

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



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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 five 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.
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- Dan Simberloff, Department of Ecology and Evolutionary Biology, University of Tennessee.

The GLEI collaborators as a whole met eight times during the course of the five-year effort as well as having conference calls at intervals of three weeks to two 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 five major national/international symposia (two at Ecological Society of America, one at the American Society of Limnology and Oceanography, one at Society of Environmental Toxicology and Chemistry, and one 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 two undergraduate theses, 14 master's degrees (one in progress), 3 PhDs were completed (four 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 five 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!

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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 eight 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 five 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 two 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 nine 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 five-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 include:



- identify environmental indicators that are useful to define the condition, integrity, and change of the ecosystems within the coastal region,
- test indicators with a rigorous combination of existing data and field data to link stressors of the coastal region with environmental responses, and
- recommend 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 eight states and the Canadian province of Ontario. A boundary in climatic and physiographic features divides the basin into two 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.

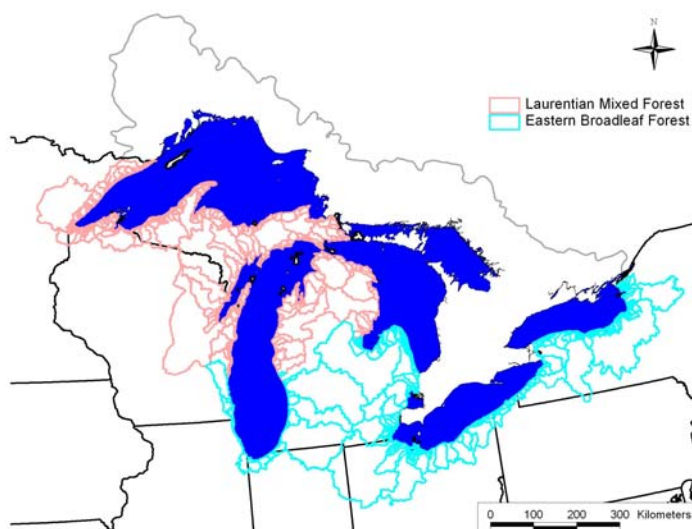


Figure 1. A total of 762 segment sheds identified for the U.S. Great Lakes Watershed.

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 delineated by 1) a segment of shoreline extending in both directions from the mouth of a 2nd-order or higher stream to one-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 are found in connecting channels between the lakes.

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 six 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 one 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 of categories of stress were combined into one 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.

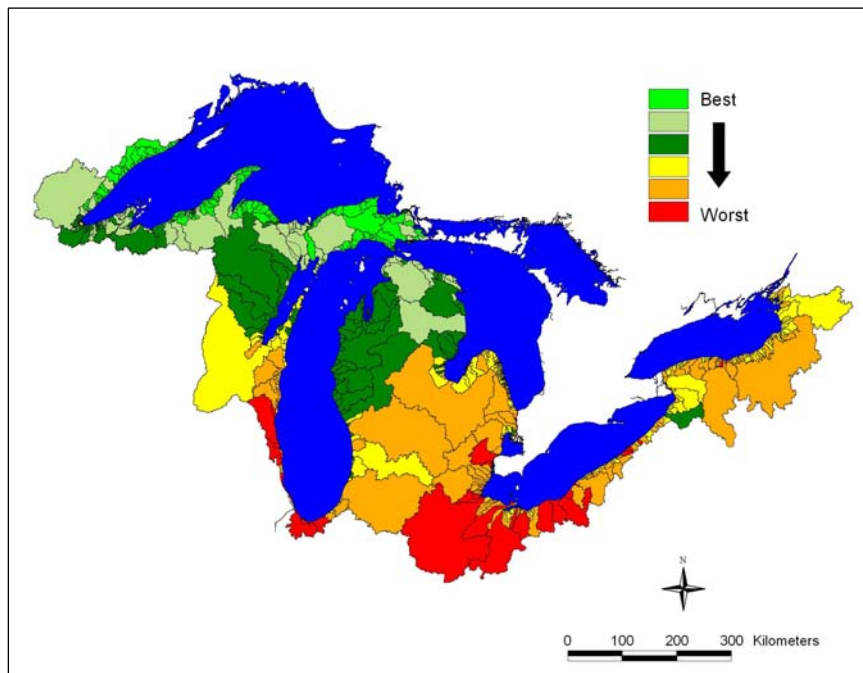


Figure 2. The overall Stress Index for the U.S. Great Lakes coastal region.

A final phase of the analysis included an integration phase in which we simultaneously analyzed 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), hydrogeomorphic 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 three 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 four components of this collaboration and over 58 wetland complexes were sampled by three 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).

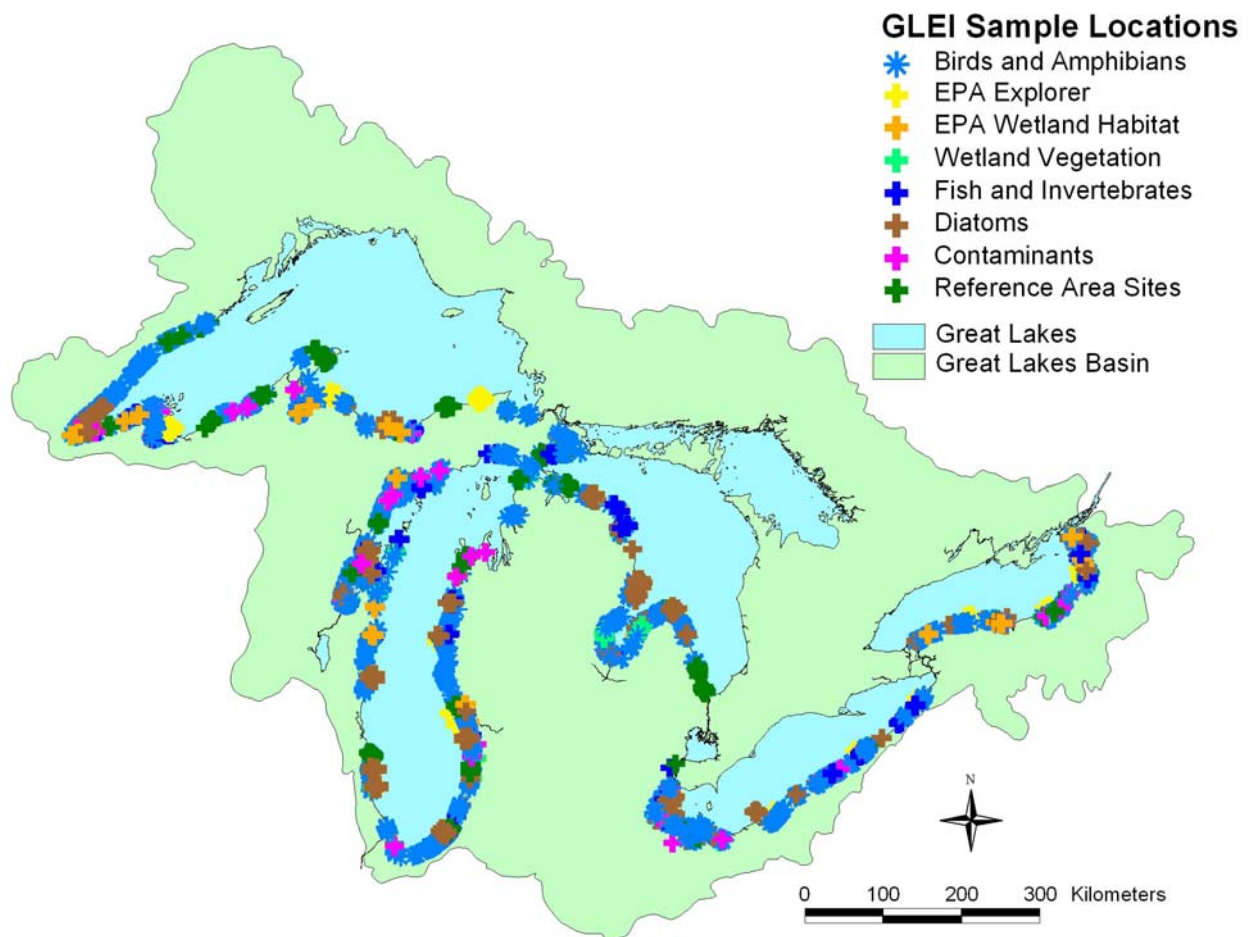


Figure 3. General locations of study sites across the U.S. Great Lakes coastal region.



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 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 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 two-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*, which 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 one time with an initial five 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 the Marsh Monitoring Program (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 three 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 four times as much to complete compared to a wetland bird survey and that an amphibian sample was approximately three 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), three of which were observed at fewer than five and another (Mink Frog, *Rana septentrionalis*) at only 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, which was 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 (*Pseudacris crucifer*). 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 six 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 four 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 ten-minute point counts. In order 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 two 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 six 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 four-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 (*Pseudacris crucifer*). 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. 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 six others indicating high quality sites; and Mallard, Ring-billed Gull, Marsh Wren, Common Grackle, and Red-winged Blackbird and eight others indicating poorer quality sites. In order 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 (species-specific sensitivity/detectability or 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. In order 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 species-specific responses (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 two 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 two 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 nine 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

Algal assemblages such as diatoms 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 disadvantage 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 two 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, two 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 *Achnanthes 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 CI 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 two 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 one 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 four 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 five distinct assemblages, associated with ecoregions and wetland type. For each of the five 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 two 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 six 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 two 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 two 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. 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).

We developed several 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-taxon index or a 4-taxon 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 which 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 a number of 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 one of seven forms of dominance. The index combines three related attributes of dominance in a similar fashion that is commonly used by plant ecologists for the calculation of importance values. Dominance uses three 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) 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 two 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 fourth most dominant LULC type in the watershed, covering ~2 million ha.

The three 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 three 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 one 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 three 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 one 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 three 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 five 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.nrri.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.