

## FOREWORD

# Environmental Indicators for the Coastal Region of the North American Great Lakes: Introduction and Prospectus

Gerald J. Niemi<sup>1,\*</sup>, John R. Kelly<sup>2</sup>, and Nicholas P. Danz<sup>1</sup>

<sup>1</sup>Center for Water and the Environment  
Natural Resources Research Institute  
University of Minnesota Duluth  
5013 Miller Trunk Highway  
Duluth, Minnesota 55811-1442

<sup>2</sup>U.S. Environmental Protection Agency  
Office of Research and Development  
National Health and Environmental Effects Research Laboratory  
Mid-Continent Ecology Division  
6201 Congdon Boulevard  
Duluth, Minnesota 55804-2495

**ABSTRACT.** *The Great Lakes coastal region is a dynamic area at the interface between land and water. It is heavily influenced by the magnitude of the large lakes themselves, by natural abiotic and biotic processes in the watershed, and especially by human activity. This special issue contains a series of 21 papers that are organized into four major themes: 1) landscape characterization and coastal linkage, 2) integration, 3) indicator development, and 4) supporting information. The results of these papers emphasize that many environmental response signals are linked to their physio-biogeographic location in the basin and with human activity in coastal watersheds or in the immediate coastal margin. If lake levels continue to fluctuate and decline, if the climate continues to warm, if agricultural activity expands, if exotic species continue to invade, and if the human population density in the watershed increases, then environmental indicators of the Great Lakes coastal region reported here will point to further degradation of water quality and native amphibian, bird, diatom, fish, macroinvertebrate, and wetland plant communities. These environmental indicators are benchmarks for the current conditions of the Great Lakes coastal region and provide measurable endpoints to assess the success of future management, conservation, protection, and restoration of this important resource.*

**INDEX WORDS:** *Great Lakes, disturbance, stressors, responses, watershed, integration.*

## INTRODUCTION

Coastal ecosystems, whether freshwater or marine, are under serious threat from many human-related stressors. These ecosystems are the repositories for land use practices, they are the sites of many industries, they are places where people like to live and recreate, and they are especially threatened by climate change (Niemi *et al.* 2004, Mackey and Goforth 2005). The North American Great Lakes are an important global resource and

are critical to the health of the economy and environment of the United States and Canada. The Great Lakes watershed is over 500,000 km<sup>2</sup>, including more than 15,000 km of shoreline and over 250,000 km<sup>2</sup> of open water area which holds over 18 percent of the world's fresh water volume. The Great Lakes region contains 46 unique species and 279 globally rare plants and animals (The Nature Conservancy 2006). More than 35 million people live in the Great Lakes watershed, while industry in the Great Lakes accounts for a major part of the economy of the United States and Canada.

\*Corresponding author. E-mail: gniemi@d.umn.edu

Great Lakes coastal ecosystems are heavily impacted by non-point and point sources of sediment, nutrients and contaminants, invasions by exotic species, water level fluctuations (partially due to climate change), and changes from natural to human-dominated land use (Mackey and Goforth 2005). Coastal vulnerability to landscape stressors is significant because the coastal region plays a vital role in many ecosystem processes that have lake-wide importance. These processes include primary and secondary production, water quality improvement, flood control, and protection against shoreline erosion (Ray and McCormick-Ray 2004). Coastal ecosystems have an influence much larger than would be inferred from the relatively small area they represent in comparison to open water area (Brazner *et al.* 2000). In the Great Lakes, coastal regions are extremely important from the perspective of fisheries, where fish species diversity is high and many coastal habitats provide a critical component in the life history of many species, including those typically associated with pelagic areas (Brazner 1997, Brazner *et al.* 2000, Mackey and Goforth 2005)

### The Need for Coastal Indicators

While scientific attention has traditionally focused on the open water of the Great Lakes, coastal ecosystems and watershed influences are increasingly becoming targets for research and conservation (Mackey and Goforth 2005). For instance, the Great Lakes Wetlands Consortium (Lawson 2004) has recently completed a series of studies on coastal wetlands of the Great Lakes, while Simon and Stewart (2006) presented a series of papers on the health, habitat, and indicators of Great Lakes coastal wetlands. This special issue of the *Journal of Great Lakes Research* substantially adds to the growing body of literature on the ecological condition of coastal areas. Most of the papers in this issue present the results of a cooperative effort between the Great Lakes Environmental Indicators (GLEI) project and research at the U.S. Environmental Protection Agency's (U.S. EPA) Mid-Continent Ecology Division. This collaboration was a basin-wide study of ecological conditions across human disturbance gradients, primarily on the U.S. side of the Great Lakes (Danz *et al.* 2005, 2007). The GLEI project was part of a larger effort by the U.S. EPA for all estuarine and Great Lakes coastal regions of the U.S. (Niemi *et al.* 2004, [www.epa.gov/ncer/eagle/](http://www.epa.gov/ncer/eagle/)). In addition, papers by Chow-

Fraser and her research group are included to incorporate several comprehensive community-based indicators developed for both the U.S. and Canada. The majority of papers in this special issue focus on coastal wetlands; however, some consider a range of aquatic coastal ecosystems and others consider biota in the terrestrial regions adjacent to coastal waters.

Primary purposes of environmental indicators are to identify the condition of the environment, to measure trends in these conditions, and potentially diagnose the causes for any changes in these conditions (Niemi and McDonald 2004). One general strategy in the development of indicators is to identify a response (e.g., biological, physical, or chemical) to a stressor or stressors and then determine a representative indicator or indicators which best represent the ecological condition that result from the stressor or stressor regime. In recent years there has been a proliferation of work completed in the development of indicators, including the emergence of a journal, *Ecological Indicators*, dedicated to the subject.

Information on indicators is legislatively mandated by the governments of the U.S. and Canada, because of public demand to know the status of the Great Lakes ecosystem. In addition, management agencies need information on indicators to make sound decisions on the maintenance, conservation, and protection of the Great Lakes as well as the ability to judge whether their management actions are achieving the desired effects. The State of the Lake Ecosystem Conference (SOLEC) process has identified a large number of potential environmental indicators for application in the Great Lakes ecosystem, some of which are relevant to the coastal region of the Great Lakes (Environment Canada and U.S. EPA 2007).

The papers in this special issue are intended to fill a major gap in development of ecological indicators for the coastal region, and they represent a logical follow-up to a recent special issue in the *Journal of Great Lakes Research* by Mackey and Goforth (2005). The coastal region of the Great Lakes has been defined in many ways. Mackey and Goforth (2005) focused on the nearshore aquatic and coastal margins. Nearshore aquatic was defined as the area between the shoreline and the 10 m depth contour. Coastal margins were defined as the area of the land-water interface, primarily influenced by lake-effect events, including coastal wetlands, estuaries, river mouths, and the lower reaches of tributaries. We consider "coastal" to in-

clude all of these aquatic systems, but further emphasize the important influence of coastal watersheds and the activities in watersheds which influence downstream aquatic coastal ecosystems. Many of the papers in this issue focus on coastal wetlands because they have an important role in habitat and the overall functioning of coastal processes, but also because more than half of these ecosystems have been destroyed (e.g., Whillians 1982, Dahl 1990, Herdendorf 1992).

### Setting the Stage for Indicators: Human Disturbance Gradients for the Great Lakes

Developing response indicators requires understanding the relationship between anthropogenic stressors and ecological response. Response indicators are particularly useful if they vary predictably across a stressor gradient (Dale and Beyeler 2001). Ideally, the linkage between stressor and response is completed through a manipulative experiment; however, at large scales (e.g., a watershed) or with human disturbance (e.g., human population density or agricultural activity), manipulation is difficult, expensive, or impossible (Niemi *et al.* 2004). Hence, “natural experiments” across gradients of disturbance are essential and are employed by studies in this issue, even though such an approach is far from a “controlled” single factor or multi-factor experiment. Due to the complex nature of such real-world gradients, many multivariate statistical approaches are used by authors in this issue to evaluate subsequent stressor-response relationships, including regression, variance partitioning, probability modeling, and curve fitting. But a common thread among these analyses is use of stressors (pressure variables) as *x*-variables and ecological responses (state variables) as *y*-variables. It is important to interpret and quantify relationships through resultant *x*-*y*-plots, but also to map and interpret the spatial pattern of stressor-response relationships across a study region.

A primary source of stressors to coastal ecosystems is land-based human development. While lake-based biophysical factors including wave action, seiche, and currents have long been recognized as drivers of Great Lakes coastal ecosystems (Keough *et al.* 1999), we are increasingly aware of the strong effects of terrestrial human activity. In the Great Lakes, agriculture, urbanization, land cover changes, hydrological modifications, point-source pollution, atmospheric deposition, climate change, and invasive species have acted alone and

in concert to cause changes in coastal ecosystems. Prior work on the Canadian and U.S. portions of the basin demonstrated the influence of land use changes on water quality and biotic structure in coastal wetlands (Crosbie and Chow-Fraser 1999, Lougheed *et al.* 2001, Albert and Minc 2004, Uzarski *et al.* 2004, Uzarski *et al.* 2005, Brazner *et al.* 2007a, Morrice *et al.* in press). In some cases, the ultimate source of stress may be distant from the receiving system, while in other cases, stressors originate in close proximity to the system—such as shoreline alteration.

Quantification of stressors includes two components, the actual stressor measurement and the spatial area it occupies. Papers in this issue use a variety of stressor measurements and corresponding areal units. For example, water chemistry indicators may be primarily influenced by agricultural stressors within the watershed (Trebitz *et al.* 2007), while bird indicators may be more tightly linked to land cover adjacent to a wetland (Howe *et al.* 2007). While there is likely no single universally best method for quantifying stressors, in recent work we developed integrated stress gradients for the entire U.S. Great Lakes basin which can serve multiple objectives (Danz *et al.* 2005, 2007).

The approach in the Danz *et al.* papers involved taking advantage of numerous preexisting, publicly-available spatial datasets describing human activity in the basin and combining them into stressor measures across the entire spatial extent of the U.S. Great Lakes basin. Briefly, we obtained over 200 variables from data types related to human activity in the basin and used spatial data transformations to convert these to three sets of target units: segments, complex-specific watersheds, and ArcHydro catchments (further detailed in Hollenhorst *et al.* 2007). We then classified the variables into five separate types of stress: agriculture, atmospheric deposition, human population, land cover, and point-source pollution. We used principal components analysis (PCA) within each category of stress to reduce dimensionality and integrate across the multiple variables in each category. The first principal component (PC) from each category was interpreted as an overall gradient of stress. For example, PCA for 21 agricultural variables representing the major types of agricultural stress (e.g., nutrient runoff, fertilizers, pesticides, and erosion) yielded an integrated stress gradient that explained over 70% of the variance in the agricultural input variables (Danz *et al.* 2007).

Interpretation of the integrated stress gradients re-

**TABLE 1.** Relative length of environmental gradients on a scale of 0–1. Values indicate the range in principal component (PC) scores for each lake as a proportion of the total basin-wide range in the PC.

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

\*Cumulative stress index comprised of the 5 individual stress gradients but excludes the soils category

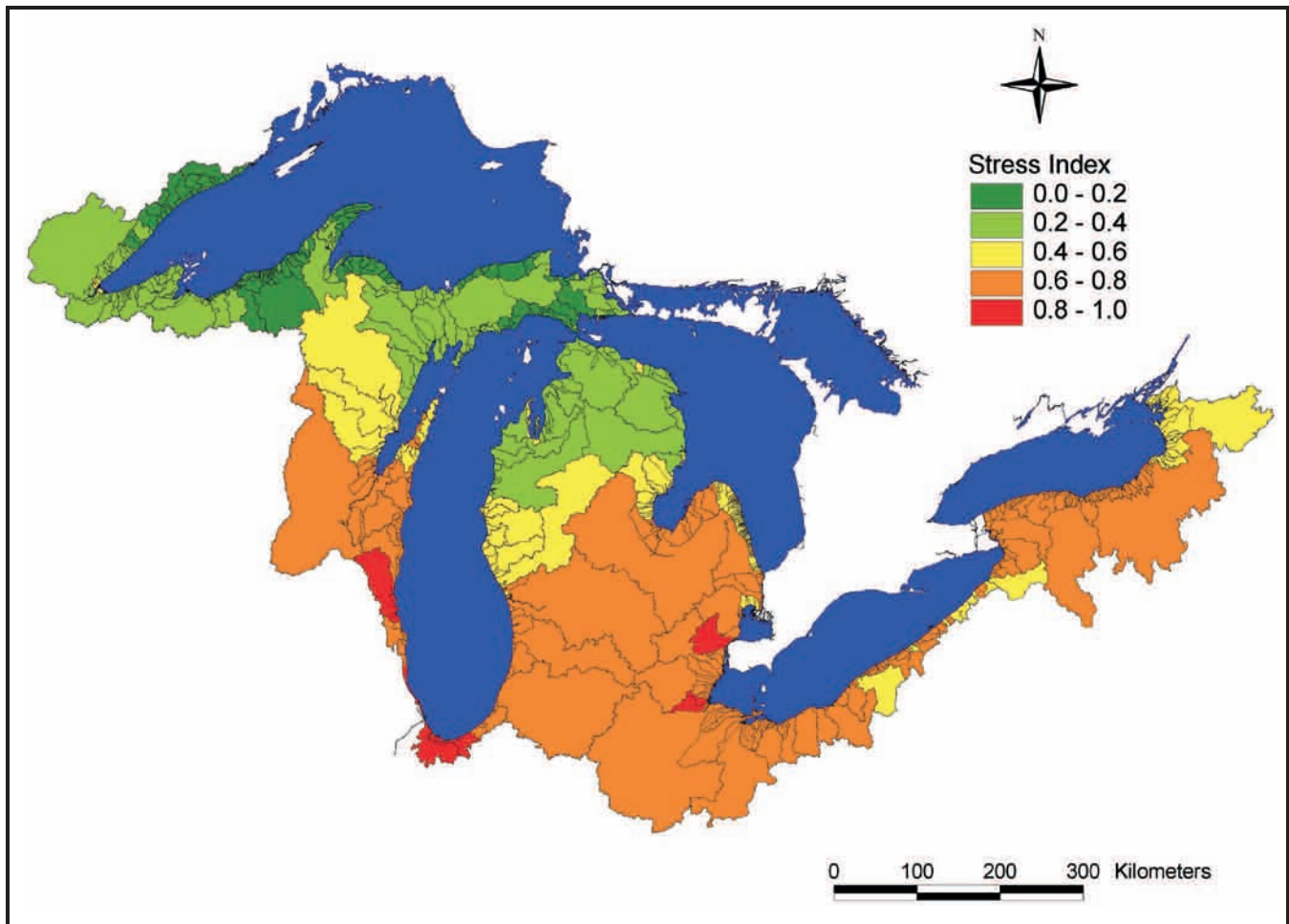
vealed strong spatial patterns of disturbance across the basin. Generally, agricultural activity and non-natural land cover is concentrated in the lower lakes, especially around southern portions of Lakes Michigan and Huron and the western portion of Lake Erie. Atmospheric deposition displays a strong gradient from west (low deposition) to east (high deposition) because the prevailing winds are from the west. Human population density tends to be greater in the lower lakes, but there are substantial population centers in the upper lakes as well. Point-source pollution tends to be concomitant with human population density. Some lakes have especially short gradients for some types of stress (Table 1). For example, segment-sheds in Lake Superior cover only the lowest 33% of the basin-wide agriculture gradient, while segment-sheds in Lake Ontario cover only the upper 23% of this gradient. Lake Erie segment-sheds covered only 16% of the basin-wide atmospheric deposition gradient. On the other hand, Lakes Michigan and Huron had broad gradients for all stressors, both covering over 75% of the cumulative stress index. This is primarily because both Lakes Michigan and Huron cover wide latitudinal areas. Disentangling relationships between stressors and responses may require explicit consideration of the length of gradients for particular stressors or the potentially confounding influence of overlapping stresses that are geographically co-located. Brazner *et al.* (2007b) found strong differences across biological taxa by partitioning the variance by the Great Lake where data were collected.

Keeping stressor categories separate allows diagnosis of the major influence upon specific ecological indicators, while combining the stressors in some way may better represent their cumulative, overlapping nature. Danz *et al.* (2007) created a cumulative stress index by combining stress measures into an overall index. Here, we preview a more so-

phisticated version of the cumulative stress index, one which “calibrates” the landscape-measured disturbance gradient by weighting it according to the strength in relationships with biological responses. To accomplish this, we weighted a cumulative stress index according to the total proportional reduction in error (analogous proportion of variance explained) for 66 ecological response indicators described in Brazner *et al.* (2007b) (Fig. 1). Brazner *et al.* (2007b) found that agriculture and human population density were two of the primary, broad stressor categories which had the greatest influence on the 66 indicators examined. Point-source pollution had less influence on most of the indicators, except for diatoms, which was likely related to water quality. The observed lack of point-source pollution having a greater impact on the indicators was partly due to less intensive field sampling near industrial centers, plus the extensive areas of the Great Lakes shoreline impacted by agriculture and human populations (Table 1).

The calibrated index modifies the picture of the spatial distribution and intensity of stressors compared with the cumulative stress index presented by Danz *et al.* (2007). This calibrated index emphasizes the ability to iterate the stressor and response relationships and express these relationships visually. This also reinforces our view that one definition of a disturbance gradient is not the goal, because different coastal biota and ecosystems are likely to have different response attributes.

There are other formulations of stressor-response indices (Howe *et al.* 2007) that try to take into account joint variability in the  $x$ - and  $y$ -axes of stressor-response relationships. More are likely to be developed, but this framework can provide a characterization of landscape-level conditions in a con-



**FIG. 1.** Response-based stress index calibrated to biotic responses for 762 segment-sheds of the U.S. Great Lakes basin. The index was calculated as a weighted sum of three stress gradients from Danz et al. (2007): agriculture, human population, and point source pollution. Weights were the total proportional reduction in error (0.23, 0.27, 0.01, respectively) attributed to these three types of stress from 66 response-based classification trees in Brazner et al. (2007b).

sistent and comprehensive manner across the U.S. Great Lakes coast and offer a template to evaluate coastal indicators.

#### Synopsis of Papers in this Volume

We have organized this issue into four major theme sections:

1. **Landscape characterization and coastal linkage**—two papers emphasize how to quantify the linkages between the Great Lakes watershed and coastal ecosystems;
2. **Integration**—four papers synthesize information on potential environmental indicators;
3. **Indicator development**—eight papers largely

focus on the development, testing, and application of specific indicator taxa; and

4. **Supporting contributions**—seven papers focus on sampling or more specific issues associated with the development of environmental indicators.

Each of these papers is briefly summarized below.

#### Landscape Characterization and Coastal Linkage

Hollenhorst *et al.* (2007) describe an evolving process of watershed delineation and stressor characterization for different purposes, starting with

segment-sheds used in sampling design (Danz *et al.* 2005), progressing to watersheds that encompass the land area draining to sampled wetlands, and culminating in ArcHydro catchments that are at the finest spatial resolution and can be used for detailed analysis. Each spatial characterization of coastal watersheds provides slightly different formulations of the potential landscape stressors. The use of different stressor formulations by papers in this volume and other recent publications of the GLEI project is summarized by Hollenhorst *et al.* (2007). The diversity of stress gradients and watershed delineations employed by different authors is reflected by variability in the independent variables used in figures and tables. This diversity of gradients is a natural evolution of work in progress, but it also reinforces an important point. There is no absolute depiction of the landscape gradient or a “correct” gradient. The landscape characterization is a function of the scale used, further dependent on the resolution of the raw stressor data which are entered into the analysis, and even further dependent on the nature of the receiving system. As emphasized by Hollenhorst *et al.* (2007), we do not know the relevant scales to be examined for all coastal ecosystem types as receiving systems, especially for open nearshore systems.

Nonetheless, we now have considerable evidence to demonstrate that the condition of many coastal receiving systems is strongly tied to the quality of the landscape “sending” systems. Previously, Danz *et al.* (2007) and Morrice *et al.* (in press) have shown statistically-strong relationships between watershed character and water quality for coastal wetlands. Peterson *et al.* (2007) carry this connection further using  $^{15}\text{N}$ , a more time- and space-integrative measure than water quality.  $^{15}\text{N}$  carefully measured in biological tissues of organisms from the water and sediments of coastal wetlands, embayments, and shallow nearshore ecosystems reflected the landscape gradient adjacent to the ecosystem sampled. They suggest this stable isotope measurement serves as an “exposure” indicator and their study confirms the watershed-aquatic connection across a Great Lakes disturbance gradient.

### Integration

The four papers included in this section examine relationships among several response variables to stressors in the coastal zone. Brazner *et al.* (2007b) is a follow-up to a previous paper (Brazner *et al.* 2007a) in the evaluation of how geography such as

lake, geomorphic factors such as wetland type, and a general stress index are related with many taxa (e.g., birds, fish, and macroinvertebrates). Brazner *et al.* (2007b) extend their 2007(a) analysis by examining scales of cumulative stressors and the aggregate multi-species response in more detail. The major stressors contributing to the overall index were agriculture, human population density, and contaminants. These stressors were then related with 66 potential indicators in the context of geographic and geomorphic covariables. In contrast, Trebitz *et al.* (2007) examined many water quality variables in relation to an agricultural gradient across the entire U.S. portion of the basin as well as biogeography and geomorphic type. Their results show that water quality is strongly related with agricultural activity in coastal watersheds of the U.S. Great Lakes. Water quality varies considerably among the Great Lakes and the incorporation of this information is essential in the development of water quality criteria and in the establishment of monitoring programs for coastal wetlands.

Diatoms as a multi-species assemblage are well known indicators for water quality but are just now being used in Great Lakes coastal systems. Reavie (2007), following Reavie *et al.* 2006, develops the connection among landscape variables, water quality, and biological character of coastal ecosystems that can be inferred by diatom assemblages. He reports on a diatom-based model, using a suite of WQ variables rather than a single stressor such as total phosphorus (TP), and finds the resultant model has a high degree of reconstructive power. Howe *et al.* (2007) similarly uses multiple species (here using birds as the example) and models of abundance in relation to a suite of environmental variables that define a gradient in the landscape across the Great Lakes. They suggest how an integrated condition index can be obtained using species occurrences and that observations using a suite of species can provide a powerful indicator of environmental condition. They combine explicit site-by-site understanding of the local environmental milieu with local biological conditions and defined species-level gradient responses to describe an overall expectation via an index of ecological condition.

### Indicator Development

The heart of this special issue is the actual development of environmental indicators. Eight papers are included and all are directly related with indica-

tors for application to the Great Lakes coastal region.

Plant species distributions have a long history of use as ecological indicators. Johnston *et al.* (2007a) use wetland plant species as indicators of the physical environment of 90 wetlands in the U.S. Great Lakes coast. Forty common plant species out of 192 species were the most important in describing these wetland environments. Wetland indicator species were developed and linked with soil conditions and geomorphic wetland types. Frieswyk *et al.* (2007) describe a new index based on dominance of wetland plants. They found that dominance can be described in seven basic forms and is useful for describing wetland community structure. A total of 38 species out of 466 identified were used to describe dominance at the wetland scale, 23 at the lake scale, and six at the regional scale. Forms of dominance can be used as an early warning indicator of exotic plant species invasion in wetlands.

Kireta *et al.* (2007) examined some of the limits to predictability based on diatom-based indicator models. Their exploration tests diatom assemblage specificity to total phosphorus as a function of six different coastal habitats and from the perspective of each Great Lake. Observed variations in diatom-water quality model performance are sensitive to the scale of interest and related with physical and environmental variability.

Two papers by Pat Chow-Fraser's group at McMaster University describe indicators of fish and wetland macrophyte communities. Seilheimer and Chow-Fraser (2007) build on a wetland fish index that was developed for the lower Great Lakes (Erie, Ontario, and Michigan) with additional data from Huron and Superior. Their new basin-wide wetland fish index can be applied to all of the Great Lakes and is highly correlated with water quality conditions. Croft and Chow-Fraser (2007) present a wetland macrophyte index (WMI) based on plant presence/absence in 127 coastal wetlands in the Great Lakes. The WMI was also highly related with water quality conditions in the wetland. Moreover, they describe how the WMI can be used to track wetland conditions over time with data from wetlands under remedial action and invasion from exotic plant species.

Kang *et al.* (2007) describe how the distribution of a non-indigenous amphipod (*Echinogammarus ischnus*) was unrelated with a human disturbance gradient (i.e., from Danz *et al.* 2005). Instead, occurrence of this species was primarily related with occurrence of a native amphipod (*Gammarus fas-*

*ciatus*). In this case, a general human disturbance gradient was not a good indicator to predict susceptibility of invasion by an amphipod. This reinforces the concept that environmental indicators or general gradients cannot explain all biological phenomena, and more detailed investigations are often essential. Price *et al.* (2007) develop biological response functions for species of frogs and toads in relation to landscape disturbances in coastal wetlands. Their analysis suggests that the occurrence of only one species, Spring Peeper (*Hyla crucifer*), has attributes necessary as a species-level indicator: relatively abundant, regular occurrence, and a consistent relationship with disturbance. In general, species of frogs and toads were found to have relatively low abundance and inconsistent responses with disturbance to be useful as species-level indicators. However, they may be combined to form a more integrative biological index.

A substantial amount of work has previously been presented on the use of fish as indicators (e.g., Seilheimer and Chow-Fraser 2007) in the Great Lakes. Bhagat *et al.* (2007) expand on previous research by Uzarski *et al.* (2005) in which fish community composition in Great Lakes wetlands could be effectively described if stratified by plant zones. Bhagat *et al.* (2007) simultaneously examined a fish index of biological integrity (IBI) with plant zones and along with a human disturbance gradient. Their fish-based IBI was related with plant zone type (*Typha* or *Scirpus* species dominated), was non-linearly related with a disturbance gradient, and potentially showed a threshold response by the fish community.

### Supporting Studies

In addition to developing indicators, several studies examine specific sampling or analytical methodologies in ways that would help clarify how indicators could or should be put to use in efficient monitoring programs. For example, Brady *et al.* (2007) and Hanowski *et al.* (2007) look at economies and merits of some survey details that would use fish or birds as wetland indicators. Brady *et al.* (2007) tested the power of longer net set duration for fish sampling to provide suitable data on fish species richness, one of the indicators explored in the multi-indicator analysis of Brazner *et al.* (2007b). Hanowski *et al.* (2007) evaluate how to maintain a Great Lakes-wide wetland survey approach, examining some statistical trade-offs between intensive surveys at fewer sites versus

greater numbers of sites, and the associated costs of such approaches. The study provides an explicit method for estimating statistical power as well as costs of different monitoring scenarios. Remote sensing and geographic information systems will be essential tools in future development of environmental indicators. Johnston *et al.* (2007b) show how past aerial photography can be used with contemporary satellite imagery to identify land use change over a 60-year period in a 100 km<sup>2</sup> area in the western end of Lake Erie. In contrast, Tulbure *et al.* (2007) track the invasion of *Phragmites* and non-native *Typha* over a 5-year period as water levels changed at Point au Sable, Green Bay, Wisconsin. Detailed studies of this sort will aid in the future development of wetland plant indicators associated with water level changes.

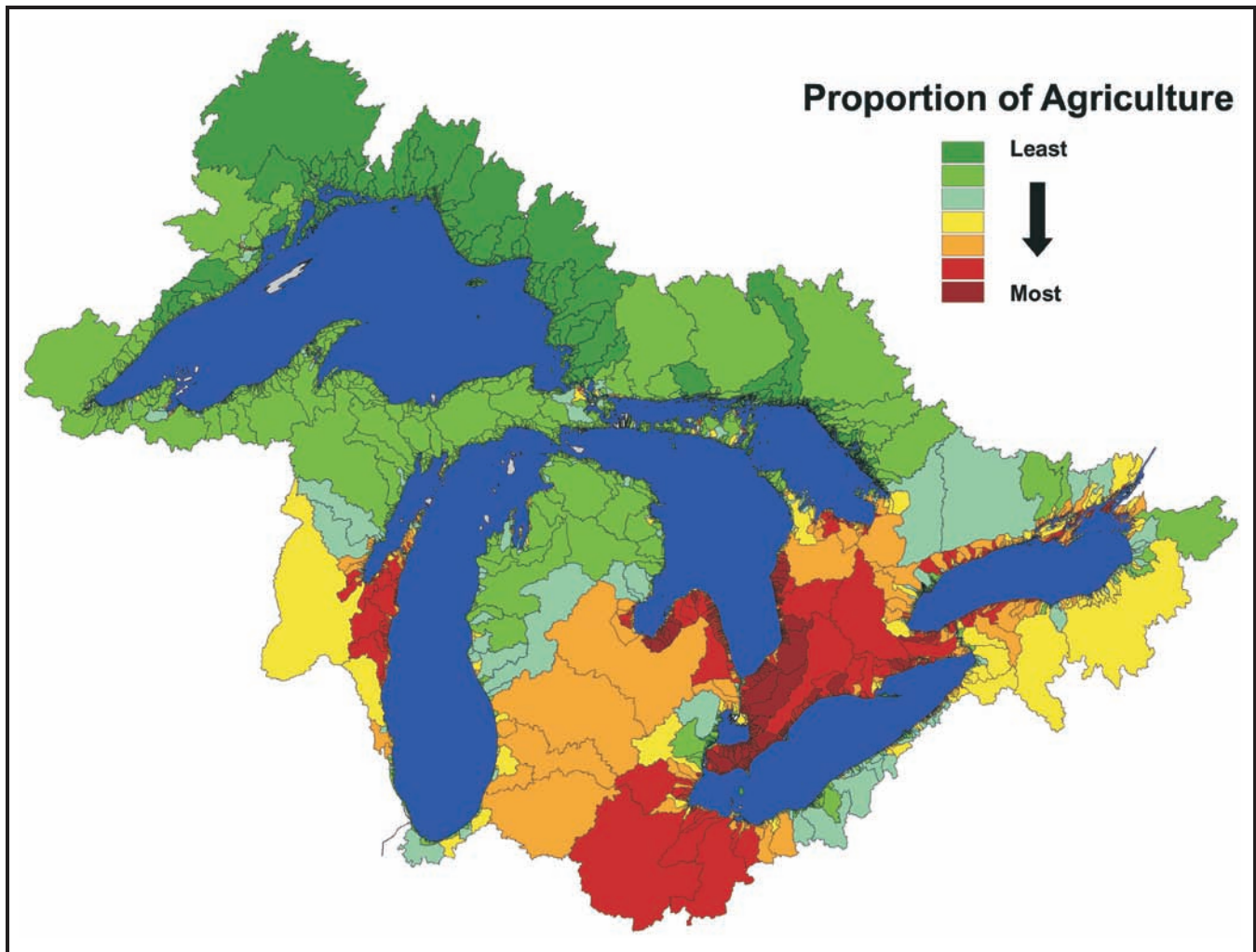
Peterson and Niemi (2007) explicitly test application of the Ohio Rapid Assessment Method for wetlands. This method was not developed for the Great Lakes, but their application of breeding birds to coastal wetland habitats leads to further suggestions on the potential for the development of rapid assessments for the Great Lakes. Grandmaison and Niemi (2007) examine the potential to measure nest productivity for one of the most abundant bird species of Great Lakes wetlands, the Red-winged Blackbird (*Agelaius phoeniceus*), as an indicator of wetland health. The results showed that nests were relatively easy to find, nest success was related with landscape attributes surrounding wetlands, and nest success was potentially useful as an indicator of ecological health of the wetland. Miller *et al.* (2007) is one of the few papers to explore the development of indicators for the upland portion of the Great Lakes coast. They examine breeding bird communities across a gradient from residential, urbanized, and industrial areas to agricultural lands and to heavily forested areas. Many species showed significant relationships with this gradient. Breeding bird communities can be used as indicators of ecological condition and can be useful in regional planning strategies that incorporate goals for maintaining native biological diversity.

### Future Considerations

Socioeconomic indicators for the Great Lakes basin show that agricultural activity is unlikely to become less, but most likely to expand with the current interest in biomass-associated fuels. Similarly, the human population shows little indication of declining and coastal regions are predicted to become

even more popular in the future. Current climate change models for the Great Lakes region indicate that the temperatures will rise, but precipitation patterns are still unpredictable. Recent trends have been toward much higher water temperatures and lower water levels in the Great Lakes, and burgeoning coastal populations will put more pressure on water resources. There has been a steady increase in the number of exotic species of plants and animals in the region in recent times. Clearly the North American Great Lakes region will continue to change and some ecological changes may be rather unexpectedly rapid (cf. Holleck *et al.* 2004, Drake *et al.* 2005, Austin and Coleman 2007). Conditions now present along the margins of the more developed watersheds of the lakes can be expected to press outward as development and urban sprawl continues; fewer and fewer locations of “reference” or undisturbed/least disturbed will remain. The time and space translation of landscape-derived coastal impacts to lake-wide change, of course, remains another significant scientific challenge.

All environmental indications, based on an aggregate sense of the work presented in this volume, are that the health of coastal ecosystems will concomitantly decline. For example, increased human disturbance, as measured by a human disturbance gradient, primarily in the form of agricultural activity and human population density, has been related with negative effects on water quality (Trebitz *et al.* 2007), birds (Howe *et al.* 2007), diatoms (Reavie *et al.* 2006), fish (Bhagat *et al.* 2007), wetland vegetation (Johnston *et al.* 2007), and collectively in a multi-taxa analysis (Brazner *et al.* 2007a, 2007b). How much further degradation will occur, and at what pace? Landscape development-related changes may seem inexorable and inevitable with human population increases, but the most appropriate question might be—How might negative influences be minimized? The human disturbance gradients described in this special issue and in more detail by Danz *et al.* (2005, 2007) provide independent axes upon which to judge the potential changes that could occur in water quality and in the biota with increased human influence in the Great Lakes watershed. Changes in landscape character can (Wolter *et al.* 2006, Johnston *et al.* 2007) and should be a part of the continuing assessment of change, and one means to judge the pace that will stimulate further coastal impacts. However, this volume also makes the case that inclusion of directed coastal monitoring and assessment with some of the indicators developed here will provide a quality of understanding



**FIG. 2.** Summary of agricultural land cover in the Great Lakes basin for the U. S. and Canada. Note that 6,000 detailed watersheds were delineated for the entire Great Lakes basin using techniques similar to those described in Hollenhorst et al. (2007). For each of these watersheds, the proportion of agricultural land cover (pasture, hay and row-crop) was summarized within a GIS using 1990s era land cover developed by Wolter et al. (2006) (U.S. portion) and Ontario Land Cover Data (2002) (Canadian portion).

that cannot be gained by only using remote sensing and landscape change metrics.

Perhaps the most unique contribution of this issue is the quantification of the relationship of many biological, chemical, and physical aspects of coastal ecosystems to human disturbance gradients or related water quality gradients (e.g., Trebitz *et al.* 2007, Seilheimer and Chow-Fraser 2007, Croft and Chow-Fraser 2007). The human disturbance gradients represent multiple stressors derived from the multitude of human activities within the basin. These gradients formed the basis of the GLEI project. The strength of using human disturbance gra-

dients is the ability to examine environmental responses across common, independent axes. In the terminology of cause-and-effect, the responses can be related with a stressor or stressors. If there is a relationship, then an indicator can be linked with its cause, and having both measures together strengthens the case for restoration or future planning decisions. Linkage to the stressor(s) may allow management actions to rectify the cause for change, and ultimately to improve environmental protection and the condition of these coastal ecosystems (Niemi *et al.* 2004).

We reemphasize, there is no one correct or

unique depiction of a human disturbance gradient for the Great Lakes. Recognizing this, Hollenhorst *et al.* (2007) have laid the foundation for flexibility in how we examine and evaluate scales of stressor delivery and response in continuing indicator and assessment research. An appropriate human disturbance gradient is one that describes important human activity for a specified spatial area and is related with an important environmental response (indicator). The best indicators are those that are most reliable, efficient, and economical to measure. However, an indicator that is expensive to measure can be useful if it has high explanatory power.

It is clear that one important metric is the agricultural stress gradient, which is a driver for water quality in coastal systems and the related cascade of direct biological and indirect change mediated through habitat and food-web effects. The work of creating a wall-to-wall inventory of landscape character and related coastal indicators must not stop at the international border and collaborative efforts are ongoing. Figure 2 is thus a preview of the future, an emergent picture of agricultural use with both U.S. and Canadian watersheds delineated in a seamless fashion. We end with this figure to highlight that the work represented in this issue is not the end to research on the Great Lakes coastal region, but another step in improving both our understanding of coastal ecosystems, their protection, and their restoration, and our ability to effectively monitor them. Even with the remarkable sampling/analytical effort and the striking results reported here, there is a continuing need to better integrate all of the available and voluminous information, especially as efforts can include both Canadian and U.S. shorelines. It will still take a substantial amount of time and effort because the North American Great Lakes constitute such a vast area. The work of the multitude of excellent organizations and scientists involved in the Great Lakes needs to continue in this pursuit. The enormous inspection and evaluation of so many potential indicators, as reflected in this issue, ultimately will ring hollow unless we, as a scientific and social community, move forward to organize consistent and comprehensive monitoring and assessment programs using some of these indicators to watch over the coasts as a sentinel for basin-wide and lake-wide change.

#### ACKNOWLEDGMENTS

The authors thank all the contributors to the special issue for meeting all requests related to reviews

and/or timely revisions of their papers. We are grateful to Tom Hollenhorst for producing the figures of this introductory paper. Thanks to Lucinda Johnson and Jan Ciborowski for permission to use Figure 2—result of collaborative international funding efforts for Lake Erie, the GLEI project, and other partnerships.

Production of the issue would not have been possible without the coordination of Margy Bell at the University of Minnesota Duluth. The guest editors gratefully acknowledge Margy's efforts. We also thank Mary Ann Starus at the Mid-Continent Ecology Division of the U.S. EPA in Duluth MN for final editing assistance with this paper and all those in this special issue.

This research was supported by a grant to Gerald Niemi from the U.S. Environmental Protection Agency's Science to Achieve Results Estuarine and Great Lakes program through funding to the Great Lakes Environmental Indicators project, U.S. EPA Agreement EPA/R-8286750. This document has not been subjected to the agency's required peer and policy review and therefore does not necessarily reflect the view of the agency, and no official endorsement should be inferred. This is contribution number 456 of the Center for Water and the Environment, Natural Resources Research Institute, University of Minnesota Duluth.

#### REFERENCES

- Albert, D.A., and Minc, L.D. 2004. Plants as regional indicators of Great Lakes coastal wetland health. *Aquat. Ecosyst. Health Manage.* 7:233–247.
- Austin, J.A., and Coleman, S.M. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: a positive ice-albedo feedback. *Geophys. Res. Lett.*, Vol. 34, L06604, doi:10.1029/2006GL029021.
- Bhagat, Y., Ciborowski, J.J.H., Johnson, L.B., Uzarski, D.G., Burton, T.M., Timmermans, S.T.A., and Cooper, M.J. 2007. Testing a fish index of biotic integrity for responses to different stressors in Great Lakes coastal wetlands. *J. Great Lakes Res.* 33 (Special Issue 3):224–235.
- Brady, V.J., Ciborowski, J.J.H., Johnson, L.B., Danz, N.P., Holland, J.D., Breneman, D.H., and Gathman, J.P. 2007. Optimizing fishing time: One vs. two-night fyke net sets in Great Lakes coastal systems. *J. Great Lakes Res.* 33 (Special Issue 3):236–244.
- Brazner, J.C. 1997. Regional, habitat, and human development influences on coastal wetland and beach fish assemblages in Green Bay, Lake Michigan. *J. Great Lakes Res.* 23:36–51.
- \_\_\_\_\_, Sierszen, M.E., Keough, J.R., and Tanner, D.K.

2000. Assessing the ecological importance of coastal wetlands in a large lake context. *Verh. Internat. Verein. Limnol.* 27:1950–1961.
- \_\_\_\_\_, Danz, N.P., Niemi, G.J., Regal, R.R., Trebitz, A.S., Howe, R.W., Hanowski, J.M., Johnson, L.B., Ciborowski, J.J.H., Johnston, C.A., Reavie, E.D., Brady, V.J., and Sgro, G.V. 2007a. Evaluation of geographic, geomorphic and human influences on Great Lakes wetland indicators: a multi-assemblage approach. *Ecol. Indicators* 7:610–635.
- \_\_\_\_\_, Danz, N.P., Trebitz, A.S., Niemi, G.J., Regal, R.R., Hollenhorst, T.P., Host, G.E., Reavie, E.D., Brown, T.N., Hanowski, J.M., Johnston, C.A., Johnson, L.B., Howe, R.W., and Ciborowski, J.J.H. 2007b. Responsiveness of Great Lakes wetland indicators to human disturbances at multiple spatial scales: A multi-assemblage assessment. *J. Great Lakes Res.* 33 (Special Issue 3):42–66.
- Croft, M., and Chow-Fraser, P. 2007. Use and development of the wetland macrophyte index to detect water-quality impairment in fish habitat of Great Lakes coastal marshes. *J. Great Lakes Res.* 33 (Special Issue 3):172–197.
- Crosbie, B., and Chow-Fraser, P. 1999. Percentage land use in the watershed determines the water and sediment quality of 22 marshes in the Great Lakes basin. *Can. J. Fish. Aquat. Sci.* 56:1781–1791.
- Dahl, T.E. 1990. *Wetland losses in the United States 1780s to 1980s*. Department of the Interior, U.S. Fish and Wildlife Service, Washington, DC.
- Dale, V.H., and Beyeler, S.C. 2001. Challenges in the development and use of ecological indicators. *Ecol. Indicators* 1:3–10.
- Danz, N.P., Regal, R.R., Niemi, G.J., Brady, V.J., Hollenhorst, T.P., Johnson, L.B., Host, G.E., Hanowski, J.M., Johnston, C.A., Brown, T.N., Kingston, J.C., and Kelly, J.R. 2005. Environmentally stratified sampling design for the development of Great Lakes environmental indicators. *Environ. Monit. Assess.* 102:41–65.
- \_\_\_\_\_, Niemi, G.J., Regal, R.R., Hollenhorst, T.P., Johnson, L.B., Hanowski, J.M., Axler, R.P., Ciborowski, J.J.H., Hrabik, T., Brady, V.J., Kelly, J.R., Morrice, J.A., Brazner, J.C., Howe, R.W., Johnston, C.A., and Host, G.E. 2007. Integrated measures of anthropogenic stress in the U.S. Great Lakes basin. *Environ. Manage.* 39:631–647.
- Drake, J.M., Costello, C., and Lodge, D.M. 2005. When did the discovery rate for invasive species in the North American Great Lakes accelerate? *BioScience* 55(1):4.
- Environment Canada and U.S. Environmental Protection Agency. 2007. *State of the Great Lakes 2007 highlights*. Canada and United States of America.
- Frieswyk, C.B., Johnston, C.A., and Zedler, J.B. 2007. Identifying and characterizing dominant plants as an indicator of community condition. *J. Great Lakes Res.* 33 (Special Issue 3):000–000.
- Grandmaison, D.D., and Niemi, G.J. 2007. Local and landscape influence on red-winged blackbird (*Agelaius phoeniceus*) nest success in Great Lakes coastal wetlands. *J. Great Lakes Res.* 33 (Special Issue 3):292–304.
- Hanowski, J.M., Danz, N.P., Howe, R.W., Regal, R.R., and Niemi, G.J. 2007. Considerations for monitoring breeding birds in Great Lakes coastal wetlands. *J. Great Lakes Res.* 33 (Special Issue 3):245–252.
- Herdendorf, C.E. 1992. Lake Erie coastal wetlands: an overview. *J. Great Lakes Res.* 18:533–551.
- Holleck, K.T., Mills, E.L., MacIsaac, H.J., Dochoda, M.R., Colautti, R.I., and Ricciardi, A. 2004. Bridging troubled waters: biological invasions, transoceanic shipping, and the Laurentian Great Lakes. *BioScience* 54:919–929.
- Hollenhorst, T.P., Brown, T.N., Johnson, L.B., Ciborowski, J.J.H., and Host, G.E. 2007. Methods for generating multi-scale watershed delineations for indicator development in Great Lake coastal ecosystems. *J. Great Lakes Res.* 33 (Special Issue 3):13–26.
- Howe, R.W., Regal, R.R., Hanowski, J.M., Niemi, G.J., Danz, N.P., and Smith, C.R. 2007. An index of ecological condition based on bird assemblages in Great Lakes coastal wetlands. *J. Great Lakes Res.* 33 (Special Issue 3):93–105.
- Johnston, C.A., Bedford, B.L., Bourdaghs, M., Brown, T.N., Frieswyk, C., Tulbure, M., Vaccaro, L., and Zedler, J.B. 2007a. Plant species indicators of physical environment in Great Lakes coastal wetlands. *J. Great Lakes Res.* 33 (Special Issue 3):106–124.
- \_\_\_\_\_, Watson, T., and Wolter, P.T. 2007b. Sixty-three years of land alteration in Erie Township. *J. Great Lakes Res.* 33 (Special Issue 3):253–268.
- Kang, M., Ciborowski, J.J.H., and Johnson, L.B. 2007b. The influence of anthropogenic disturbance and environmental suitability on the distribution of the non-indigenous amphipod *Echinogammarus ischnus* at Laurentian Great Lakes coastal margins. *J. Great Lakes Res.* 33 (Special Issue 3):198–210.
- Keough, J.R., Thompson, T.A., Guntenspergen, G.R., and Wilcox, D.A. 1999. Hydrogeomorphic factors and ecosystem responses in coastal wetlands of the Great Lakes. *Wetlands* 19(4):821–834.
- Kireta, A.R., Reavie, E.D., Danz, N.P., Axler, R.P., Sgro, G.V., Kingston, J.C., Brown, T.N., and Hollenhorst, T. 2007. Coastal geomorphic and lake variability in the Laurentian Great Lakes: Implications for a diatom-based monitoring tool. *J. Great Lakes Res.* 33 (Special Issue 3):136–153.
- Lawson, R. 2004. Coordinating coastal wetlands monitoring in the North American Great Lakes. *Aquat. Ecosyst. Health Manage.* 7:215–221.
- Lougheed, V.L., Crosbie, B., and Chow-Fraser, P. 2001.

- Primary determinants of macrophyte community structure in 62 marshes across the Great Lakes basin: latitude, land use, and water quality effects. *Can. J. Fish. Aquat. Sci.* 58:1603–1612.
- Mackey, S.D., and Goforth, R.R. 2005. Special issue on Great Lakes nearshore and coastal habitats. *J. Great Lakes Res.* 31(1).
- Miller, C., Niemi, G.J., Hanowski, J.M., and Regal, R.R. 2007. Breeding bird communities across an upland disturbance gradient in the western Lake Superior region. *J. Great Lakes Res.* 33 (Special Issue 3):305–318.
- Morrice, J.A., Danz, N.P., Regal, R.R., Kelly, J.R., Niemi, G.J., Reavie, E.D., Hollenhorst, T.P., Axler, R.P., A.S. Trebitz, A.S., Cotter, A.M., and Peterson, G.S. 2008. Human influence on water quality in Great Lakes coastal wetlands. *Environ. Manage.* in press.
- Niemi, G.J., and McDonald, M. 2004. Application of ecological indicators. *Annu. Rev. Ecol. Evol. Syst.* 35:89–111.
- , Wardrop, D., Brooks, R., Anderson, S., Brady, V., Paerl, H., Rakocinski, C., Brouwer, M., Levinson, B., and McDonald, M. 2004. Rationale for a new generation of ecological indicators for coastal waters. *Environ. Health Perspect.* 112:979–986.
- Ontario Land Cover Data [computer file]. 2002. The Ontario Ministry of Natural Resources, Land Information Ontario, Toronto.
- Peterson, A.C., and Niemi, G.J. 2007. Evaluation of the Ohio Rapid Assessment Method for wetlands in the western Great Lakes: An analysis using bird communities. *J. Great Lakes Res.* 33 (Special Issue 3): 280–291.
- Peterson, G.S., Sierszen, M.E., Yurista, P.M., and Kelly, J.R. 2007. Stable nitrogen isotopes of plankton and benthos reflect a landscape-level influence on Great Lakes coastal ecosystems. *J. Great Lakes Res.* 33 (Special Issue 3):27–41.
- Price, S.J., Howe, R.W., Hanowski, J.M., Regal, R.R., Niemi, G.J., and Smith, C.R. 2007. Are anurans of Great Lakes coastal wetlands reliable indicators of ecological condition? *J. Great Lakes Res.* 33 (Special Issue 3):211–223.
- Ray, G.C., and McCormick-Ray, J. 2004. *Coastal-marine conservation: science and policy*. Malden, Massachusetts: Blackwell Publishing.
- Reavie, E.D. 2007. A diatom-based water model for Great Lakes coastlines. *J. Great Lakes Res.* 33 (Special Issue 3):86–92.
- , Axler, R.P., Sgro, G.V., Kingston, J.C., Kireta, A.R., Brown, T.N., Danz, N.P., Hollenhorst T.P., and Ferguson M.J. 2006. Diatom-based weighted-averaging transfer functions for Great Lakes coastal water quality: relationships to watershed characteristics. *J. Great Lakes Res.* 32:321–347.
- Seilheimer, T.S., and Chow-Fraser, P. 2007. Application of the wetland fish index to northern Great Lakes marshes with emphasis on Georgian Bay coastal wetlands. *J. Great Lakes Res.* 33 (Special Issue 3): 154–171.
- Simon, T.P., and Stewart, P.M. 2006. *Coastal wetlands of the Laurentian Great Lakes—health, habitat and indicators*. Bloomington, Indiana: Author House.
- The Nature Conservancy. 2006. *Conservation of biological diversity in the Great Lakes basin ecosystem: issues and opportunities*. Chicago, IL.
- Trebitz, A.S., Brazner, J.C., Cotter, A.M., Knuth, M.L., Morrice, J.A., Peterson, G.S., Sierszen, M.A., Thompson, J.A., and Kelly, J.R. 2007. Water quality in Great Lakes coastal wetlands: Basin-wide patterns and responses to an anthropogenic disturbance gradient. *J. Great Lakes Res.* 33 (Special Issue 3):67–85.
- Tulbure, M.G., Johnston, C.A., and Auger, D.L. 2007. Rapid invasion of a Great Lakes coastal wetland by non-native *Phragmites australis* and *Typha*. *J. Great Lakes Res.* 33 (Special Issue 3):269–279.
- Uzarski, D.G., Burton, T.M., and Genet, J.A. 2004. Validation and performance of an invertebrate index of biotic integrity for Lakes Huron and Michigan fringing wetlands during a period of lake level decline. *Aquat. Ecosyst. Health Manage.* 7(2):269–288.
- , Burton, T.M., Cooper, M.J., Ingram, J.W., and Timmermans, S. 2005. 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. *J. Great Lakes Res.* 31:171–187.
- Whillians, T.H. 1982. Changes in marsh area along the Canadian shore of Lake Ontario. *J. Great Lakes Res.* 8:570–577.
- Wolter, P.T., Johnston, C.A., and Niemi, G.J. 2006. Land use land cover change in the Great Lakes basin 1992–2001. *J. Great Lakes Res.* 32:607–628.