Multi-Metric Plant-Based IBIs for Great Lakes Coastal Wetlands

Leah D. Minc,
Data Analyst

Dennis A. Albert,
Ecologist

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The overall goal of these analyses is to define and substantiate multi-metric plant-based indices of biological integrity (PIBI) for Great Lakes coastal wetlands. Rather than focusing on a single gradient of wetland quality, this study seeks to develop PIBI's sensitive to different sources of anthropogenic stress, including nutrient loading, sedimentation from agriculture, and chemical contaminants from urban or industrial sources. This study draws on a regional database of vegetation transects, combined with GIS-based assessments of land use surrounding wetlands and site sampling for water chemistry at a subset of sites, to monitor individual sources of degradation and identify the extent to which distinct dimensions of disturbance are reflected in wetland vegetation.

We first briefly define the natural regional variability within coastal wetland plant communities and identify the major ecological factors generating distinct wetland types that must serve as a backdrop for any discussion of species distribution. Secondly, we outline the major factors degrading Great Lakes coastal wetlands, and based on a review of the literature, identify species or species groups that potentially function as metrics of individual dimensions of anthropogenic stress. Finally, we examine the utility of several of these metrics for monitoring wetland health at both regional and local scales, utilizing a database that encompasses the full range of coastal wetland quality and diversity along the Great Lakes shoreline.

Regional Variability in Great Lakes Coastal Wetlands

Great Lakes coastal wetlands form a transition between the Great Lakes and adjacent terrestrial uplands, and are influenced by both (Minc, 1997a; Minc and Albert, 1998; Albert and Minc, 2001, 2004). Local and regional variability in aquatic system, surficial bedrock, geomorphic context, substrate, climate, and land use, as well as temporal variability in Great Lakes water levels, combine to create a series of distinctive wetland types, with predictable patterns of regional distribution along the Great Lakes shoreline.

Our understanding of the major Great Lakes wetland types and the key factors determining their distribution is based on field sampling of over 110 coastal wetlands along the U.S. shoreline between 1987 and 1994. These data were integrated with regional and site-specific information on bedrock type, glacial landform, latitude, aquatic system, and human activities. The resulting Great Lakes coastal wetland classification identifies nine regional types, reflecting not only distinctive plant associations, but also corresponding to differences in major physical factors (Minc, 1997a; Albert and Minc, 2001, 2004). Physical and vegetation characteristics of these regional wetland groups are summarized (Table 1; for details, see Albert and Minc, 2001). The challenge is to develop floristic indices of wetland health that can both function across the range of Great Lakes wetland types and can highlight differences in wetland health within a regional type.

Types of Degradation Within Great Lakes Wetlands

Patterson and Whillans (1985) have identified three major classes of stresses to Great Lakes wetlands. Broadly, these include (1) hydrologic flow modification, (2) water quality degradation, and (3) ecological structural breakdown. In the brief discussion that follows, we identify specific stresses within each of these broad categories that adversely affect Great Lakes wetlands, and briefly review known plant responses to altered conditions.

Table 1. Regional Classification of Great Lakes Coastal Wetlands

Regional Type	Location	Bedrock	Geomorphic Context (Site Type)	Substrate	Characteristic Vegetation	Significant Human Impacts
Lake Superior Poor Fen	Northern (Lake Superior)	Granitic, Sandstone	Barrier beach lagoon, Drowned river-mouth, Deltas.	Deep organic (acid).	Bog (Poor Fen) with sphagnum and leatherleaf, associated with a narrow fringe of low-density, emergent marsh of spike-rush and bulrush.	None or localized.
Northern Rich Fen	Northern (Straits of Mackinac)	Limestone	Open lacustrine (Open bay, Open shore).	Calcareous mineral (clay, marl); pH as high as 8.2.	Calciphiles dominate the diverse herbaceous zone (rich fen); low-diversity emergent zone of muskgrass, spike-rush, and bulrush.	None or localized.
Northern Great Lakes Marsh	Northern (Lakes Michigan, Huron, Superior, and St. Marys River)	Granitic, Sandstone, Limestone	Protected embayment, Connecting channel.	Diverse mineral (circumneutral); moderate organics.	Extensive northern wet meadow associated with a low density emergent marsh dominated by bulrush and spike-rush.	None or localized.
Green Bay Disturbed Marsh	Tension Zone (Green Bay, WI)	Limestone	Drowned river-mouth, Deltas, Sandspit embayments.	Silt-rich mineral; Deep organics.	Wet meadow dominated by blue-joint grass and exotics; adjacent emergent zone features floating and canopy-forming species.	Nutrient enrichment; Sedimentation; Chemical contamination.
Lake Michigan Drowned River Mouths	Northern and Southern (along eastern shore of Lake Michigan)	Limestone, sandstone	Drowned river-mouths.	Deep organics (muck and peat).	Southern wet meadow; high coverage of floating emergent species and diverse submergent flora.	Nutrient enrichment.
Saginaw Bay Lakeplain Marsh	Tension Zone (Saginaw Bay)	Limestone	Open shoreline, Open bay, Sandspit embayment, Delta.	Sand or sand over clay.	Broad southern wet meadow featuring early successional and disturbance species. Low density cat-tail and bulrush marsh; submergent pondweeds largely absent.	Nutrient enrichment; Sedimentation.

Regional Type	Location	Bedrock	Geomorphic Context (Site Type)	Substrate	Characteristic Vegetation	Significant Human Impacts
Lake Erie - St. Clair Lakeplain Marsh	Southern (Lakes Erie and St. Clair; St. Clair River)	Limestone	Open shoreline, Open bay, Sandspit embayment, (Delta).	Sand or sand over clay.	Southern wet meadow with exotics; emergent zone features floating duckweeds and canopy-forming submergents.	Nutrient enrichment; Sedimentation; Shoreline modification.
Lake Ontario Lagoon	Southern (Lake Ontario)	Limestone	Barrier beach lagoon, Barred drowned river-mouth.	Deep organics.	Near monoculture of cat-tail in emergent and wet meadow zones; high coverage of canopy-forming submergent vegetation.	Lake-level regulation; Nutrient enrichment.
St. Lawrence River Drowned River Mouths	Southern (upper reaches of St. Lawrence River affected by Lake Ontario)	Granitic	Delta, Buried river-mouth.	Deep organics.	Broad wet meadow and emergent zone dominated by cat-tail; high coverage and diversity of submergent and floating vegetation.	Lake-level regulation; Nutrient enrichment.

A. Hydrologic Flow Modification

Water Level Regulation of the Great Lakes. Limited water level control is achieved by regulating the outflows from Lakes Superior and Ontario (U.S. Army Corps of Engineers, 1987, 1997). Regulating the outflow from Lake Superior (via the control station on the St. Marys River) affects the level of Lake Superior, Lakes Michigan-Huron, and to a lesser extent, Lake Erie. Regulating the outflow from Lake Ontario affects levels on that lake and on the St. Lawrence River, but has no effect on the upper lakes. Since 1959, regulation has significantly reduced the occurrence of extreme high and low water levels on Lake Ontario. For example, Lake Ontario was the only Great Lake that did not set record high water levels in 1985-1986, largely owing to the dredging of the St. Lawrence River channel, which allows for the release of greater amounts of water when lake levels are high.

Reduced natural water fluctuations, through manipulation of lake levels, can lead to an overall loss of both species richness and diversity (Stuckey, 1975, 1989; Van der Valk, 1981; Keddy, 1990; Wilcox et al., 1993), as well as genetic diversity (Keough, 1987, 1990). Disruption of the natural cycle favors species intolerant of water-depth change and associated stresses, and/or excludes species requiring periodic exposure of fertile substrates. The result is frequently a monoculture of the most light-competitive species (Keddy, 1989), particularly cat-tail (*Typha* spp.), at the expense of a diverse shoreline flora. Thus, relative dominance of *Typha* spp., along with measures of species diversity, potentially provide an index of stress resulting from water level regulation.

Diking. Diking of coastal wetlands has been widespread along the southern Great Lakes. Diking was necessary to maintain coastal wetlands along the western Lake Erie shoreline (Herdendorf, 1987; Robb, 1989). The purpose for almost all dikes constructed in coastal wetlands was waterfowl management, with water control structures to allow vegetation to be manipulated. Large impoundments were built elsewhere in the Great Lakes, on Lake Ontario near Rochester, NY, on Lake St. Clair, Saginaw Bay, the St. Marys River, and Green Bay. All of these diked wetlands were created for waterfowl management, often resulting in major alteration of natural coastal wetlands and degradation of the wetlands for other values, such as fish spawning and nursery areas.

Problems associated with diked wetlands include (1) development of monocultures, again including cat-tails, (2) accumulation of organic material that would have been flushed from the wetland, and (3) increased temperatures, which result in increased emergent plant and algal growth (Francis et al., 1979). In turn, extensive algal growth reduces the amount of submergent macrophyte growth and reduces oxygen availability, negatively impacting a broad range of fauna (Chow-Fraser, 1998).

B. Water Quality Degradation

Nutrient enrichment. Nutrient loading is well recognized as a major form of water quality degradation and the effect of increased nutrient loading on aquatic plants is documented from lakes and streams throughout the northern hemisphere (Kimbel, 1982; Anderson and Kalff, 1986; Niemeier and Hubert, 1986; Rorslett et al., 1986; Madsen and Adams, 1988; Chambers and Fourqurean, 1991; Scheffer et al., 1992; Craft et al., 1995; Srivastava et al., 1995; Toivonen and Huttunen, 1995; Coops and Doef, 1996), as well as laboratory studies (Gutenspergen, 1984; Neely and Davis, 1985; Jordan et al., 1990). At least two common forms of nutrient enrichment occur along the Great Lakes shoreline, introduction of animal wastes, typically as sewage effluent or untreated agricultural animal wastes, and the introduction of fine-textured mineral soils (siltation) and fertilizers from agricultural activities. The effects of these is not easily separated, especially in the southern Great Lakes, where both agricultural and urban land use are intense. In the northern Great Lakes, where agricultural land use is both less extensive and less intensive, these two sources of nutrient enrichment can often be distinguished.

Several species of Great Lakes aquatic macrophytes respond with increased growth when organic nutrients are added to wetlands. Common submergent species known to respond to high levels of nutrients include *Myriophyllum spicatum*, *Potamogeton crispus*, *Potamogeton pectinatus*, *Elodea canadensis*, and *Ceratophyllum demersum* (Kimbel, 1982; Rorslett et al., 1986; Scheffer et al., 1992; Toivonen and Huttunen, 1995). Similarly, the emergent species *Typha* spp. and *Phragmites australis* can increase greatly in coverage in response to nutrient enrichment (Niemeier and Hubert, 1986; Srivastava et al., 1995). Other species known to respond to nutrient enrichment include blue-green algae and several floating-leaved plant species, especially species of *Lemna*, *Spirodela,* and *Wolfia* (Tubea et al., 1981). Algae blooms and dense growths of duck weed on the surface can greatly reduce the available light for submergent aquatic plants, thus limiting their survival.

Sedimentation. Increased sedimentation from agricultural land usein the watersheds adjacent to the Great Lakes is one of the greatest source of wetland degradation in many regions, especially in western Lake Erie, Green Bay of Lake Michigan, and Saginaw Bay of Lake Huron. Herdendorf et al. (1977) list three sources of suspended sediments in western Lake Erie: run-off from the land, resuspension of bottom sediments and erosion of shore materials by wave action, and vessel operation, including dredging. Satellite imagery of western Lake Erie taken during late March, 1973, shows large sediment plumes from both the Detroit and Maumee Rivers (Herdendorf et al., 1977). An important factor resulting in further turbidity is the presence of another exotic species, common carp (*Cyprinus carpio* L.), which resuspends fine sediments both when it breeds and feeds (Anderson, 1950; Chow-Fraser, 1998; Crivelli, 1983; Sager et al., 1998). Subsequent widespread establishment of zebra mussels into the Great Lakes has resulted in reduced turbidity and increases in submergent plant coverage within some coastal wetlands (Fahnenstiel et al., 1995; Nalepa et al., 1999).

High turbidity, with light penetration of only a few centimeters, is inadequate for most aquatic macrophytes and algae to photosynthesize and survive (Carter and Rybicki, 1985). The deposition of thick sediments can also result in loss of seed germination for both emergent and submergent aquatic plants (Barko et al., 1986; Rybicki and Carter, 1986; Hartleb et al., 1993; Jurik et al., 1994; Wang et al., 1994; Wardrop and Brooks, 1998). The result is often a severe loss of plant diversity within the submergent zone. However, several species are known to be more tolerant of low light levels. Key submergent species in the turbidity tolerant category include *Potamogeton pectinatus*, *P. crispus*, *P. foliosus*, *P. pusillus*, *Ceratophyllum demersum*, *Elodea canadensis*, *Heteranthera dubia*, *Ranunculus longirostris*, *Butomus umbellatus*, and *Myriophyllum spicatum* (Stuckey, 1989; van Dijk and van Vierssen, 1991).

In the wet meadow or shoreline herbaceous zone, the deposition of thick sediments over the surface favors a suite of aggressive colonizing species. Characteristic species include aggressive native annuals (*Polygonum lapathafolium*, *Bidens cernua*, *Impatiens capensis*, *Leersia orizoides*, and *Rorippa palustris*) and a host of exotics (particularly *Lythrum salicaria*, *Phragmites australis*, and *Phalaris arundinacea*). Note that the native species also respond heavily to interannual water-level fluctuations, and expand rapidly onto recently exposed shoreline as water levels drop.

Chemical pollution. Little work has been done in the Great Lakes regarding tolerance of specific plant species to chemical pollution, although aquatic plants are known to bioaccumulate and concentrate toxic chemicals (Lewis and Wang, 1999; Stewart et al., 1999). Decreased wetland species richness and diversity have been associated generally with higher levels of pollutants (Stewart et al., 1999), but to date, no species or species groups have been identified as "a good biological indicator" for a specific heavy metal or other toxic chemical for the Great Lakes region. However, the question of plant tolerance to chemical pollution has been addressed in other parts of the world and can be used to direct further research within Great Lakes wetlands (Phillips, 1978; Bosserman, 1985; Greger and Kautsky, 1991; Manny et al., 1991; Reimer and Duthie, 1993; Snowden and Wheeler, 1993; Dushenko et al., 1995; Sajwan and Ornes, 1996).

Work elsewhere indicates that either absence of certain species or growth characteristics of *Vallisneria americana* (Potter and Lovett-Doust, 1997) can be used to characterize site quality. Several studies investigate the uptake of toxic chemicals or metals by plants; most of these have been conducted on streams, but a few have been conducted in small lakes (Mayes et al., 1977; Welsh and Denny, 1980). More commonly, the ability of plants to bioaccumulate heavy metals and other toxics over time provides the opportunity to measure pollution that may be sporadic within a system (Vanderpoorten and Palm, 1998). However, in some cases bioaccumulation can also be a disadvantage, as it is difficult to document the time of pollution if the plants are long lived, as with aquatic mosses and some other perennial macrophytes. Aquatic plants with floating leaves and well-developed root systems were also found to be useful for detection of phenols (Pridham, 1964).

In the Great Lakes, Herdendorf (1983, 1987) identifies the presence of nine heavy metals (Cd, Cr, Cu, Pb, Mn, Hg, Ni, Ag, and Zn) and six organic pollutants (benzene, chloroform, methylene chloride, bis [2 ethylexyl] phthalate, tetra-chloroethylene, and toluene) in the effluents from major municipal wastewater treatment plants in the Lake Erie basin, but none in alarmingly high concentrations. Similarly, high concentrations of some metals, including Pb, Ni, Cu, Ag, V, Hg, Zn, Cd, Cr, are known contaminants in the surface sediments adjacent to tributaries in major industrial areas. There have been other studies conducted within the Great Lakes and their connecting channels that have documented the incorporation of heavy metals and other chemical pollutants into the tissues of aquatic macrophytes (Estabrook et al., 1985; Manny et al., 1991; Wells et al., 1980). However, no Great Lakes literature was found documenting specific response by aquatic plants to high levels of toxic chemicals, including heavy metals. Nor was literature found that demonstrated a relationship between relative abundance of aquatic plant species and chemical degradation in Great Lakes coastal wetlands, thus limiting the use of our regional Great Lakes wetland plant database to identify chemical pollutant metrics.

Debate continues concerning the usefulness of aquatic plants as indicators of chemical pollution. While several studies conducted in the Great Lakes conclude that plants offer potential as effective indicators of chemical contaminants (Stewart et al., 1999; Simon et al., 2001; Stewart et al., 2003), other researchers (Lewis and Wang, 1999) counter that the relative sensitivity of most vascular plant species to various toxicants and hazardous substances remains poorly understood, making it difficult to differentiate the various environmental stressors affecting the community dynamics of aquatic plants.

C. Ecological Structural Breakdown and Physical Degradation

Physical modification and elimination of coastal wetlands is responsible for a large part of the wetland loss in the Great Lakes (Patterson and Whillans, 1985). Wetland elimination resulted from a broad range of activities that hardened the shoreline or altered the sediments of a wetland; these activities including dredging, filling, diking, rip-rapping shoreline, and many others. All of these actions result in elimination or major alterations of wetland vegetation.

The loss of coastal wetlands can be most readily documented by comparing early maps or aerial photos to recent maps and photos. Examination of aerial photos is a commonly used method to document changes in wetland extent resulting from human modification of wetlands, such as along western Lake Erie and Lake St. Clair (Jaworski and Raphael, 1976), Green Bay (Bosley, 1978), and Lake Ontario and the upper St. Lawrence River (Busch and Lewis, 1984). Aerial photos have also been used to show the changes in Great Lakes wetlands resulting from Great Lakes water-level fluctuations on several of the Great Lakes, including Green Bay, Lake Michigan (Harris et al., 1981), Lakes Erie and St. Clair (Jaworski et al., 1979), the St. Marys River (Williams and Lyon, 1997), and the northeastern shoreline of Lake Michigan (Lyon et al., 1986). The tremendous reduction in size of the deltaic marshes at the mouths of the Raisin River on Lake Erie, the Saginaw River on Lake Huron, and the Fox River on northern Lake Michigan typify the scale of alteration that has occurred on many of our coastal wetlands.

While remote imagery, photo interpretation, and study of historic documents can provide us with important information for the evaluation of the area of wetland loss, specific plants also function as indicators of wetland degradation and wetland health. In particular, several exotic plant species respond rapidly to physically modified wetlands and thus are potentially good indicators of disturbance.[1]

Some of the more wide-spread exotic species include *Phragmites australis*, *Phalaris arundinacea*, *Lythrum salicaria*, species of the wet meadow or emergent marsh zones, along with *Myriophyllum spicatum* and *Potamogeton crispus*, submergent species, and *Hydrocharis morsus-ranae*, a floating plant of the emergent and submergent marsh zones.[2] These exotics can form dense monotypic stands, often excluding the native flora (Nichols and Mori, 1972; Carpenter, 1980; Sabol, 1983). Because they have no natural predators, exotics often replace the native flora of wetlands, while providing few of the benefits of the native flora to the fauna.

It has been suggested that the number of exotic plant species present at a wetland site is a good indicator of the level of site degradation (Gerne and Helgen, 1999; Stewart et al., 1999; Simon et al., 2001). Analysis of regional marsh data for this study does not strongly support this assumption. Rather, the number of exotic species covaries with wetland size: the larger the wetland, the greater number of exotic species that was typically encountered. In only a few of the most degraded wetlands was the number of exotic species high, as in a small coastal wetland within the city of Escanaba on Lake Michigan; in this wetland 22 exotic species were encountered in a wetland less than 50 hectares in area (authors' unpublished data, 2002). Most regional marsh types contain several exotic species, from two to seven exotic species being typical in the wet meadow or emergent zones, with up to three submergent exotic species often present. It is also not uncommon to find a small number of exotic species in intact coastal wetlands dominated by native plant species.

Based on our research, the total coverage of exotic plants appears to more accurately access the present condition of a wetland than the number of exotic species (Minc, 1997a). Wetlands within highly modified urban or industrial environments are often dominated by exotic species, even though the number of exotic species may be relatively low. However, the coverage of exotics is not necessarily predictable over time, as exotics may respond rapidly to water-level fluctuations.

[1] Exotic plants establish through several mechanisms, not just physical modification of a wetland; some responding positively to increased nutrient levels or increased sedimentation.

[2] There is some debate about whether *Phragmites australis* and *Phalaris arundinacea* should be treated as exotics, as both species also have native, less aggressive races that also occur within Great Lakes wetlands.

Large expanses of moist, nutrient-rich substrate can be exposed when a low-water year follows a high-water year. These conditions are ideal for the establishment of *Lythrum salicaria*; wildlife biologists on western Lake Erie report rapid expansion of *Lythrum salicaria* in such conditions (Robert Humphreys, Michigan Department of Natural Resources, personal communications).

II. Possible PIBIs

Several approaches have attempted to summarize plant responses to these different stresses, either jointly or as separate dimensions of stress. Three of these were tapped as potential PIBIs and evaluated in this study.

A. *Floristic Quality Assessment* (FQA)

The FQA reflects a single dimension of wetland quality based on the concept of species conservatism or fidelity to a natural landscape (Herman et al. 1996). Each native Michigan species was assigned a coefficient of conservatism (*C)* following the methodology and philosophy detailed in Swink and Wilhelm (1994) and Wilhelm and Masters (1005). Coefficients of conservatism range from 0 to 10 and represent "an estimated probability that a plant is likely to occur in a landscape relatively unaltered from what is believed to be a presettlement condition" (Herman et al. 1996:2). A *C* of 0 indicates plants that have demonstrated little fidelity to any remnant natural community and may be found almost anywhere, while a *C* of 10 indicates a species almost always restricted to a high quality natural area.

In practice, the FQA is based on species presence/absence, as determined from random walk or transect data. For each site or sampling area, the Mean Coefficient of Conservatism is calculated by summing the coefficients of conservatism (C) of the inventory of plants and dividing by the total number of plant taxa. The Floristic Quality Index (FQI) is then calculated by multiplying the mean C value by the square root of the total number of plants. The square root multiplier transforms the mean coefficient of conservatism to allow for better comparison between large sites with a high number of species and small sites with fewer species.

Based on a state-wide assessment across a wide variety of habitats in Michigan, an FQI less than 20 indicates disturbed sites with minimal natural significance, while an FQI score greater than 35 indicates a site with sufficient conservatism and richness to be floristically important at the statewide level. At the highest extreme, sites with an FQI score of greater than 50 are extremely rare, and represent high-quality sites containing a significant component of the region's native biodiversity.

B. Regional Indicators of Great Lakes Wetland Health

Based on the literature search above, Albert and Minc (2004) suggested a series of potential metrics that appear to reflect regional differences in anthropogenic stress and in wetland health. Specifically, they suggest key species for monitoring altered water-level fluctuations, nutrient enrichment, sedimentation and increased turbidity, and physical degradation (Table 2). No species were identified as sensitive to chemical contaminants.

Table 2. Wetland Species Response to Anthropogenic Stresses

Stress	Responsive Species[1]		Proposed Metrics
	Submergent /Emergent Zone	**Emergent/Wet Meadow Zone**	
Dampening of Water-Level Fluctuation		*Typha* sp.(++)	**a. Total coverage value of *Typha* in emergent and wet meadow zones.** b. Width of *Typha* zone. **c. Algal coverage.**
Nutrient Enrichment	*Myriophyllum spicatum* (++) *Potamogeton crispus* (++) *Potamogeton pectinatus* (++) *Elodea canadensis* (++) *Ceratophyllum demersum* (++) *Lemna minor* (++) algae (++)	*Typha* sp.(++) *Phragmites australis* (++) *Lemna minor* (++)	**a. Total coverage value for submergent species.** **b. Dominance of nutrient responsive submergent species.** **c. Total coverage of *Typha* spp. and *Phragmites australis* in emergent and/or wet meadow zones.** d. Algal coverage.
Sedimentation and Increased Turbidity	*Megalodonta beckii* (-) *Myriophyllum exalbescens* (-) *Najas flexilis* (-) *Potamogeton amplifolius* (-) *P. robbinsii* (-) *P. zosteriformis* (-) *P. freisii* (-) *Vallisneria americana* (-) *Potamogeton pectinatus* (+) *P. crispus* (+) *P. foliosus* (+) *P. pusillus* (+) *Ceratophyllum demersum* (+) *Elodea canadensis* (+) *Heteranthera dubia* (+) *Ranunculus longirostris* (+) *Butomus umbellatus* (+) *Myriophyllum spicatum* (+)	*Carex stricta* (-) *C. aquatilis* (-) *Calamagrostis canadensis* (-) *Lythrum salicaria* (++) *Phragmites australis* (++) *Phalaris arundinacea* (++) *Polygonum lapathifolium* (++)	**a. Absence of turbidity intolerant species.** **b. Relative dominance of species tolerant of low light levels in submergent zone.** c. Loss of submergent species diversity. d. Relative dominance of perennials vs. annuals in wet meadow zone.

Stress	Responsive Species[1]		Proposed Metrics
	Submergent /Emergent Zone	Emergent/Wet Meadow Zone	
Physical Degradation		*Lythrum salicaria* (++) *Phragmites australis* (++) *Phalaris arundinacea* (++) *Polygonum lapathifolium* (++)	a. Major loss of species diversity. b Elimination of natural zonation. c. **Relative dominance of exotics and aggressive native species in wet meadow zone.**

C. EPA Wetland Plant Sensitivities

A third set of potential metrics was drawn from the EPA's *National Database of Wetland Plant Sensitivities to Enrichment and Hydrologic Alteration* . This database compiles information from published, peer-reviewed sources on the responses of plants to anthropogenic stress. The database contains references to over 2300 genera and species, drawn from 222 studies (including field observations and measurements, and laboratory experiments) documenting species responses to changes in nutrient inputs and water regime.

In compiling this list, the authors note that published studies are seldom accompanied by adequate measurement of the stressors which are alleged to have caused the response, e.g., the exact loading rates and concentrations of nutrients, and duration of exposure. However, the species list provides a general guideline for assessing wetland quality, in that "Sites with a large component of reputedly tolerant species but with only few intolerant species might be considered in many instances to be ecologically degraded."

Further, the database offers the potential for developing multi-metric PIBIs, in that species responses were recorded for 15 different stresses. These include:

1. ***General Pollution Increase***: Response of the species to an increase in an unspecified stressor, e.g., "increased site disturbance."

2. ***Nutrient Increase***: Response of the species to an increase in an unspecified nutrient, generally nitrogen or phosphorus.

3. ***N Increase***: Response of the species to an increase in soluble nitrogen.

4. ***P Increase***: Response of the species to an increase in phosphorus.

5. ***Nutrient Decrease:*** Response of the species to a decrease in an unspecified nutrient, generally nitrogen or phosphorus.

6. ***N Decrease:*** Response of the species to a decrease in soluble nitrogen.

7. ***P Decrease***: Response of the species to a decrease in phosphorus.

8. ***Flood Duration Increase***: Response of the species to an increase in duration of flooding.

9. ***Flood Depth Increase***: Response of the species to an increase in water depth, i.e., flooding.

10. ***Flood Fluctuation Increase***: Response of the species to an increase in frequency of water level fluctuations.

11. ***Flood Duration Decrease***: Response of the species to a decrease in duration of flooding.

12. ***Flood Depth Decrease***: Response of the species to a decrease in water depth, i.e., drawdown.

13. ***Flood Fluctuation Decrease***: Response of the species to a decrease in frequency of water level fluctuations.

14. ***Sediment Increase***: Response of the species to an increase in depth of deposited sediment.

15. ***Salinity/Other***: Response of the species to an increase in salinity (mostly) or other stressors.

Species responses to these stresses were recorded as either INC (Increased) or DEC (Decreased), or along a 6-point scale of tolerance, ranging from intolerant to unaffected, somewhat tolerant, moderately tolerant, tolerant, and very tolerant.

In comparison with the metrics proposed by Albert and Minc (2004), the EPA wetland plant sensitivity database potentially encompasses a much broader range of species, and thus may be less sensitive to regional differences in species abundance due to natural factors such as climate and substrate. For example, nearly 400 species are coded for a response to "General Pollution Increase", while nearly 300 are listed as responsive to "Nutrient Increase". In addition, the EPA lists species sensitive to salinity and other contaminants, an important dimension missing in other potential PIBIs.

III. Vegetative Database

The assessment of potential PIBI's utilizes vegetative transect data from Great Lakes coastal wetland sites representing four regions: Northern Lakes Huron and Michigan, Saginaw Bay, Long Point (Lake Erie), and Lake Ontario Specifically, sampling of aquatic macrophyes was conducted within both wet meadow and emergent marsh zones at 32 sites on the U.S. shoreline of Lakes Huron and Michigan, 16 sites on the Canadian shoreline near Long Point on Lake Erie, and 12 Canadian sites on Lake Ontario (Table 3).

Table 3. Number of Vegetation Transects by Region and Community Code

Vegetation Zone	N. Lakes Huron & Michigan	Saginaw Bay, Lake Huron	Long Point, Lake Erie	Lake Ontario	Total
Wet Meadow	20	11	2	9	42
Emergent	22	13	46	12	93
Submergent	0	0	13	9	22
Total	42	24	61	30	157

Species coverage values were recorded along short transects located perpendicular to the hydrological gradient. Five randomly located 0.5 m^2 quadrats were sampled in each vegetation zone along each transect. The starting point for each transect was randomly located, beginning within 25 meters of the upland edge of the wet meadow zone, with sampling points located 25 meters apart. The location of each sampling quadrat around a sampling point was selected using randomly selected compass bearings and distances from 1 to 9 meters. Percent cover was estimated for each plant species in the sample quadrat; coverage was estimated for all emergent, floating, and submergent species. Substrate, organic depth, water depth, and water clarity (using secchi disk) were recorded. For most wetlands, sampling was restricted to the wet meadow and emergent/submergent zones. Where there was a wide submergent zone without emergent vegetation, five additional sampling points were included. Aquatic-macrophyte data were then summarized and the mean cover value for each species determined for each site.

Since overall species diversity is viewed by many as a good indicator of wetland quality or health, plant species diversity was evaluated in this study. Plant species diversity was evaluated by conducting a fifteen-minute or longer random observation in each plant zone. Many extensive coastal wetlands required a longer random walk to adequately assess habitat and species diversity.

This was especially the case for wet meadow zones, where sampling was often slow. For most wetlands, joint sampling of submergent and emergent zones during the fifteen minute random walk was adequate. In the emergent/submergent zone, the random walk required use of a rake to guarantee an adequate sampling of submergent species. The calculation of other potential metric values was as follows:

A. The **FQI** was based on species presence/absence, and calculated from the total range of species encountered in the vegetation quadrats or the random walk at a sampling site. Based on this scale, only a handful of sites approach or exceed the value for "floristically important", with FQI values of 35 or greater. In addition, the FQI was calculated individually for each vegetation zone, to facilitate comparisons between sites where not all zones were represented in the transect.

B. To quantify the **Regional Health Indicators** (Albert and Minc 2004), cover values were summed for the species and species groups identified as potential metrics in Table 2, above. Overall, 9 metrics were evaluated, including:

1. Total % cover for *Algae*
2. Total % cover for *Typha* sp.
3. Total % cover for nutrient tolerant submergents
4. Total % cover for nutrient tolerant emergents
5. Total % cover for turbidity intolerant submergents
6. Total % cover for turbidity tolerant submergents
7. Total % cover for emergent species
8. Total % cover for submergent species
9. Total % cover for floating species

C. The **EPA Plant Sensitivities** were converted to potential metrics by identifying groups of species with similar responses to the individual stresses. Many species have multiple entries in the EPA database, indicating that more than one published study reported on their response to a specific stress. To synthesize these entries, species responses were given a numeric code corresponding to the 6-point response scale, and the mean response value calculated for each species to each stressor.

Species responses were applied to the Great Lakes coastal wetland vegetation as a simplified scale, representing responses to each stressor as either intolerant or tolerant (Table 4). Due to the small number of species in certain categories, potential species groups were dropped, including species tolerant of nutrient decrease, N decrease, and P decrease, as well as species intolerant of nutrient increase, N increase, and P increase. For each transect, species coverage values were summed for each category and converted to percentage of total. This resulted in the following 15 potential metrics:

%Poll_Inc_IT	%Poll_Inc_Tol,
%Nut_Inc_Tol	--
%N_Incr_Tol	--
%P_Incr_Tol	--
%Flood_Dep_Incr_IT	%Flood_Dep_Incr_Tol
%Flood_Dur_Tol	%Flood_Fluc_Tol
%Flood_Dep_Decr_IT	%Flood_Dep_Decr_Tol
%Sed_Inc_IT	%Sed_Incr_Tol
%Sal_Inc_IT	%Sal_Inc_Tol.

Table 4. EPA Wetland Plant Sensitivities: Number of species identified as tolerant or intolerant of anthropogenic individual stressors.			
Stress	**Tolerant Species**	**Intolerant Species**	**Total Species**
General Pollution Increase	326	9	335
Nutrient Increase	283	1	284
N Increase	17	1	18
P Increase	11	1	12
Flood Duration Increase	282	4	286
Flood Depth Increase	93	25	118
Flood Fluctuation Increase	5	9	5
Flood Depth Decrease	9	11	20
Sedimentation Increase	17	15	32
Salinity Increase	25	259	284

IV. Determination of Anthropogenic Disturbance

In order to evaluate the success of potential metrics, all metrics were screened again independent measures of the extent and kind of anthropogenic stress in wetlands. For this study, independent measures of disturbance were based on (1) surrounding land use data in conjunction with (2) water quality data, and (3) site specific observations of wetland modification and point-source pollution.

A. Land Use and Point Sources of Stress

Land use was determined from existing digitized maps, specifically the EPA national land cover data set (1992), and from aerial photography. The EPA data were the most recent data available to us for the entire study region. Visual observations of these data and current land use suggested that land use had not changed substantially for most of the wetlands included in our study. The EPA maps provide data on 28 classes of land use based on color infra-red photography (Table 5). Working within a GIS environment, upland land-use within a 5-km radius of each study site was summarized in three main categories: % Agriculture (classes 25 and 26), %Urban (24), and %Forest (13, 14, 15, 16, 17, and 19); wetlands included classes 1, 5, 6, 7, and 8. The percent of upland in urban, forest, or agriculture provides the most consistent representation of land use at a regional scale.

In addition, for the Michigan sites, a more detailed assessment was made to identify and quantify sources of anthropogenic stress affecting each coastal wetland, based on photo-interpretation of the July, 1997 black-and-white aerial photography. Data on the number of buildings, roads, ditches, and other variables reflecting industrial, residential, and recreational land use were recorded within a 1-km radius of each wetland.

A principal components analysis of these variables (Table 6) suggests that they represent several distinct dimensions or sources of stress. Overall 6 significant but fairly weak principal components were identified (i.e. those having eigenvalues > 1.0), of which the first four are readily interpretable. The first PC, accounting for 24% of the variance, reflects urban and industrial factors, with high positive structure coefficients for % urban land use, number of industrial sites, parking lots, paved roads, and hardened shoreline. The second and third PC, in contrast, reflect residential and recreational use, while the fourth suggest agricultural and construction/ditching operations.

Table 5. Pseudo-Color Code and Land-Use Classes for 28 class Landcover

Color Values			Class	
Red	Green	Blue	Code	Land-Use Description
0	0	255	1	Water
0	130	255	2	Coastal Mudflats
160	210	255	3	Intertidal Marsh
215	255	255	4	Supertidal Marsh
162	0	149	5	Freshwater Coastal Marsh / Inland Marsh
199	0	161	6	Deciduous Swamp
169	198	147	7	Conifer Swamp
255	203	215	8	Open Fen
240	161	215	9	Treed Fen
240	200	255	10	Open Bog
177	53	212	11	Treed Bog
207	123	180	12	Tundra Heath
255	0	0	13	Dense Deciduous Forest
15	141	0	14	Dense Coniferous Forest
0	109	40	15	Coniferous Plantation
183	93	78	16	Mixed Forest — mainly Deciduous
20	220	0	17	Mixed Forest — mainly Coniferous
187	255	129	18	Sparse Coniferous Forest
205	146	135	19	Sparse Deciduous Forest
169	169	223	20	Recent Cutovers
111	119	115	21	Recent Burns
157	165	165	22	Old Cuts and Burns
210	212	217	23	Mine Tailings, Quarries, and Bedrock Outcrop
217	86	126	24	Settlement and Developed Land
255	175	0	25	Pasture and Abandoned Fields
255	255	123	26	Cropland
245	255	209	27	Alvar
255	255	255	28	Unclassified (Cloud & Shadow)

Table 6. Principal Components for Land Use and Stress Variables (Michigan Sites Only)

	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
Eigen Value	4.995	3.665	2.33	1.885	1.537	1.235
% Variance	23.785	17.452	11.104	8.975	7.317	5.880
Cumulative % Variance	23.785	41.237	52.341	61.316	68.634	74.514
Total Structure Coefficients for Land-Use Variables:						
% upland urban	**0.8944**	0.0555	-0.0401	-0.0543	-0.1418	-0.0565
% hardened shoreline	**0.7960**	-0.3382	0.1415	0.0561	0.3088	0.2512
Types of industry within 5 km	**0.7362**	-0.0887	0.3146	-0.3677	-0.1272	-0.2860
# of dwellings	**0.6055**	**0.4982**	0.0052	0.1138	0.0082	-0.2410
% shoreline with visible paved road	**0.6676**	0.1152	-0.1551	-0.0827	-0.1867	0.1005
# of paved parking lots	**0.6152**	-0.1686	0.2638	-0.2815	0.3895	-0.0646
# of 'other' buildings	**0.5498**	**0.6207**	0.0950	-0.0012	-0.2765	-0.1963
Possible hydrological alterations	**0.4881**	0.0410	0.3576	0.1921	0.0275	0.0083
# of industries	**0.4809**	-0.1727	0.0785	-0.4024	-0.1970	0.2502
# of boat docks	0.1331	**0.7567**	0.0867	0.1543	-0.0979	-0.2305
# of boat launches	0.3322	-0.1981	**-0.6672**	0.0180	0.0008	0.2128
% upland in agriculture	0.1797	**-0.5771**	-0.1840	**0.7658**	0.1037	0.0586
# of channels cut through wetland	0.3116	0.0328	-0.2660	**0.7126**	0.4337	0.3446
# of drainage ditches entering wetland	0.2463	-0.2014	-0.4546	**0.7884**	**0.5758**	0.3548
# of dirt parking lots	-0.1276	-0.1962	**-0.6466**	**0.6950**	0.1828	0.2762
# of culverts entering the wetland	0.1486	0.2314	0.1783	**0.5044**	0.1348	0.4745
% upland in forest	***-0.7876***	0.3496	0.1484	-0.4896	0.0548	-0.0056
% eroding shoreline	-0.0377	0.0048	0.2197	-0.2731	0.0894	***-0.7167***
% shoreline with visible dirt road	0.0908	-0.3512	0.4011	0.2121	**0.6515**	0.3466
Mining within 5 km	-0.0591	0.1115	0.3831	0.0166	-0.4069	0.2836
Construction sites or sedimentation	0.2179	**-0.4594**	0.3537	0.2678	-0.4229	-0.0902

This study also explored the availability of more detailed information on agricultural land use. For example, the USDA Census of Agriculture provides a series of maps and cartographic resources reflecting agricultural activities at a state and national level for 2002 and earlier (http://www.nass.usda.gov/research/atlas02/). As part of the census, isopleth maps are presented for a broad range of agriculture-related land-use variables, including:

Farms and Farmlands

- Number of Farms
- Acres of Land in Farms
- Acres of Land in Farms as Percent of Land Area in Acres
- Acres of Total Cropland
- Acres of Harvested Cropland
- Acres of All Types of Pastureland
- Acres of All Types of Pastureland as Percent of Land in Farms Acreage
- Acres of Irrigated Pastureland, Rangeland, and Other Unharvested Land
- Acres Enrolled in the Conservation Reserve or Wetlands Reserve Programs

Agricultural Chemicals Used

Acres Treated with Commercial Fertilizer, Lime, and Soil Conditioners
Acres of Cropland Fertilized (Excluding Cropland Pastured) as % of All Cropland
Acres of Cropland and Pastureland on Which Animal Manure Was Applied
Acres Treated with Chemicals to Control Insects
Acres of Crops Treated with Chemicals to Control Weeds, Grass, or Brush
Acres Treated with Chemicals to Control Disease in Crops and Orchards

Livestock, Poultry, and Other Animals

Cattle and Calves - Inventory
Average Number of Cattle and Calves per 100 Acres of All Land in Farms
Number of Farms with 200 or More Cattle and Calves
Hogs and Pigs - Inventory
Number of Farms with 200 or More Hogs and Pigs

Unfortunately, the agricultural census data are presented at the county, or at best, township level. This relatively coarse-grained data set was difficult to integrate with existing site-specific data on wetland buffers, and the development of GIS protocols for modeling these land-use variables at a more appropriate scale was not possible within the scope of the present study. As a result, this potentially rich source of information on land use was not utilized here.

However, these data present intriguing possibilities for large-scale or regional modeling of inputs to specific water sheds or drainages. For example, within Michigan, the number of acres of total cropland (Fig. 1) is greatest for the Saginaw Basin watershed, highlighting the elevated stress from agricultural run-off and chemicals to wetlands in the Saginaw Bay.

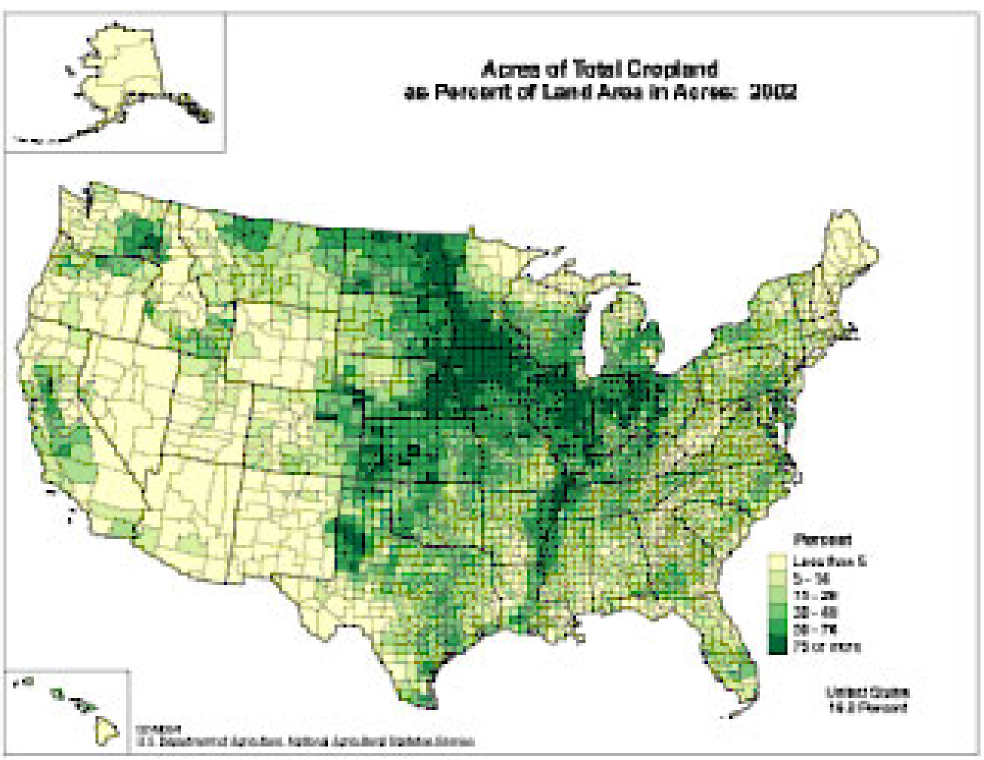

Figure 1. Acres in cropland by county, 2002.

Conversely, the density of cattle (Fig. 2) suggests more localized “hot-spots” of bovine density along the Grand River, flowing west to Lake Michigan, and within the Au Sable drainage, north of Saginaw Bay. These more localized patterns suggest that general measures of land use, such as “% of upland in agriculture” may not adequately capture spatial and qualitative differences in agricultural inputs to coastal wetlands.

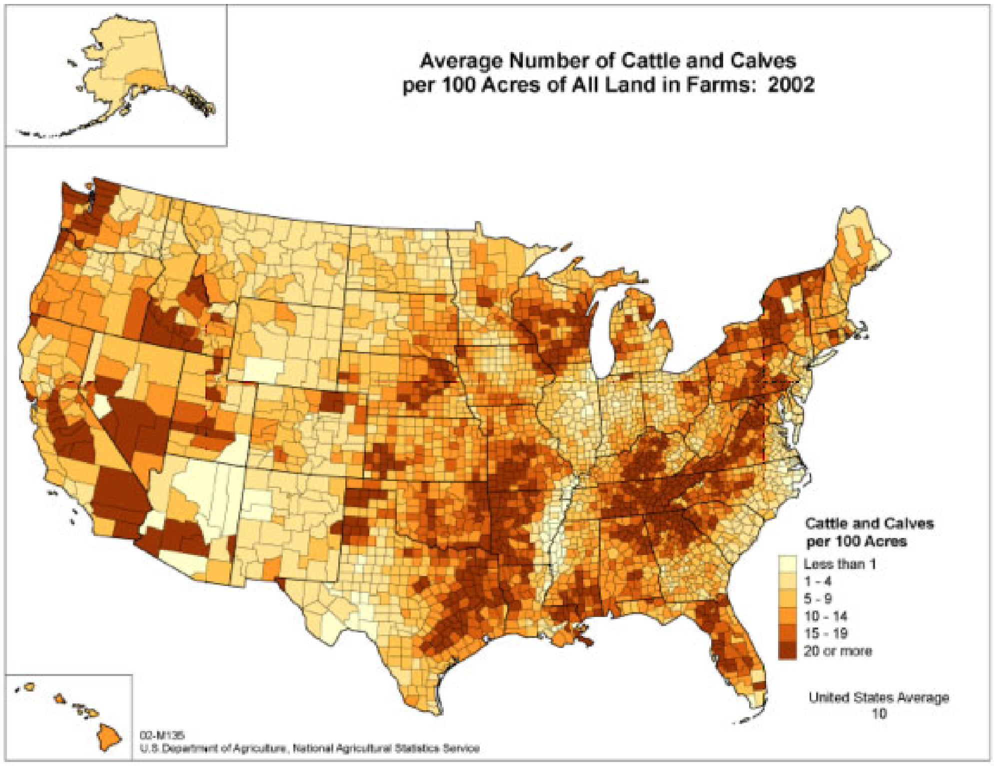

Figure 2. Density of cattle by county, 2002.

B. Chemical and Physical Measurements

The impact of these diverse human activities on wetlands was assessed through field sampling of water quality (Table 7). Water chemistry data, including soluble reactive phosphorus (SRP), nitrate-N, ammonium-N, turbidity, DO, chlorophyll " , redox potential, and specific conductance, were collected for most of the sampling sites, with data for 18 sites (43 samples) on Lakes Michigan and Huron, 16 sites (37 samples) on Lake Erie, and 12 sites (24 samples) on Lake Ontario. Analytical procedures followed protocols recommended in *Standard Methods for the Examination of Water and Wastewater* (APHA 1985).

The database on water chemistry presented several challenges for analysis. First, not all project participants performed the same suite of analyses for all study sites. Measures of DO, specific conductivity, pH, turbidity, and Ammonia-N were taken for most sites. In contrast, data on TDS, ORP, chloride, and sulphate content were only available for the Michigan sites, representing about half of the total sites for which vegetation data are available. The incomplete data set clearly limits the geographic scope of IBI assessment.

Further, many of these water quality and water chemistry measures may be highly variable over time. For example, turbidity is a measure of water clarity and can be affected by both organic (e.g. algae) and inorganic (e.g. sediment) suspended solids. Turbid waters frequently result from run-off from agricultural and construction activities and are associated with local and regional differences in land use. However, repeated turbidity measurements in 15 Lake Ontario coastal wetlands indicates that turbidity is highly variable through time, even within the same land-use environment (Environment Canada, 2004). Total daily rainfall, wind-speed, and wildlife activity (such as bottom-feeding by carp and waterfowl) altered water clarity from week to week, with 6-fold increases in turbidity noted within a given wetland following a major rain storm. In addition, inter-annual variation (2002-2003) in turbidity was significant for most of these sites. Although repeat measurements were not taken for other water quality variables, the Canadian data on turbidity suggest that a single sampling of water quality may not reflect the range of conditions to which aquatic vegetation is responding.

Table 7. Water Chemistry as Reflecting Anthropogenic Stress on Wetlands

Water Quality Variables	Interpretation and Source
DO	Nutrient enrichment; eutrophication.
Specific Conductivity	Dissolved ions in water; a good indicator of urban run-off.
Salinity	Salting of roads with sodium and potassium chloride.
Turbidity	Sediment run-off from agricultural and ditching operations.
Chlorophyll "	Phytoplankton production; nutrient enrichment.
TDS	
ORP	Nutrient enrichment (sewage, fertilizer, and manure).
Chloride (mg/L)	Salting of roads with sodium and potassium chloride.
Sulfate (mg/L)	Urban and industry contaminants.
Nitrate-N (mg/L)	Nutrient enrichment (sewage, fertilizer, and manure).
Ammonia-N (mg/L)	Industries, primarily wastewater treatment plants.
SRP-P* (mg/L)	Nutrient enrichment (sewage, fertilizer, and manure).
Alkalinity (mg $CaCo_3$ /L)	

V. Statistical Methods and Results

All potential metrics were screened against the independent measures of anthropogenic stress identified above using biviarate plots to determine whether an association (either linear or non-linear) was apparent between stressor and presumed response (potential metric). Visual screening also allowed the identification of outliers that might create spurious correlations. Where sample sizes permitted, the sample was stratified by both region and vegetation zone.

A metric was determine to be suitable if (a) the attained significance (p-value) for correlation coefficient (*r)* between the metric and disturbance was less than 0.20; and (b) the observed relationship made intuitive sense. Although the convention in statistical analyses is to recognize only p-values #.05 as significant (indicating a confidence in the result at the 95% level), the Environment Canada group note that lower levels of confidence can still indicate a significant trend in the data. Further, the IBI achieves increased accuracy from the incorporation of several metrics (Environment Canada 2004:112).

Results are presented below for each set of potential metrics: the FQA, the Albert and Minc (2004) proposed metrics of wetland health, and the EPA wetland plant sensitivity-derived multi-metrics. Each set is compared against the three independent measures of environment degration: regional land-use, local sources of stress (Michigan only), and water chemistry data.

A. FQA (Table 8)

1. ***General Land-Use***

    • FQI declines with % Upland Agriculture across all sites combined; largely a function of differences between regions (northern Lakes Michigan and Huron vs. others).

    • FQI for submergent zones declines strongly with % Upland Ag across all sites combined; sample sizes are small, and correlation appears to be largely a function of differences between regions (northern Lakes Michigan vs. Saginaw).

2. **Local Sources of Stress (Michigan sites only)**

    • FQI, C increases with Stress PC-3 (low numbers of boat launches and parking lots).

    • FQI increases with # of culverts (?).

3. ***Water Chemistry***

    • FQI and C decline with increasing chloride content (Michigan only); however, several chloride outliers exist. For eample, high salinity values were recorded at St. Ignace near Mackinac Bridge, but the open, high-energy environment may have dispersed salts and allowed for higher plant diversity.

    • FQI and C decline with increasing sulfate content (Michigan only).

Table 8. Assessment of FQI and C as potential composite metrics

Strata or Subset	Observed association	N	r^2	p-value
all transects	FQI declines with % Upland Ag	85	.28	.0001
MI submergent zones	FQI declines with % Upland Ag	17	.70	.0001
Michigan sites	C declines with chloride content	32	.74	.0010
Michigan sites	FQI declines with chloride content	32	.28	.0017
Michigan sites	C declines with sulfate content	33	.43	.0001
Michigan sites	FQI declines with sulfate content	33	.38	.0001
Michigan sites	FQI increases with Stress PC-3 (low boat launches and parking lots)	58	.30	.0001
Michigan sites	FQI increases with # of culverts	36	.32	.0002
Michigan sites	C increases with Stress PC-3 (low boat launches and parking lots)	58	.30	.0001

B. Albert and Minc (2004) Regional Indicators of Wetland Health (Table 9)

1. ***General Land-Use***

   • % emergent cover declines in emergent zones with increases in % Upland Ag across all regions combined.

2. **Local Sources of Stress (Michigan sites only)**

   • Northern Lake Michigan and Huron, % cover of Turbidity Intolerant species declines with % hardened shoreline and % upland urban, and increases with % upland forest. Not a linear function; small sample sizes.

3. **Water Chemistry**

   • Northern Lake Michigan and Huron, % emergent cover increases with salinity. At least one northern bulrush is known to tolerate a broad range of salinity values (Hammer and Heseltine 1988); bulrushes are the dominant emergent vegetation along these northern wetlands.

   • Northern Lake Michigan and Huron emergent zones, % emergent cover increases with pH. Typical pH values range between 7 and 9 in these sites, well above the point at which pH is known to adversely affect plant productivity, suggesting that this response may be spurious and not provide a reliable metric.

Table 9. Assessment of Albert and Minc (2004) PIBI as potential multi-metrics

Strata	Observed association	N	r^2	p-value
emergent zone	% emergent cover declines with % Upl Ag	41	.47	.0001
N. Michigan/Huron	% emergent cover increases with salinity	7	.81	.006
N. Michigan/Huron emergent zones	% emergent cover increases with pH	10	.47	.001

C. EPA Wetland Plant Sensitivity PIBI

1. ***General Land Use***:

   • No relationships observed between proposed metrics and % upland agriculture, forest, or urban across all transects, or when stratified by region or vegetation zone.

2. **Local Sources of Stress (Michigan sites only)**

   • No relationship was observed between individual stressors and EPA PIBI.

   • No relationship was observed between Stress PCs and EPA PIBI.

3. **Water Chemistry**

• In Northern Lake Michigan and Huron, %Poll_Incr_IT declines with salinity; small sample size.

• In Northern Lake Michigan and Huron, % Sal_Inc_IT increases with salinity (?), and increases with alkalinity.

Table 10. Assessment of EPA Plant-Sensitivity Multi-Metrics

Strata	Observed association	N	r^2	p-value
N. Michigan/Huron	% Gen_Poll_IT decreases with salinity	10	.44	.035
N. Michigan/Huron	% Nut_Inc_Tol increases with salinity	10	.79	.0001
N. Michigan/Huron	% Sal_Inc_Tol increases with salinity	10	.71	.002
N. Michigan/Huron	% Sal_Inc_IT increases with salinity (?)	10	.39	.052
N. Michigan/Huron	% Sal_Inc_IT increases with alkalinity	25	.24	.013
N. Michigan/Huron	% Flood_Dur_Tol increases with salinity	10	.75	.001

VI. Discussion and Recommendations

Overall, a total of 26 potential PIBIs were evaluated against three independent measures of anthropogenic stress, including upland land use within a 5-km buffer, specific or localized sources of stress within a 1-km buffer (Michigan sites only), and field-sampled data on water quality and chemistry. Surprisingly few of the potential PIBIs held up to testing against these independent measures.

None of the potential PIBI functioned well across the entire Great Lakes region. Only two metrics were significant region-wide. The site FQI decreased with increases in Upland Agriculture, although the predictive value was low (r^2 = .28) and largely reflected differences between regions (northern Lakes Michigan and Huron vs. others). A somewhat better predictor of agricultural influence was the total cover value for emergent species in the emergent zone (r^2 = .47).

In contrast, several of the potential PIBIs appear to have higher predictive values for more localized areas. For example, within the Michigan sites, the FQI for submergent zones declines markedly in response to upland agriculture (r^2 = .70, n=17), while C strongly decreases with chloride content across all vegetation zones (r^2 = .74, n=32).

Other apparently significant PIBI's are not readily interpretable. For example, while the EPA salinity-tolerant species increases in cover value in response to water salinity in Northern Lakes Michigan and Huron, so did the salinity intolerant species group.

As noted above, however, the independent measures of "success" are not without problems. Land-use cover values combine a broad range of activities of varying intensity and spatial scale of impact, ranging from intense local point sources to broad regional influences. Frequently, the appropriate spatial scale of analysis is not readily apparent, and may in fact depend on wetland site configuration and degree of exposure to the Great Lakes.

In contrast, water chemistry and water quality are subject to temporal variations with major fluctuations over both the short- and long-term. Isolated measurements may well not reflect the prevailing chemical environment within which aquatic macrophytes grow. These issues of scale, both temporal and spatial - combined with an inadequate documentation of the relationships between specific aquatic macrophytes and chemical stressors - underscore the difficulty in defining robust plant-based indicators of wetland health.

In this study, several other factors compounded the difficulty in understanding the complex relationships between aquatic plants and their environment. In particular, chemical and plant sampling were not adequately coordinated to provide a strong relationship between these two data sets. Not all cooperators conducted the same suite of physical and chemical analyses, resulting in an incomplete data set. Small sample sizes spread across a diversity of wetland types severely limited the ability to define sensitive and robust PIBIs.

If more complete understanding of the quality of wetlands is to be based on plants, more intensive studies of the relationship between specific types of chemical and physical stressors and aquatic plants are needed. These studies will likely require several years of data collection to provide adequate information for creation of an effective plant ibi of Great Lakes coastal wetlands.

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1. Species responses are coded as : - Intolerant of stress; + Tolerant of stress; ++ Positive response to stress.