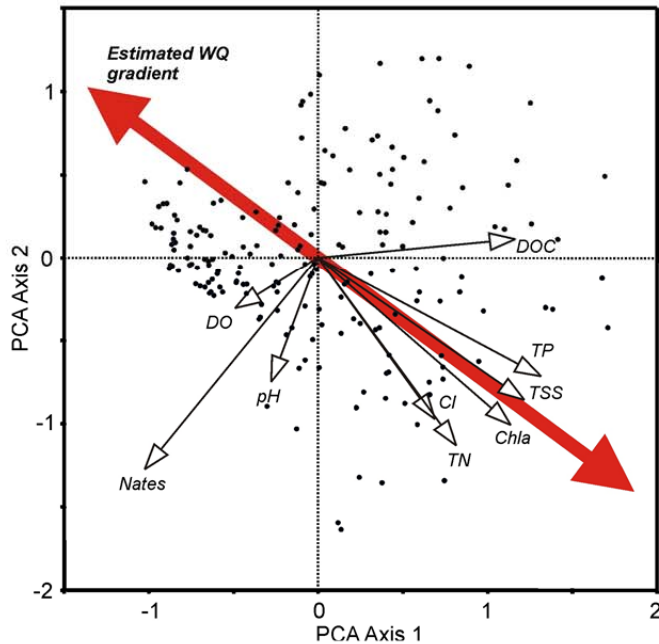


Figure 1. PCA of the suite of water quality parameters from 191 discrete samples collected from Great Lakes shorelines. Sample scores are shown as dots (●), environmental variables are indicated by vectors, and the thick gray arrow reflects the approximate gradient distinguishing clear, low-nutrient sites (upper left quadrant) from turbid, nutrient-rich sites (lower right quadrant).

Training sets have become the mainstay of modeling methods to calibrate diatom indicators to water quality variables of interest. Typically the present-day distributions of diatoms (or any of several indicator organisms) are calibrated across the gradient of a selected environmental parameter. These models use a species-based weighted average (WA) approach, and have consistently provided a valuable tool to infer past conditions from sedimentary records (see associated GLEI-diatom indicator). If we are to continue refining these models we need to focus on better characterization of species-environmental relationships. Previous applications have typically been limited to single water quality variables, such as phosphorus, nitrogen, pH, or salinity, because these variables are often of interest to water quality managers. Inevitably however, weaknesses in these models are associated with a loss of ecological information, resulting from the inability of a single water quality variable to account for a large amount of variation in the diatom assemblages. This model

weakness is a result of the fact that a specific variable of interest captures only a fraction of the variation in the diatom data that may be explained by other measured variables. For instance, it is well known that the measured phosphorus gradient from a suite of sites is typically correlated with nitrogen, water clarity, organic compounds and suspended solids, all of which can have water quality implications. A diatom model based on an integrated water quality gradient provides a means to reconstruct general environmental quality at a locale.

A diatom-based model to infer phosphorus and other water quality parameters in Great Lakes coastlines was developed as part of the GLEI project. This evaluation used the same set of chemical and diatom data to instead derive an integrated water quality (WQ) model. PCA of all chemical variables identified the major environmental gradient that would be considered ranging from “high” (i.e., low-nutrient, clear-water sites) to “low” (i.e., high-nutrient, high Cl, turbid sites) water quality (Fig. 1). Characterizing this dominant gradient allowed the suite of WQ data to be summed up in a comprehensive WQ variable, which was then related to diatom assemblages.

Watershed stressor data (including agricultural intensity and urban development) were regressed against (A) measured and (B) diatom-inferred WQ data using multiple linear regression. For both models, DI parameters were better correlated to watershed characteristics than measured parameters (Fig. 2). This finding endorses the use of diatoms in monitoring programs as well as their frequent applications to paleoecology; the diatoms better integrate aquatic conditions,



which are subject to watershed influences, and so provide more reliable inferences of the prevailing condition than spot measurements of water chemistry. The combined WQ variable is better correlated to watershed characteristics than measured TP, a probable result of the fact that WQ is derived from several chemical parameters, and so should better reflect overall chemical condition than a single nutrient. Combination of these variables into a single WQ variable offers a notable advantage to characterizing watershed-measured water quality relationships.

Summarizing water chemistry variables into a comprehensive index of water quality appears to proffer some advantages over using specific environmental variables in diatom models. A disadvantage of using a WQ index this way would be some loss of information for water quality managers who may be interested in specific variables, such as phosphorus or water clarity. However, an integrated measure of water quality is a useful means to provide a more holistic view of limnological conditions at a site.

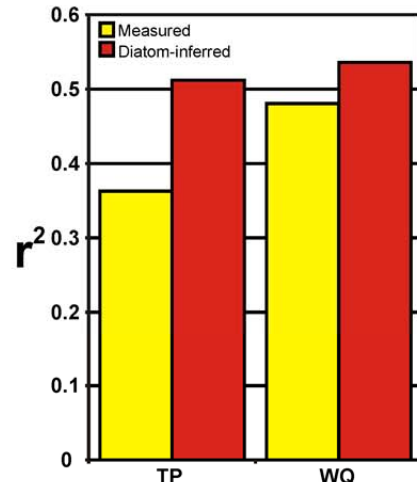


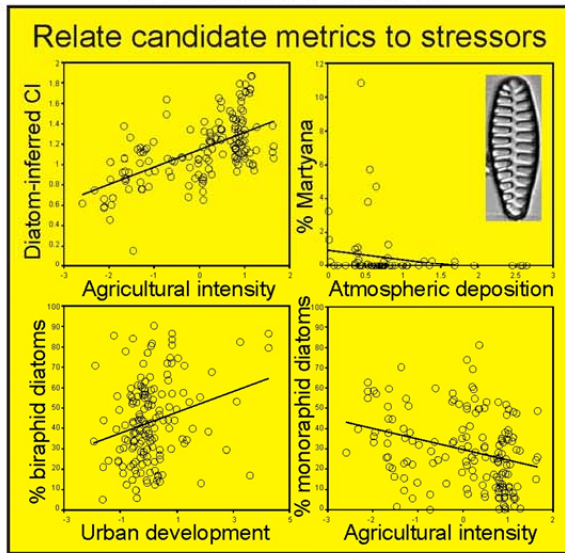
Figure 2. Comparison of squared correlation coefficients from regression of watershed characteristics against measured and diatom-inferred total phosphorus (TP) and water quality (WQ).

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A.7. DIATOM-BASED MULTIMETRIC INDEX OF DISTURBANCE

DEVELOPMENT



Identify metrics with meaningful responses to stressors. The strength of the metric-stressor relationship serves as a metric's "weight" later on.

Eliminate redundant metrics (highly correlated metrics provide no additional environmental information).

APPLICATION

A weighted sum of selected metrics provides the multimetric index score.

Selected metric	Weight	Metric score equation	Score
% <i>A. minutissimum</i>	0.305	$0.014 + x/73.62$	
% <i>Cocconeis</i>	0.379	$0.983 - x/58.25$	
% araphid	0.845	$0.011 + x/89.26$	
% monoraphid	0.462	$0.000 + x/81.19$	
% biraphid	0.832	$1.059 - x/85.21$	
% <i>Amphora</i>	0.309	$0.977 - x/42.67$	
% <i>Eunotia</i>	0.301	$0.026 + x/37.89$	
% <i>Geissleria</i>	0.727	$0.026 + x/37.78$	
% <i>Martyana</i>	0.536	$0.052 + x/19.4$	
% <i>Hippodonta</i>	0.984	$0.975 - x/40.53$	
% <i>Psammothidium</i>	0.993	$0.028 + x/36.31$	
% <i>Navicula</i>	0.858	$0.986 - x/53.88$	
% <i>Rossthidium</i>	0.226	$0.085 + x/11.72$	
Shannon-Weaver	0.222	$-0.468 + x/2.97$	
Diatom-Inferred CI	2.060	$1.094 - x/1.71$	
Multimetric score ==>			

The final score reflects site quality.

Organism-based indices have been a valuable monitoring tool in lotic waters and small lake systems, and have been commonly applied as fish and invertebrate indices. Algal indices, such as those using diatoms, are starting to be incorporated into routine monitoring assessments in the U.S.

Diatoms have become a widely-applied indicator group because they are taxonomically distinct, abundant in almost all aquatic environments, respond rapidly to changing conditions, and are well preserved in sediment deposits. Furthermore, evaluations of diatoms can provide a description of water quality that is not achievable from chemical analyses; the value of an integrative biological response can offset the inconsistency of rapid changes in water chemistries.

GLEI personnel developed a robust diatom-based model that uses quantified unimodal response coefficients of the species across environmental gradients. While this model will be of interest to Great Lakes managers and paleoecologists, it has some logistic constraints such as time and monetary dedication, taxonomic expertise, specialized software and a significant learning curve. Index approaches provide a more accessible choice for managers who may be considering the algae as an environmental quality indicator; they provide a means to evaluate environmental quality at a locale based on the diatom assemblage, and can be flexible enough to suit user groups with monetary or logistic limitations.

A diatom-based multimetric index to infer coastline disturbance was developed for Great Lakes coastal sites (Fig. 1). We defined 38 metrics based on autecological and functional properties of each species assemblage, including species diversity, percentages of motile, planktonic and dominant taxa, as well as taxonomic metrics (e.g., proportion of the genus *Martyana* or "Stephanodiscoid" taxa). Comparisons of individual metrics to watershed stressors revealed that many of the proposed metrics

Figure 1. The development and application process for the diatom-based multimetric index for Great Lakes coastlines.



responded to human stressors, and so were considered for further development. Metrics that were redundant, or had no response to stressors, were excluded. The final multimetric index is a cumulative score – a sum of the important metrics, each weighted by the strength of their respective relationships to anthropogenic stress. While individually the metrics have relatively weak responses to stress, the multimetric approach provides a cumulative assessment of site quality. We anticipate future applications of this new index to monitoring programs and downcore analyses.

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A.8. DIATOM DEFORMITIES REFLECT POLLUTION

The nearshore waters of many areas of the Laurentian Great Lakes are examples of ecological instability. Large population and industrial centers on the shores of these originally highly oligotrophic lakes lead to large spatial and temporal gradients in nutrient, conservative ion, and toxic material concentrations. Lake Erie is generally considered the most modified of the Laurentian Great Lakes, and became a focus of concerns about water pollution in the later decades of the twentieth century. The occurrence of morphological abnormalities in birds, fish and invertebrates, particularly in the coastal region of Lake Erie and its tributaries, is well known. Reports of similar effects on benthic diatoms are more rare, but not unknown.

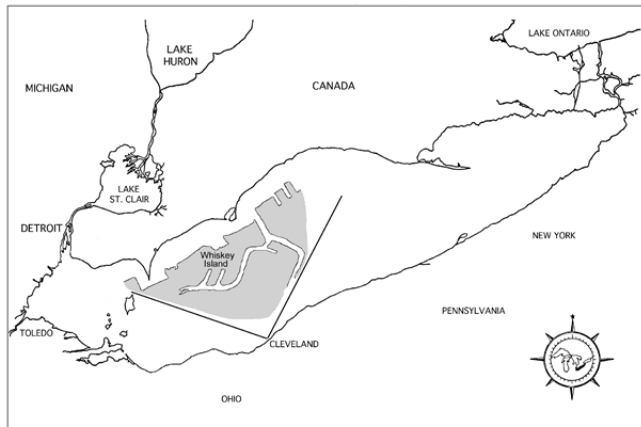


Figure 1. The sample location at Whiskey Island, Lake Erie.

Populations of the diatom genus *Tabularia* from a coastal site near Cleveland, Ohio, exhibit highly abnormal morphology. The locality of collection is locally known as Whiskey Island (Fig. 1), an area with a legacy of environmental problems. The “island” is actually a peninsula at the mouth of the Cuyahoga River. Its name is derived from a distillery that was built in 1836, and it has been an industrial site, ship graveyard and waste disposal area. It is currently the site of a salt mine, and has recently been developed as a large marina. The collection site is subject to numerous discharges, including industrial contaminants. The

Cuyahoga River is particularly notorious because at one time it was so contaminated that it occasionally caught fire. The more obvious ecological problems have now been contained, but the legacy of previous environmental insults remains. There are many causes of morphological abnormalities in diatom frustules, and based on our observations it appears that abnormalities are common in diatom communities that undergo toxic stress, and the abnormalities present near Cleveland are likely related to these factors.

Observations showed an extreme variety of atypical shapes (Fig. 2); frustules were bent, asymmetric, had irregular striae and margins, or any combination of these characters.

Abnormalities in diatom valve structure have been noted and reported virtually since the group was first studied. In general, deformities have been associated with pollution or eutrophication. More specific chemical causes include silica limitation and increased salinity in freshwater habitats.

Morphological abnormalities of the diatoms was not originally anticipated to be one of the GLEI indicators, and so to date we have only assessed these site-specific data near Cleveland. However, the presence of benthic diatoms that are atypical (in terms of both

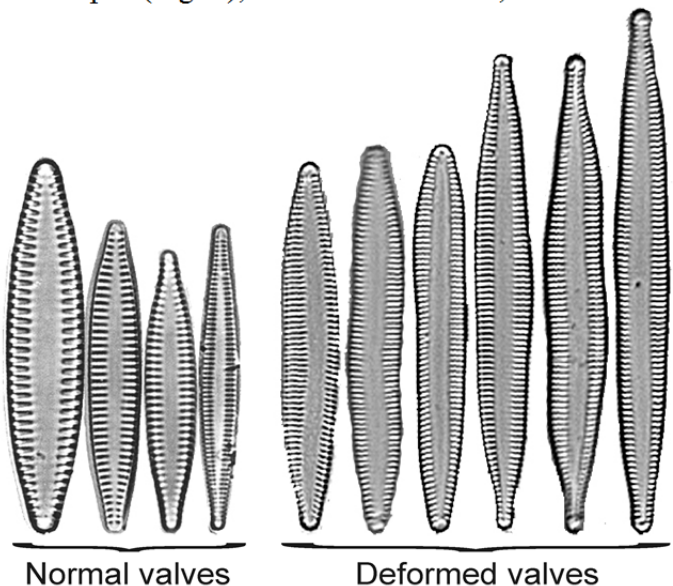


Figure 2. Comparison of normal and deformed valves of the diatom species *Tabularia*.



distribution and morphology) in the Great Lakes may offer valuable insights into toxic effects. Although the present state of knowledge does not permit firm conclusions concerning the populations described here, investigation of benthic diatom populations in the Great Lakes is a neglected topic that deserves more research attention.

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A.9. AND A.10. TWO FISH INDICATOR INDICES

Introduction

Scientists with the Great Lakes Environmental Indicator (GLEI) Project and their collaborators have tested and confirmed the validity of 2 indices that indicate the condition of Great Lakes coastal wetlands. Wetland ecological condition has been especially difficult to assess because changing water levels have such a dramatic impact on the extent and local conditions. Wetlands are often characterized by their vegetation. But each species tends to have specific requirements of water depth and clarity. Wetland fauna often depend on particular plant species when picking places to build nests or lay eggs.

Ecological Indicator: Scientists with the Great Lakes Coastal Wetlands Consortium had previously proposed that because submergent plant communities adapt quickly to changing water levels, perhaps the fish communities associated with plant types could be used as indices of wetland condition. They proposed a fish Index of Biotic Integrity (IBI) for wetlands dominated by cattails (*Typha*) and another IBI for those in which bulrushes (*Scirpus*) were the most common species¹.

Measuring Fish Index Scores Across the Human Stress Gradient of Coastal Zones

GLEI researchers have developed a unique way to divide the coastal regions of the Great Lakes in the U.S. into 762 watersheds that encompassed the tributary streams and coastal wetlands. For



Typha (cattail)-dominated wetland.



Scirpus (bullrush)-dominated wetland

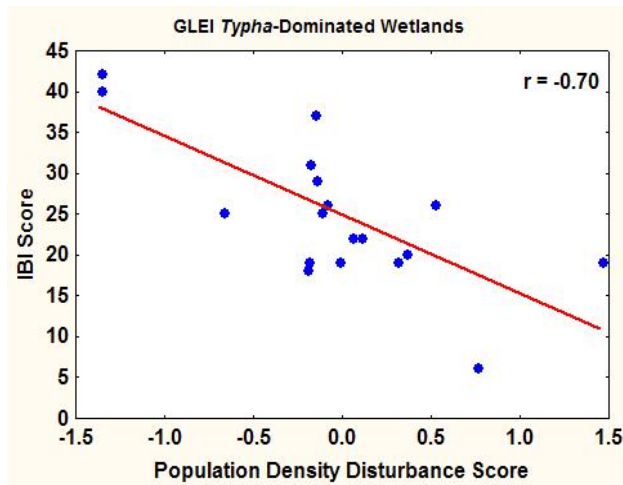
each of these watersheds, 6 different measures of human influence were calculated, based on the way the land is used and the materials carried from the land into the Great Lakes². To assess the relationship between fish community condition and the human-related stressors, GLEI

researchers used live trap nets to catch and identify the fishes in 82 Great Lakes coastal wetlands, 33 of which were dominated by either cattails or bulrushes.³

The fish IBI scores calculated for these wetlands did indeed vary, but only according to specific classes of human-related stress. Fish communities in cattail-dominated wetlands became degraded as a disturbance variable that combined population density, road density and urban development in the watershed surrounding the wetland increased.



In contrast, the fish communities of bulrush-dominated wetlands reflected the impacts of nutrient and chemical inputs associated with the intensity of agricultural activity in the surrounding landscape. These effects were observed in data collected over several years, during which time Great Lakes water levels varied by up to 100 cm, thus confirming the effectiveness of the indices under changing water conditions. The fish IBI scores in bulrush wetlands were very much lower once a threshold level of agricultural-input stress had been exceeded. In contrast, the IBI scores



in cattail wetlands gradually declined with increasing population disturbance. Thus, the proposed indices appear to effectively indicate the effects of some but not all classes of anthropogenic disturbance on fish communities at Great Lakes coastal margins.

Environmental Application

The cattail and bulrush IBI indices are useful tools for helping environmental managers to assess the condition of wetland fish communities and possible causes of their degradation. The fish species in bulrush-dominant wetlands are apparently sensitive to nitrogen and phosphorus loadings and direct pollutant discharges. Strong

changes in fish IBI were observed to correspond to specific nitrogen and phosphorus input values. These values can provide managers with potentially important guidelines for planning allowable concentrations of nutrients and chemicals in agricultural runoff. Similar guidelines can be derived for allowable inputs of total nitrogen and total phosphorus from non-agricultural sources that would protect the fish communities of receiving wetlands. In addition, these data provide information that is of value to managers seeking to understand the causes of impairment at sites that do not meet designated use criteria.

The results of this study verify that the Uzarski *et al.* (2006) IBI scores reflect specific classes anthropogenic stress in coastal wetlands dominated by cattails and bulrushes. However, the indices reflect only certain types of human disturbance. They are most suitable for assessing wetland condition in response to agriculture or population density rather than generalized disturbance. Diagnosing causes of water quality impairment is an important component of the Great Lakes Water Quality Agreement of the governments of Canada and the U.S., and the U.S. federal Clean Water Act. These results address one of the weaknesses of the IBI approach, in that a single value representing ecological condition does not address the cause of impairment.

¹Uzarski, D.G., T. M. Burton, M.J. Cooper, J.W. Ingram, and S. Timmermans. 2006. Fish habitat use within and across wetland classes in coastal wetlands of the five Great Lakes: development of a fish-based index of biotic integrity. *Journal of Great Lakes Research* 32: In press.

²Danz, N.P., R.R. Regal, G.J. Niemi, V.J. Brady, T. Hollenhorst, L.B. Johnson, G.E. Host, J.M. Hanowski, C.A. Johnston, T. Brown, J. Kingston, and J.R. Kelly. 2005. Environmentally stratified sampling design for the development of Great Lakes environmental indicators. *Environmental Monitoring and Assessment* 102:41-65.

³Bhagat, Y., J.J.H. Ciborowski, L.B. Johnson, T.M. Burton, D.G. Uzarski, and J.W. Ingram. In review. Testing a



fish index of biotic integrity for Great Lakes coastal wetlands: stratification by plant zones. Submitted to *Wetlands*, April 2006.

For further information contact Carol Johnston (email: carol.johnston@sdstate.edu) regarding this indicator. For questions related to the greater GLEI project please contact Gerald Niemi (email: gniemi@d.umn.edu).



A.11. MULTITAXA WETLAND VEGETATION INDICES

What is it? Indices that use a few selected plant species to evaluate wetland condition.

What is measured? Average cover by species in the wetland, measured in plots spanning the moisture gradient within emergent vegetation stands.

When should measurements be made? When vegetation is at maximum growth stage in July or August.

Equipment needed: Sticks to define a unit area of wetland (e.g., a 1 m x 1 m square) within which plant cover is visually estimated, plant identification guides

Expertise needed: Ability to distinguish the 10 wetland plant taxa from other wetland plant taxa.

The ten-taxa index: $SUM_INDEX = 2.141 - 0.029(CAST8) - 0.027(CALAA) - 0.352(CIBU) - 0.040(EQFL) + 0.013(LEMI) + 0.161(LYTH2) + 0.025(LYSA2) + 0.020(PHAU7) + 0.039(POAM8) + 0.017(\text{invasive_Typha})$

The 4-taxa index: $SUM_INDEX = 2.239 - 0.034(CAST8) - 0.030(CALAA) + 0.015(PHAU7) + 0.019(\text{invasive_Typha})$

where: SUM_INDEX is a cumulative index of anthropogenic stress representing the major threats to coastal ecosystems in the U.S. Great Lakes developed by Danz *et al.* (in press), for which values range from 0.4 (lowest stress) to 4.0 (highest stress)

CALAA = mean percent wetland cover by *Carex lasiocarpa* var. *americana*

CAST8 = mean percent wetland cover by *Carex stricta*

CIBU = mean percent wetland cover by *Cicuta bulbifera*

EQFL = mean percent wetland cover by *Equisetum fluviatile*

LEMI = mean percent wetland cover by *Lemna minor*

LYSA2 = mean percent wetland cover by *Lythrum salicaria*

LYTH2 = mean percent wetland cover by *Lysimachia thyrsiflora*

PHAU7 = mean percent wetland cover by *Phragmites australis*

POAM8 = mean percent wetland cover by *Polygonum amphibium*

invasive_Typha = mean percent wetland cover by *Typha angustifolia* or *Typha x glauca*

Why it works: All of the taxa have widespread ranges throughout the Great Lakes, and all are sensitive to stress. Four of the plant taxa (CIBU, EQFL, and the 2 *Carex* species) decrease in abundance as anthropogenic stress increases, and 6 of the taxa (LEMI, LYSA2, LYTH2, PHAU7, POAM8, invasive_Typha) increase in abundance. Invasive_Typha, LYSA2, and PHAU7 are invasive plant taxa.

How reliable is it? The ten-taxa index has an r^2 of 0.61 with SUM_INDEX . The 4-taxa index has an r^2 of 0.50. The 4-taxa index only works if 1 or more of the 4 taxa is present within the wetland, but that condition was true for all of the 90 wetlands that we sampled. The ten-taxa index utilizes more species, and is therefore more reliable.

How transferable is it? These indices can be used throughout the Great Lakes coast, but they are not applicable to salt marshes on oceanic coasts, where species diversity is much lower. The concept



is probably transferable to other freshwater wetlands, but new formulas would have to be derived based on empirical data sets from other regions.

For further information contact Carol Johnston (email: carol.johnston@sdstate.edu) regarding this indicator. For questions related to the greater GLEI project please contact Gerald Niemi (email: gniemi@d.umn.edu).



A.12. MAXIMUM CANOPY HEIGHT

What is it? An index of plant biomass, which increases with increasing anthropogenic disturbance.

What is measured? The maximum height of the herbaceous plant canopy in the wetland. Only one measurement is needed, but it should be made in the tallest stand of plants within the wetland. It would help to first view the wetland from an elevated spot nearby to scope out areas with tall vegetation.

When should measurements be made? When vegetation is at maximum growth stage in July or August.

Equipment needed: A meter stick

Expertise needed: No special expertise needed

The index: $SUM_INDEX = 0.820 + 0.069(\text{cover_hgt_max})$

The greater the value of the index (on a scale from 0.4 to 4), the more degraded the wetland.

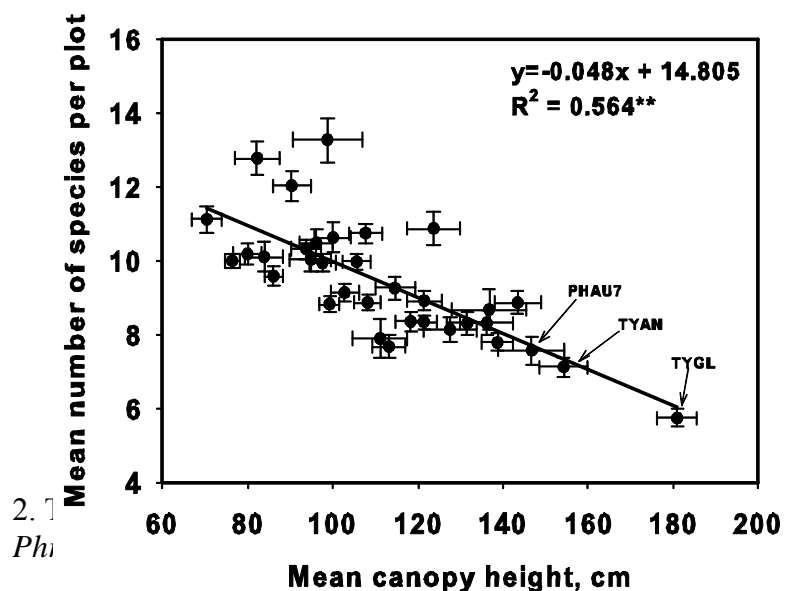
Why it works: (1) fertilization by nutrients contributed by nonpoint-source pollution increases plant growth, (2) invasive plants tend to be taller than non-invasive plants, and (3) tall plants shade out other plants, reducing the biodiversity of the plots in which they occur.

How reliable is it? The index has an r^2 of 0.41 relative to the SUM_INDEX of anthropogenic stress. Using an average value for multiple canopy height measurements within the wetland yielded less reliable results (r^2 of 0.375), and requires more effort.

How transferable is it? Although this index has not been tested outside of Great Lakes coastal wetlands, we believe that it may work in any wetland, including salt marsh wetlands, because the underlying mechanisms of fertilization and species invasion are universal.



1
c
invasive *Phragmites*





A.13. SPECIES DOMINANCE INDEX

What is it? The Species Dominance Index (SDI) indicates ecological integrity by identifying dominant species and categorizing their behavior as 1 of 7 forms of dominance.

What is measured? Average cover by species in the wetland, measured in plots spanning the moisture gradient within emergent vegetation stands.

When should measurements be made? When vegetation is at maximum growth stage in July or August.

Equipment needed: Sticks to define a unit area of wetland (e.g., a 1 m x 1 m square) within which plant cover is visually estimated, plant identification guides

Expertise needed: Ability to identify all wetland plants.

The index: SDI combines 3 related attributes of dominance to score a particular species' dominance in much the same way Curtis and McIntosh used 3 related measures of tree abundance to calculate their importance value. These 3 attributes, mean cover (MC), mean species suppression (MSS), and tendency toward high cover (THC) measure the abundance of a potentially dominant species, the number of species associated with a potentially dominant species, and the likelihood that the species is abundant when it occurs, respectively. The attributes for which a dominant species has high values determines its dominance form.

The use of SDI involves 3 steps, (1) creating a list of potential dominants, (2) computing the SDI to identify the dominant species, and (3) classifying the dominance forms. To be considered potentially dominant and subsequently subjected to the SDI, a species must occur with a minimum frequency (a third of plots when aggregated per wetland) and have >25% absolute cover and the most cover of any species in at least 1 plot. These characteristics are required for dominance rather than variable attributes of a dominant species, which are the focus of SDI.

To compute SDI, the value of each attribute must be calculated for each potentially dominant species. Attribute values can range from 0 to 1. MC is calculated by averaging the mid-point of recorded cover classes of that species. Values of zero are used when a species does not occur in a plot. MSS is the mean of the inverse of the number of species ($1/\text{number of species}$) in a plots where the potentially dominant species has >25% absolute cover and the most cover of any species. THC is the ratio of the number of times a potentially dominant species has >25% absolute cover and the most cover of any species in a plot to the number of times it is present in a plot. The attributes values for each species in a wetland or lake are averaged together to yield the SDI score ($\text{SDI} = (\text{MC} + \text{MSS} + \text{THC})/3$). Dominant species are those with above average SDI scores. Average SDI was 0.241.

Dominance form of a dominant species is assigned based on which attributes have values above the mean value of each attribute. The mean values were 0.197, 0.187, and 0.339 for MC, MSS, and THC, respectively. Using mean values to differentiate between “high” and “low” attribute values (and dominant vs. not dominant species, as above) is appropriate because samples came from a large number of wetlands distributed across the environmental gradient. The cut-off values used here should be used for determining dominant species and dominance forms in any future sampling efforts that use similar methods.



Why it works: Because a dominant species controls its habitat and the presence and performance of other species, its behavior, which may be variable depending on the environmental conditions, provides insight into the community as a whole. By examining the behavior of a dominant species in addition to its identity, SDI also acknowledges that invasive species do not always act invasive and native species sometimes do.

How transferable is it? The concept is transferable to any wetland. The index has proven useful in characterizing changes in dominance in a restoration site at the UW-Madison Arboretum, in mesocosms where reed canary grass has invaded wet prairie, and in both natural and restored salt marshes of southern California.

For further information contact Carol Johnston (email: carol.johnston@sdstate.edu) regarding this indicator. For questions related to the greater GLEI project please contact Gerald Niemi (email: gniemi@d.umn.edu).



A.14. LAND USE/LAND COVER CHANGE

Land use land cover (LULC) change is an indicator of changing human demographics, natural resource uses, agricultural technologies, economic priorities, and land tenure systems. Different land uses impose different environmental stresses on natural plant and animal communities, with consequent implications to water quality, climate, ecosystem goods and services, economic welfare, and human health (Gutman *et al.* 2004). This indicator has been identified by the SOLEC process as an important indicator (Wolter *et al.* 2006). For instance, the indicator described here can be used to fulfill indicators #7002, #7000, #8132, #8136, #8500, and possibly #7000 and #7006

This indicator can be considered both a pressure (stress) indicator as well as a state (response) indicator. LULC change in response to human activities and natural process in the landscape (e.g., state indicator). However, land use and land cover change becomes a stress to other biological community response and, hence, can best be considered a pressure or stress. This indicator was developed to establish a baseline for comparison of LULC changes throughout the U.S. portion of the Great Lakes basin. A concerted effort is needed and is currently underway to standardize this indicator throughout the Great Lakes basin in both the U.S. and in Canada.

Methods

Both raw Landsat sensor data (1992 and 2001) and existing, Landsat-based, thematic data from various state and federal sources were used to assemble and quantify LULC data for the U.S. portion of the Great Lakes watershed. Because of some incompatibilities among different

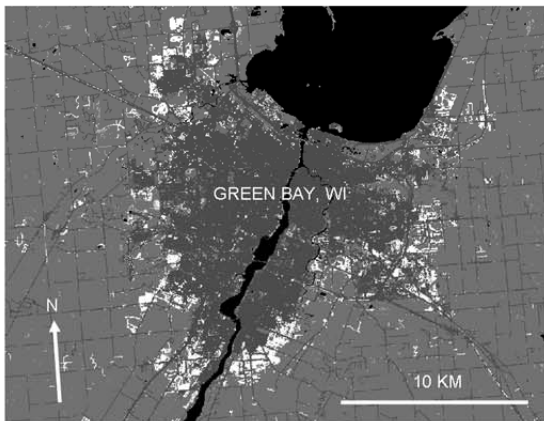


Figure 1. Agriculture to developed land conversion around Green Bay, WI between 1992-2001 in white.

temporal images of Landsat, a variety of adjustments were essential to achieve consistent imagery between the 1992 and 2001 data (see Wolter *et al.* 2006 for details).

Results

Of the total change that occurred between 1992 and 2001 (2.5% of watershed area), salient transition categories included a 33.5% increase in area of low-intensity development, a 7.5% increase in road area, and a decrease of mature forest area by over 2.3% – the largest LULC category and area of change within the watershed. More than half of the forest change that occurred involved transitions into early successional vegetation, and hence, will likely

remain in forest production of some sort. However, nearly as much forest area was permanently converted to developed land. Likewise, agriculture land area lost over 50,000 more ha to development than forestland, much of which involved transitions into urban/suburban categories (Fig. 1).

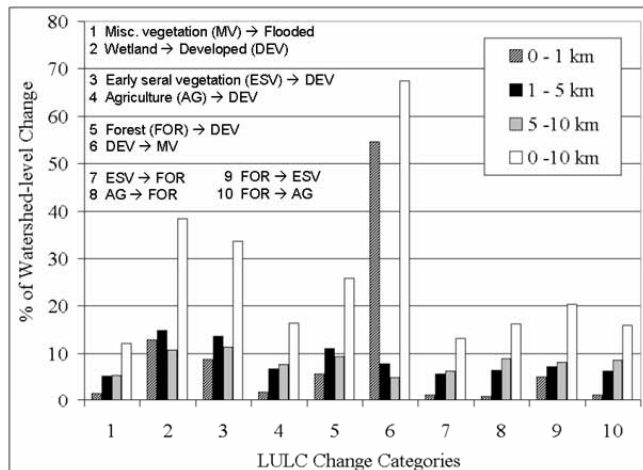


Figure 2. Percent of the overall LULC change between 1992 and 2001 that occurred in near-shore areas.

Most of the concentration of new developments occurred near coastal areas of the Great Lakes (Fig. 2). For instance, over a third of wetland losses to development between 1992 and 2001 occurred within 10 km of a coastal area, and most of that area was within the nearest 1 km. This is a concern because Great Lakes coastal wetlands provide habitat for a wide variety of fauna, support plant communities adapted to water level extremes, and buffer land-lake exchanges of nutrients and other materials.

References.

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- Wolter, P., C. Johnston, G.J. Niemi. 2006. Land use change in the U.S. Great Lakes basin 1992-2001. *Journal of Great Lakes Research*. In press



A.15. NEW INDEX OF ENVIRONMENTAL CONDITION



New Index of Environmental Condition for Coastal Watersheds in the Great Lakes Basin

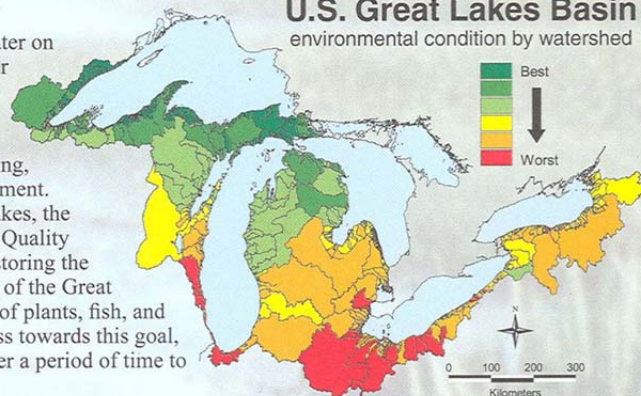
INTRODUCTION

The Great Lakes is the largest system of surface freshwater on the earth. It contains about 20% of the earth's fresh water and about 90% of the freshwater in the United States. The wealth of natural resources has made this area a center of economic activity for the United States. From mining, forestry, and agriculture to recreation and shipping, human activities have taken a toll on the natural environment. In response to the continued degradation of the Great Lakes, the United States and Canada signed the Great Lakes Water Quality Agreement in 1972. The goal of this agreement was "restoring the chemical, physical and biological integrity of the waters of the Great Lakes Basin ecosystem" to achieve healthy populations of plants, fish, and wildlife and to protect human health. To monitor progress towards this goal, measurements of human-caused stress must be made over a period of time to evaluate changes in environmental condition.

Ecological Indicator: Scientists with the Great Lakes Environmental Indicator (GLEI) Project (<http://glei.nrrri.umn.edu>) have developed a Condition Index that indicates the region's environmental condition by watershed. The index is based on 207 individual stressors* that fall into five dominant human-derived stresses to ecological condition: 1) type of land use, 2) amount of agricultural activity, 3) point sources of pollution, 4) atmospheric deposition, and 5) human population density. The stresses in each watershed were summarized and the resulting scores were distributed over a gradient from worst (red) to best (green) indicating the Environmental Condition of each coastal watershed, as depicted on the map (right) of the U.S. Great Lakes basin. Using updated versions of appropriate databases and GIS techniques, managers can produce similar Condition Indexes for their area.

* The use of all 207 stressors allowed a more complete synthesis of human impacts; however, something analogous could be done using only land-use classifications.

U.S. Great Lakes Basin environmental condition by watershed



HUMAN STRESS GRADIENT OF COASTAL ZONES

GLEI researchers have developed a unique way to divide the coastal regions of the Great Lakes in the U.S. into 762 watersheds that encompassed the larger tributary streams and adjacent shoreline. For each of these watersheds a Condition Index was calculated, as described above, that reflects the amount and type of human stress within the watershed.

To link the land-based Condition Index to the health of Great Lakes coastal aquatic ecosystems (e.g., wetlands, beaches and bays), GLEI researchers sampled communities of birds, amphibians, diatoms, fish, macroinvertebrates, and wetland vegetation at sites across the range of the Condition Index. Water quality and contaminant levels were also sampled at

many of the sites. Indicators of biological condition based on these samples were found to be correlated with the Condition Index. Researchers have also identified linkages between the particular types of stressors (such as certain types of non-point source pollution) and the biological communities of the streams and shorelines. Based on these relationships, diagnostic indices of ecological condition have been developed. Diagnostic indices can be used to guide management toward targeting specific stressors for restoration or remediation goals. Several examples are available (although not yet published) from the researchers listed below.

Danz, N.P., R.R. Regal, G.J. Niemi, V. Brady, T. Hollenhorst, L.B. Johnson, G.E. Host, J.M. Hanowski, C.A. Johnston, T. Brown, J. Kingston, and J.R. Kelly, 2005. Environmentally Stratified Sampling Design for the Development of Great Lakes Environmental Indicators. *Environmental Monitoring and Assessment* 102:41-65. (<http://glei.nrrri.umn.edu>)



Office of Research and Development
Washington DC
EPA/600/S-05/005
August 2005



Environmental Application: The Condition Index is a tool useful to environmental managers for prioritizing problems (e.g., loss of wetlands) across the Great Lakes region and placing these areas into a larger regional or national context. Generally, areas in the southern and eastern Great Lakes have much higher levels of human-induced stresses than do areas in the northern Great Lakes. This information can be used to identify areas that should be protected, and to prioritize areas in

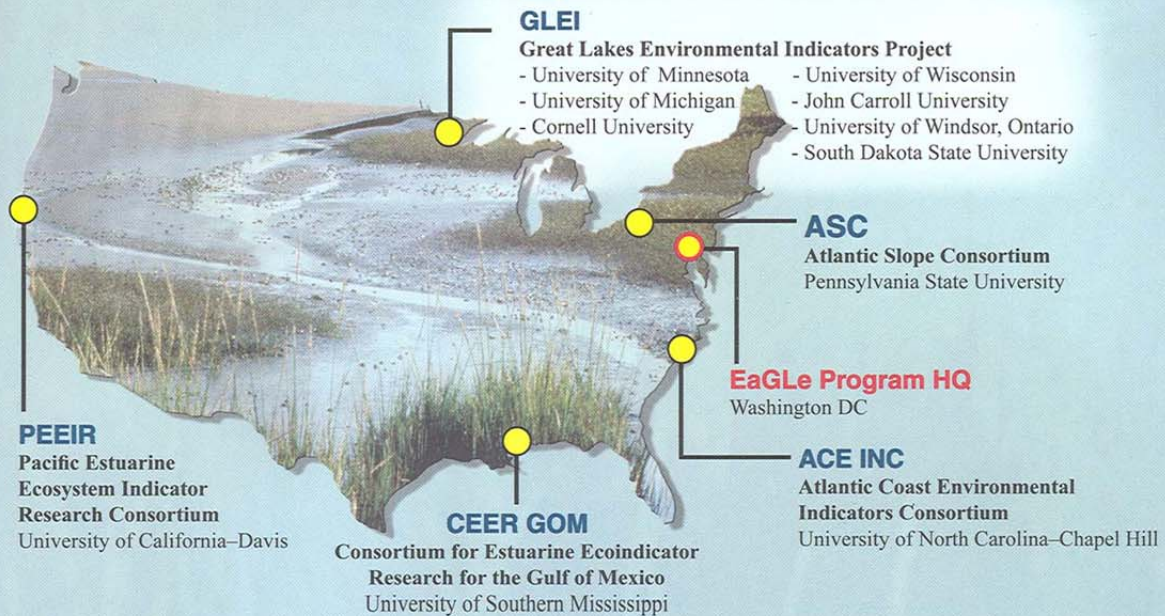
need of restoration. Although all of the datasets that make up the Condition Index are publicly available, no one has previously put them together to give an overall picture of the human pressures in this region.

The analyses also hold promise for EPA's Region V, the Great Lakes National Program Office, and other regional water programs in establishing a design framework for monitoring biological resources and diagnosing causes of

human impairment across the Great Lakes coastal zone.

The Index of Environmental Condition map provides a tool for resource managers to identify areas vulnerable to loss of wetlands, coastal areas in need of protection or restoration, and a mechanism to monitor change over time in human use and its impact on watersheds.

EPA's Science to Achieve Results (STAR) Estuarine and Great Lakes (EaGLE) Program



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Direct and indirect effects of human activities have taken a toll on the nation's estuaries, yet few direct linkages have been identified between human activities on land and responses in estuarine ecosystems. The Great Lakes Environmental Indicators (GLEI) project is one of five national projects funded by EPA's EaGLE program. The goal of the EaGLE program is to develop the next generation of ecological indicators that can be used in a comprehensive coastal monitoring program.



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