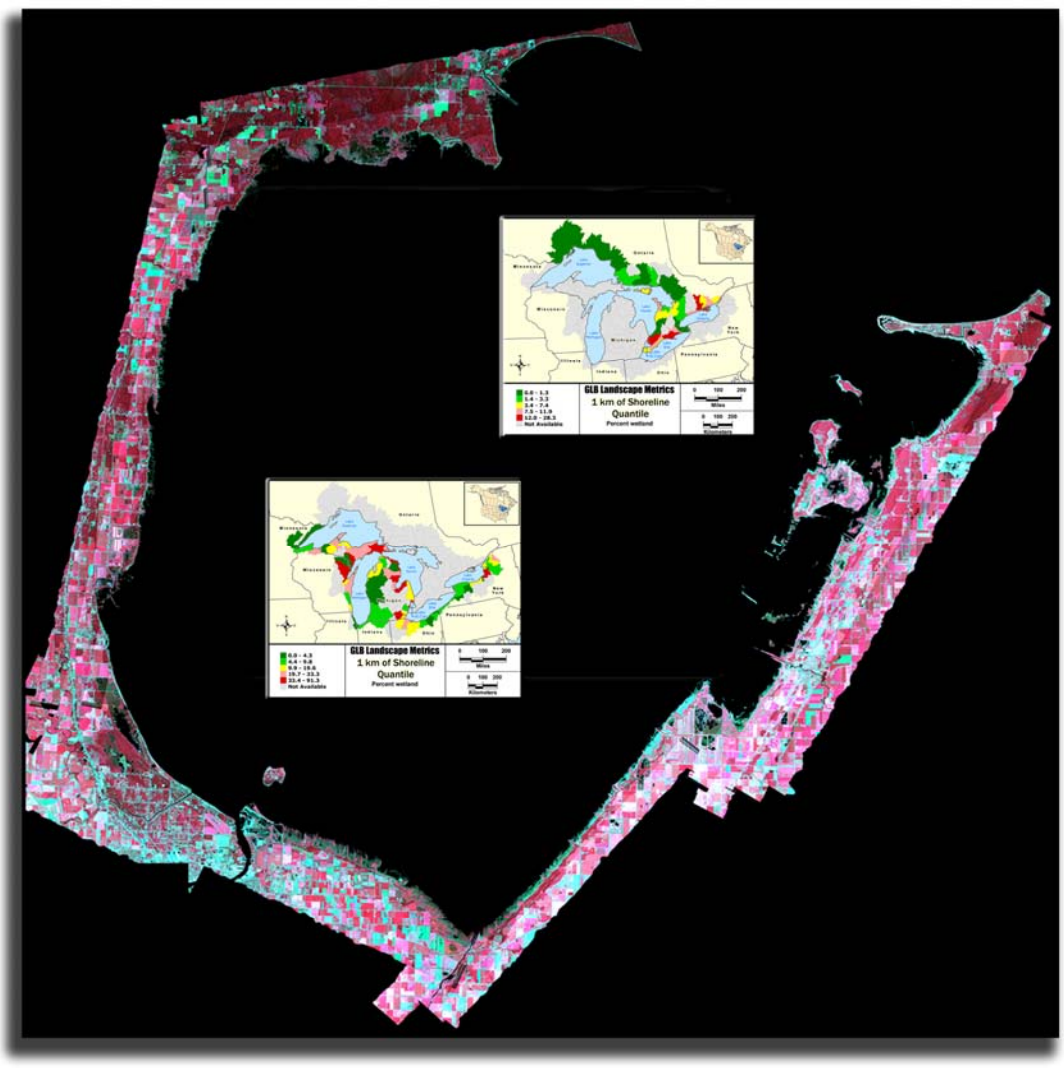
United States Environmental Protection Agency

Using Landscape Metrics to Develop Indicators of Great Lakes Coastal Wetland Condition



RESEARCH AND DEVELOPMENT

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Using Landscape Metrics to Develop Indicators of Great Lakes Coastal Wetland Condition

Ricardo D. Lopez[1], Daniel T. Heggem[1], Donna Sutton[2], Tim Ehli[2],
Rick Van Remortel[2], Ed Evanson[2], and Lee Bice[2]

[1]U.S. Environmental Protection Agency
Office of Research and Development
National Exposure Research Laboratory
Environmental Sciences Division
Landscape Ecology Branch
Las Vegas, NV 89119

[2]Lockheed Martin Environmental Services
Las Vegas, NV 89119

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U.S. Environmental Protection Agency
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Cover Image Description

The Saginaw Bay coastal area contains several regions of a coastal wetland ecosystem, shown from Point Lookout in Arenac County, Michigan, to Sand Point in Huron County, Michigan. Watershed percent wetland in the United States portion of the Great Lakes Basin is shown (center, inset), a general landscape characteristic that is an indicator of coastal wetland condition within 1-kilometer of the shoreline.

Acknowledgements

The Great Lakes Coastal Wetland Consortium funded this project. We sincerely thank Tom Rayburn, Ric Lawson, and Dr. John Schneider for their expertise and support of the project. We are grateful to Dr. John G. Lyon for his thoughtful expertise and comments regarding this manuscript and other Great Lakes topics that are the bases of this work. The U.S. Environmental Protection Agency (EPA) also funded this project and conducted this project through its Office of Research and Development (ORD).

Dedication

"The beauty of the sunset is doubled by the reflection."
Henry David Thoreau (September 7, 1854)

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Executive Summary

Chapter 1 describes the landscape setting of the Great Lakes Basin and the breadth of environmental issues that are relevant to a landscape approach to assessing the coastal wetlands of the entire basin. The objectives of this report are described in this chapter.

Chapter 2 discusses landscape ecology and the metrics and indicators used to assess ecological condition, and it addresses the quality, availability, and cost of data, metrics, and indicators, as well as useful data analysis and presentation techniques.

The information in Chapter 3 is designed to present some of the key ecological metrics in the Great Lakes that would be of particular interest and applicable to coastal areas. The selected metrics presented in this chapter and Appendix A include:

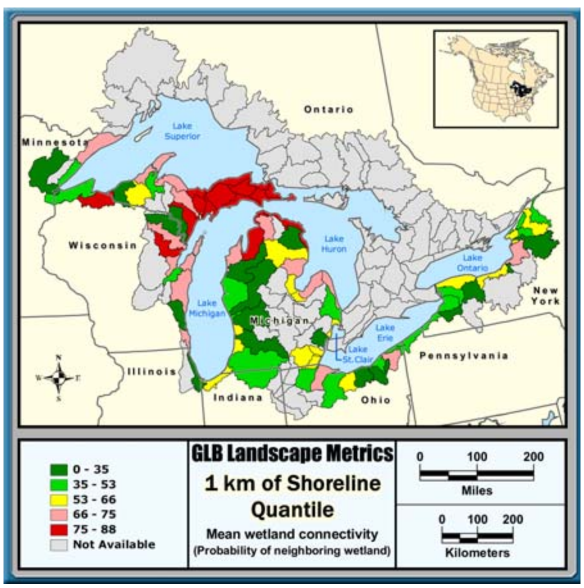
1) Areal extent of coastal wetlands

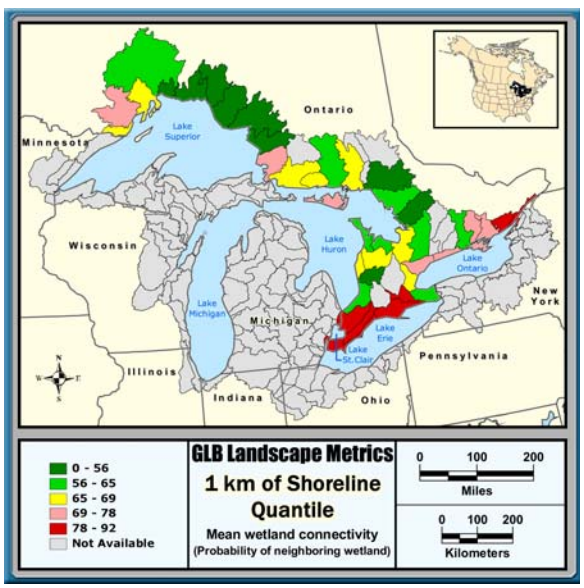
2) Distribution of coastal wetlands

3) Proximity of other land cover and land use types to coastal wetlands

4) Ecological vulnerability of coastal wetlands

5) Water quality metrics, as related to coastal wetlands





Chapter 4 describes the application of the landscape ecological approach to map invasive and opportunistic plant species, using common reed *(Phragmites australis)* as an example. In combination with the broad-scale landscape metrics described in this report, an integrated landscape ecology approach can be used to simultaneously conduct cost-effective monitoring and determine the potential effects of landscape disturbance on the influx and spread of species throughout the entire Great Lakes Basin. Discussions of ongoing efforts and recommendations for future assessments of like those in this chapter are included.

Chapter 1

Great Lakes Coastal Wetlands and Landscape Metrics

Background

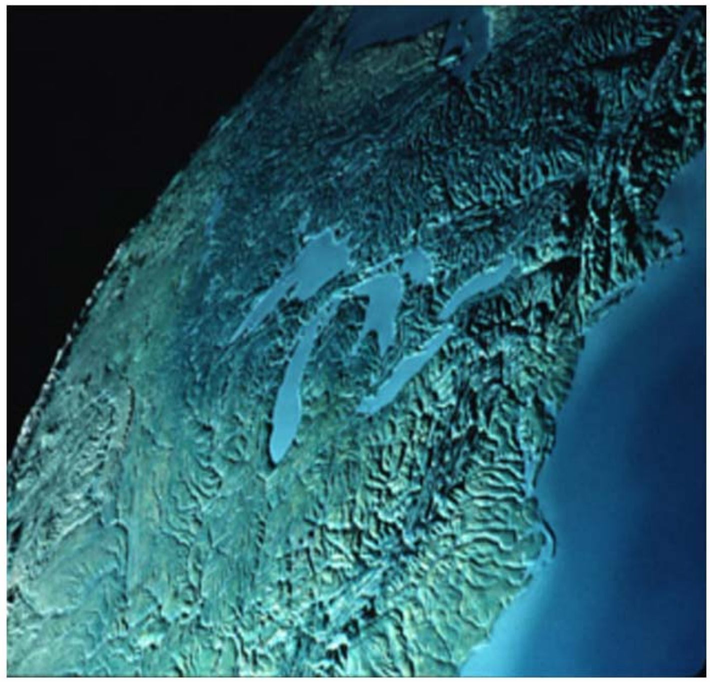


Figure 1. The Laurentian Great Lakes, as seen from an Earth-orbiting satellite, looking toward the northwest from the Atlantic Ocean (from the Michigan Department of Environmental Quality).

The Laurentian Great Lakes is an ecological system (i.e., an ecosystem) that is comprised of five large lakes (i.e., Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario), several small lakes, and their connecting channels (Figure 1). The lakes are bordered to the north by the Canadian Province of Ontario, and to the south by eight U.S. states (Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York). The Great Lakes ecosystem (hereafter, Great Lakes) forms the largest aggregated surface water body system on Earth, and comprises approximately 20% of Earth's surface water. The polar ice caps are the only other area that contains more fresh water, and the freshwater at the poles is predominantly frozen and biologically unavailable. The Great Lakes are therefore a major ecological contributor to the biosphere (e.g., regional climate and migratory wildlife), and have been of tremendous economic benefit to humans since European settlement of the Great Lakes region in the 17^{th} Century. Covering approximately 250,000 square kilometers and draining a watershed area of approximately 500,000 square kilometers, the "freshwater seas" of the Great Lakes hold an estimated 5.7 quadrillion liters of water, which is approximately 80% of the requirements for annual water supply in the U.S. (U.S. EPA, 2004). Spread evenly across the contiguous 48 states, the Great Lakes' water would be 9.5 feet (i.e., 2.9 meters) deep (GLIN, 2004).

Lake Superior is the largest (Figure 2) and the deepest (Figure 3) of the five Great Lakes and could hold the water of the four other lakes, combined. Lake Michigan is located entirely within United States territory and is the second deepest of the Great Lakes. Lake Huron is bound by the lower peninsula of Michigan and Ontario, with Georgian Bay comprising a large proportion of its water volume. The St. Clair River, Lake St. Clair, and the Detroit River connect Lake Huron to Lake Erie, which is the shallowest of the Great Lakes. Lake Erie is the shallowest and warmest of the Great Lakes, bounded by the agriculturally dominated landscapes of northern Ohio and southern Ontario. The 56-kilometer long Niagara River links Lake Erie and Lake Ontario, sending approximately 2 million liters of water per second over Niagara Falls, through the St. Lawrence River to the Atlantic Ocean, approximately 1,600

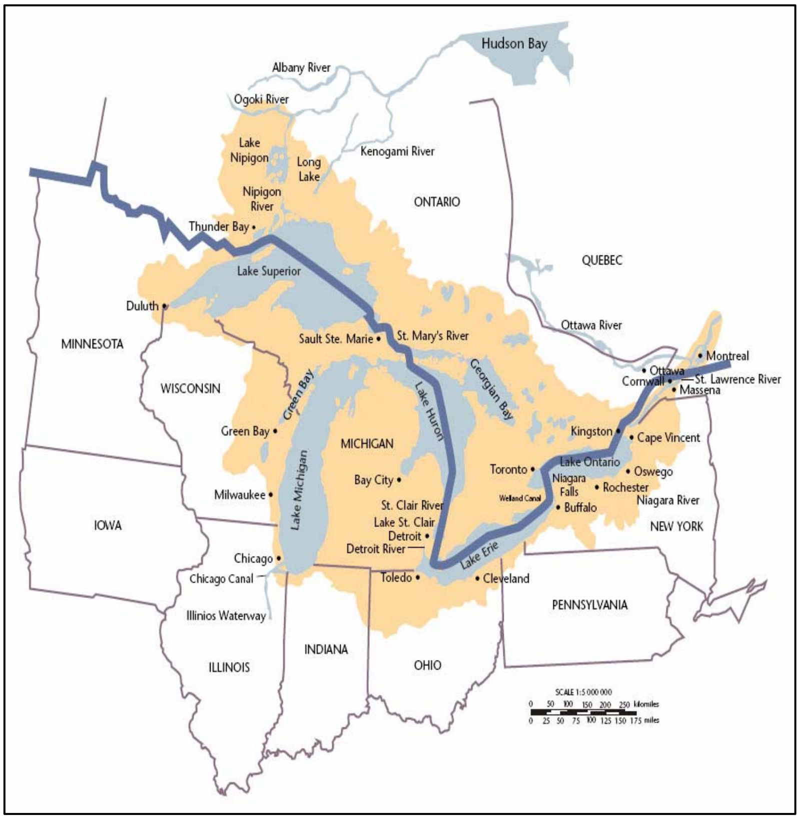


Figure 2. The Great Lakes have 9,402 miles (15,137 kilometers) of shoreline and contains the largest supply of fresh water on Earth (20% of the Earth's total fresh water). The Great Lakes are commonly shared between two nations, including eight U.S. States and one Canadian Province (from Michigan Department of Environmental Quality).

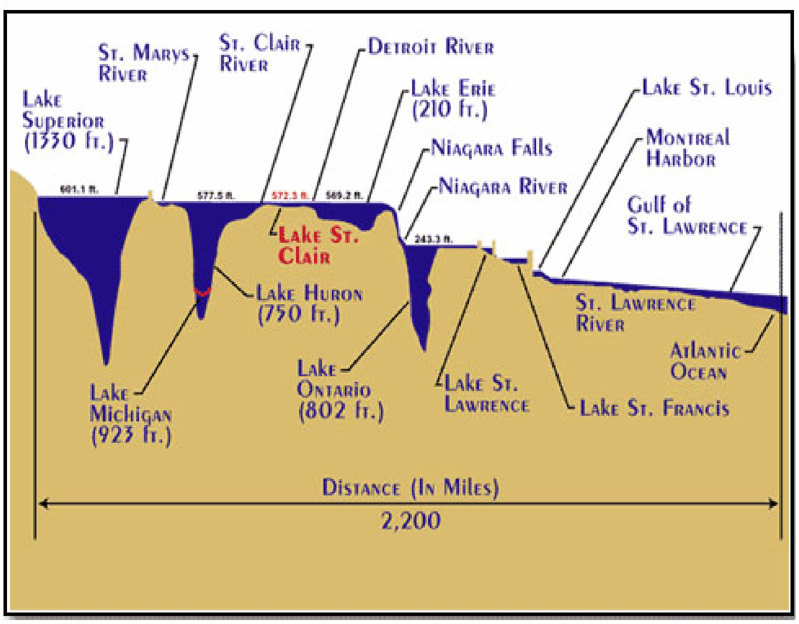


Figure 3. Cross-sectional profile of the Great Lakes and the St. Lawrence River ecosystems (U.S. Army Corps of Engineers, Detroit District).

kilometers downstream (GLIN, 2004). The approximate annual outflow of water from the Great Lakes accounts for less than 1% of their total volume (Government of Canada and GLNPO, 1995).

Despite their large size, the Great Lakes are an integration of aquatic, wetland, and terrestrial ecosystems (Figure 4), which are subject to the effects of chemical and physical changes in the area (Schlesinger, 1997). Ecosystems of the Great Lakes watershed contain approximately 30,000,000 million people on the U.S. side (approximately 10% of current U.S. population) and approximately 9,000,000 million lake people on the Canada side (31% of current Canada population). Because the human population of the Great Lakes has steadily increased over time, human-induced chemical and physical disturbances have increased, particularly during the past 50 years. Humans have also recognized the beauty and commodity value of the Great Lakes but have frequently ignored the fragile composition of the entire ecosystem. However, there have been recent conservation and restoration efforts of aquatic, wetland, and terrestrial ecosystems (Mitsch and Jorgensen, 2004). Among the many chemical and physical disturbances in the Great Lakes, many involve hydrologic alterations that may cause increased runoff of soil, fertilizers, and pesticides from agricultural areas, or storm water runoff from residential and commercial areas. The large surface area of open water in the Great Lakes also makes them vulnerable to atmospheric deposition of pollutants by precipitation, particulates, or dust (GLIN, 2004; U.S. EPA, 2004), thus entering the flow of surface water. The coastal wetlands of the Great Lakes may thus be affected by these inputs of airborne pollutants (Gorham, 1987).

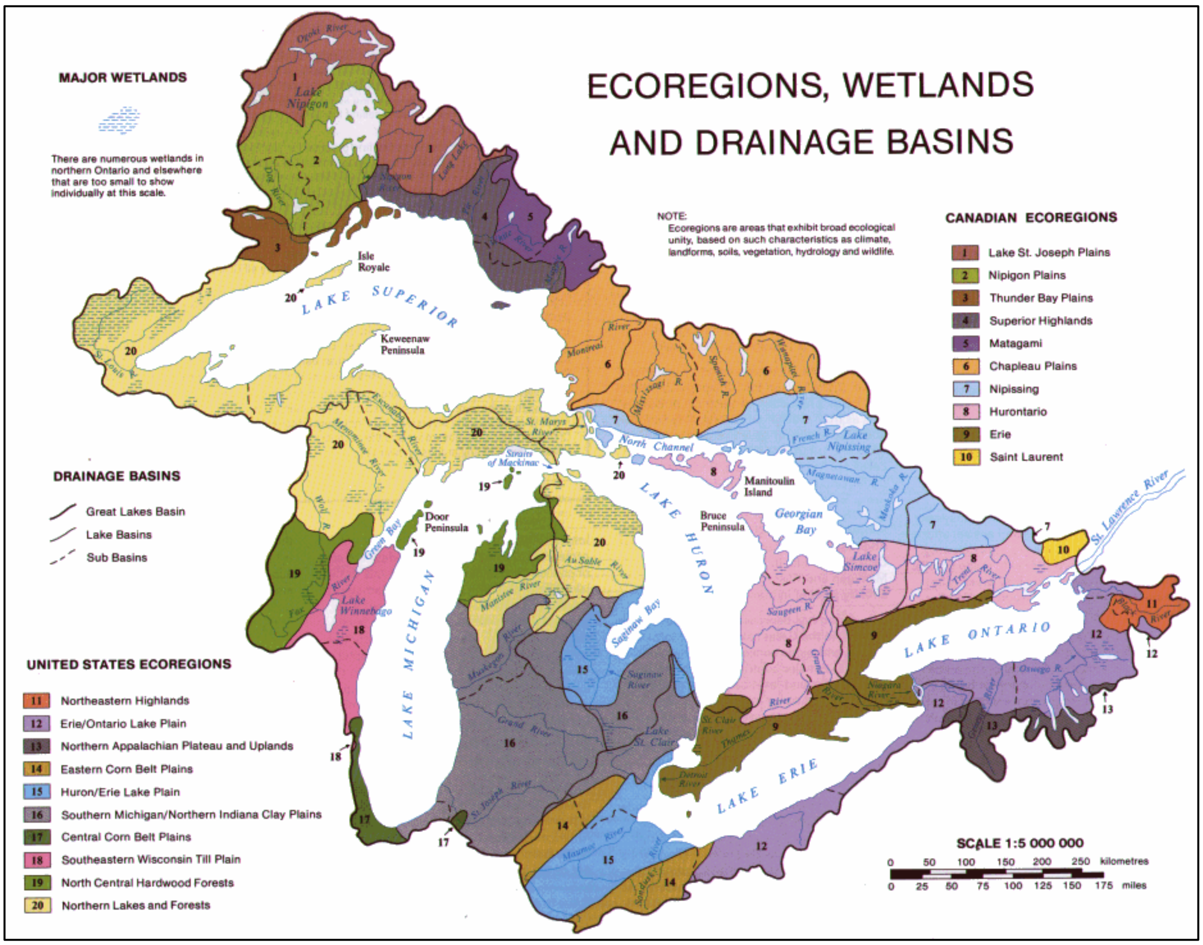
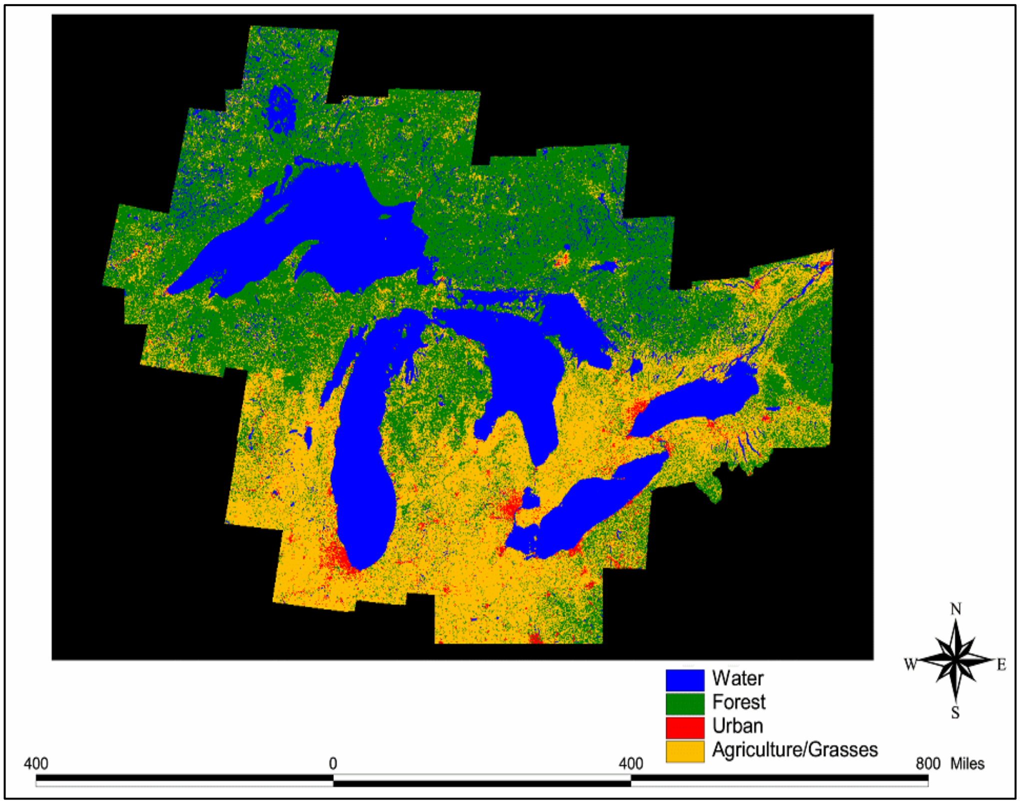


Figure 4. Overview of the surface water drainages and ecoregions of the Great Lakes Basin (Government of Canada and GLNPO, 1995).

Ambient natural conditions that exist within the Great Lakes, such as climate, topography, physiochemical characteristics of the underlying geology, and hydrologic conditions all integrate and determine the biota in a particular location. Thus, many of the coastal regions contain wetlands because they are in areas that are relatively flat, where soils are of relatively fine particle sizes, have soils with a high proportion of clay particles, and have relatively slow throughflow of water from upland areas to lake open water (Linsley and Franzini, 1979). Consequently, the vegetation of these coastal wetlands is dominated by hydrophytic plants, which are adapted to anoxic soil conditions, consequently providing specialized habitat for animals that are adapted to foraging, breeding, or living within wetlands (Costlow et al., 1960; Vernberg, 1981; Blom *et al*. 1990). Thus, coastal wetlands can serve important ecological, economic, and societal roles in the overall functioning of the Great Lakes ecosystem, often referred to as "wetland services" or "wetland functions" (Costanza, 1980). Coastal wetlands are a relatively small (by number and area) subset of all wetlands in the Great Lakes, but owing to their relative rarity, their specialized ecological functions and human services are particularly precious and important to conserve and restore. Coastal wetlands consist of a narrow margin (e.g., within approximately 5-kilometers of the coastline) along limited lengths of the Great Lakes shoreline. Coastal wetlands may also be referred to as fringe wetlands, drowned river mouths, or coastal marshes and these typically extend no further than a few kilometers inland (Keough *et al.*, 1999). Many coastal wetlands are concentrated within the large bays of the Great Lakes, such as Saginaw Bay and Green Bay, or in other smaller inlets, with many occurring at the mouths of rivers that flow to the Great Lakes. A large number of smaller areas of coastal wetland occur in all of the Great Lakes, providing the same wetland functions and human services as the larger coastal wetlands, albeit at a finer scale.

The coastal wetlands of the Great Lakes function as corridors of resting, breeding, and foraging habitat for birds (Prince *et al.*, 1992). Many species of fish, amphibians, and invertebrates are full-time residents of Great Lakes coastal wetlands, with a subset of these species dependent on coastal wetlands for critical portions of their life cycle (Leonard *et al.*, 2000). Wetlands are one of the most biologically diverse and productive ecosystems of the world (Mitsch and Gosselink, 2000). Thus, the plant communities within coastal wetlands of the Great Lakes are a large contributor to the biological diversity and productivity of the planet. In addition to providing a desirable habitat for animals and plants, vegetational communities in coastal wetlands help to stabilize the soil in which they grow and thus reduce soil erosion in the basin (Taylor, 1995). As a result of slowing the flow of surface water and uptake (and/or accumulation) of water and its constituents, coastal wetlands can also provide flood control, amelioration of point and non-point source pollution depending upon the position of the wetland in the watershed, the types of vegetation within the wetland, and characteristics of input of water and constituents to the wetland (Government of Canada and GLNPO, 1995).

Because of their relative rarity and minor portion of the overall landscape (Figure 5), coastal wetlands have been particularly impacted by the conversion of land cover within and adjacent to wetlands (Dahl, 1990; Dahl and Johnson, 1991). Many of these direct effects (e.g., draining of wetlands and conversion of wetlands to farm land) and indirect effects (e.g., increased human population or construction of roads near wetlands) are thought to result in general degradation of wetland condition by altering the hydrology of wetlands, potentially changing the water chemistry of the wetlands, or potentially reducing the biological diversity of the plant communities within coastal wetlands (Ball *et al.*, 2003). Ecological disturbance theory suggests that the intensity and duration of such disturbances may be the key factors in the loss of ecosystem integrity, i.e., the capability of an ecosystem to persist following the disturbance event (Connell and Slatyer, 1977; Rapport, 1990; Keddy *et al.*, 1993; Opdam *et al.*, 1993). As the



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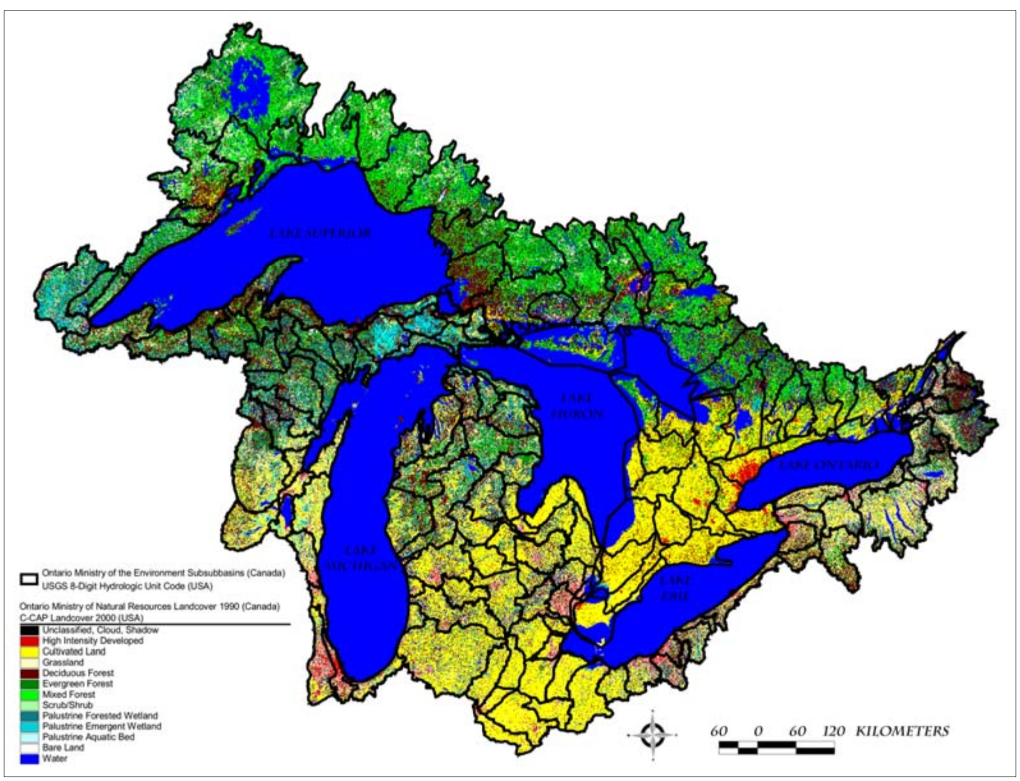

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Figure 5. Land cover in the Great Lakes Basin as seen from space, using (a) 4-class system that describes the location of water, forest, urban, and agriculture/grass (combined) areas throughout the entire Great Lakes Basin (with permission from Guindon and Zhang); (b) a more detailed classification scheme using a combination of the U.S. National Oceanographic and Atmospheric Administration's 2000s C-CAP land cover and Canada's Ontario Ministry of Natural Resource's 1990s land cover data sets.

severity, frequency, or duration of coastal wetland disturbances increases, the survival of the plants and animals of the ecosystem may also decline. One of the many observable mechanisms (Odum, 1985) of the process of ecosystem degradation is the spread of nonnative (i.e., invasive) species or native opportunistic species within coastal wetlands. Such losses of plant biological diversity in coastal wetlands of the Great Lakes have been generally described (Stuckey, 1989), and they may be an indirect effect of land cover or land use change on the periphery or within these wetlands. Chapter 4 provides an applied use of remote sensing, geographic information system (GIS), and field-based techniques to address the current status of invasive and opportunistic plant species in Great Lakes coastal wetlands. Assessments of the type described in Chapter 4 are the first important step toward routinely monitoring the presence of invasive and opportunistic plant species in wetlands across relatively large areas of the landscape. The techniques described in Chapter 4 can also be used in conjunction with the broad-scale landscape metrics demonstrated in Chapter 3 and Appendix A can be used to determine the causal relationships that may exist between landscape disturbance and the influx and spread of invasive and opportunistic plants in coastal wetlands. Other stressor variables may also be tested in this manner (e.g., water quality measurements, habitat characteristics, or wetland functional characteristics), depending on the objectives of the user, and the ecological endpoint of interest. Such coastal wetland disturbances are difficult to measure because the rate of change, the timing of the disturbance, and the length of time that the disturbance has been present are ephemeral measures and different across the basin. Thus, it is important to measure the broad spatial characteristics of landscape disturbance within and on the periphery of coastal wetlands. This report is an important first step toward measuring the spatial extent of the types of landscape disturbance patterns in the Great Lakes Basin, with emphasis on coastal wetlands.

Report Objectives

This report is designed to provide managers in the Great Lakes Basin with succinct answers to the following questions:

1) What basinwide information is available for the development of “landscape indicators”?

2) How do you use remote sensing and GIS to develop landscape indicators of ecological condition within coastal wetlands?

3) Is the available information sufficient to detect and analyze trends in landscape indicators for the Great Lakes Basin?

The answers to the above questions address the following concerns of the Great Lakes research and management communities:

1) What influences the cost of implementing basinwide techniques for the use of landscape indicators of coastal wetland condition?

2) What is the measurability of such techniques in the larger context of existing programs (e.g., what are the data and human resource constraints)?

3) What is the feasibility of applying such techniques on a basinwide scale?

4) What is the availability of complementary research and how could that research be incorporated to enhance the landscape indicator work (see Chapter 4 for a specific case study of a complementary research effort involving invasive/opportunistic plant species mapping in coastal wetlands)?

5) What is the potential indicator sensitivity (i.e., what are the predictive properties of an indicator)?

6) What is the applicability of specific landscape indicators for determining endpoints (i.e., ecological measurements) in coastal wetlands?

This report is based upon the ongoing research of the U.S. Environmental Protection Agency's (EPA) Office of Research and Development (ORD), which uses remote sensing and GIS techniques to measure the potential for ecological disturbance in the region. High-speed computers, satellite imagery, and historical databases with extensive spatial and temporal coverage facilitate analyses of these regionally applicable parameters, which directly address the question of ecological condition of Great Lakes coastal wetlands. The remote sensing and GIS techniques described in this report are two key components of routinely measuring the extent of human-induced disturbances and the presence, extent, and condition of coastal wetlands over such a vast geographic area. This report includes basic information that is required to assess landscape disturbance in the Great Lakes Basin, using existing spatial data set merging and GIS modeling.

This report and the accompanying compact disk (CD) in Appendix A provide several examples and a practical discussion that is designed to specifically address coastal wetlands in the Great Lakes Basin and its subbasins (Figure 6). The maps and discussion topics in this report describe the differences in landscape conditions among watersheds, and the contextual background required to address the following coastal wetland characteristics:

1) Areal extent of coastal wetlands by type

2) Wetland-adjacent land cover and land use

3) Proximity of coastal wetlands to anthropogenic stressors, including agriculture, urban development, and roads

4) Potential effects of anthropogenic stressors and "natural" land cover types in the vicinity of wetlands, as they relate to:
   - ecosystem structural characteristics
   - plant and animal habitat vulnerability
   - water quality

This report describes landscape composition and pattern, and how such distributions may affect key ecological processes (e.g., those processes that govern the flow of energy, nutrients, water, and biota through time and space). If we can successfully map the composition and pattern of landscape conditions, then these characterizations can be used to identify and characterize landscape vulnerability (i.e., risk of degradation as a result of disturbances), such as those disturbances that are directly and indirectly associated with natural and human-induced stressors (U.S. EPA, 2003). The broad-scale disturbances described in this report include those that may result in coastal wetland ecosystem degradation as a result of fragmentation, agricultural and urban development, and hydrologic alteration in or on the periphery of coastal wetlands. Much is still unknown about ecological relationships between stressors and the ecological condition of coastal wetlands, or other ecosystems, particularly at broad scales. Thus, at this time it is difficult to make objective assessments of Great Lakes coastal wetland condition on a basinwide scale, and to definitively determine the best ecological measurements that are indicative of coastal wetland condition, i.e., to determine ecological indicators. These problems stem from the lack of availability of appropriate monitoring data, at multiple scales, despite the continued deteriorating conditions within Great Lakes coastal wetlands (Consortium, 2003a).

In addition to a description and demonstration of basinwide landscape metrics, and their applicability to developing basinwide ecological indicators, the last chapter provides a specific example of how to implement a broad scale coastal wetland assessment, using a combination of the remote sensing, GIS, and field-based techniques described throughout the report. The case study describes the use of the techniques from this report to map invasive and opportunistic plant species. U.S. EPA is currently using the resulting maps of coastal wetland invasive/opportunistic plant species, in combination with the basinwide landscape metric maps to determine potential causal relationships between landscape disturbance and the influx and spread of invasive and opportunistic plants in coastal wetlands.

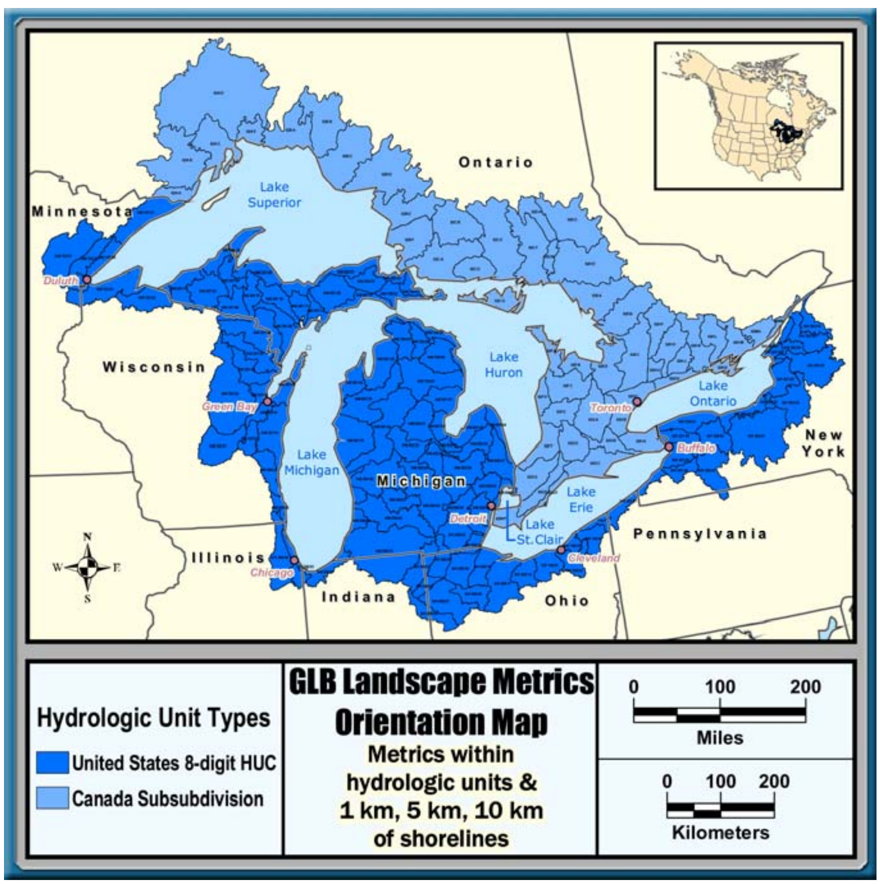


Figure 6. Orientation map for study area used to provide several examples of coastal wetland landscape metric maps for the entire Great Lakes Basin. These maps are included in this report (Chapter 3 and Appendix A) to provide specific examples of the possible outcomes of using a landscape ecology approach for developing indicators of coastal wetland condition in the Great Lakes. A detailed image of watershed identities is available in Appendix A.

Chapter 2

Using Landscape Metrics and Indicators

What do we mean by "landscape" ecology? The interdisciplinary science of landscape ecology examines the distribution (i.e., patterns) of ecological communities or ecosystems, the ecological processes that affect those patterns, and changes in both the patterns and processes over space and time (U.S. EPA, 2001a). Sometimes the broader context of land and conditions surrounding the ecological communities or ecosystems of interest is referred to as "the landscape," which serves as a conceptual unit for the study of spatial patterns in the physical environment and the influence of these patterns on important environmental resources. Although basic ecological theory and concepts are underlying landscape ecology, it is different from some fundamental elements of traditional ecology because it takes into account the spatial arrangements of the components or elements that make up the environment. Landscape ecology analyses also account for the fact that some relationships between ecological patterns and processes can change, depending solely upon the scale at which the observations occur. The discipline of landscape ecology also includes the analyses of both humans and their activities as integral parts of the environment (Jones *et al.*, 1997).

Thus, a landscape is not solely defined by its size, but by an interacting mosaic of elements (e.g., ecosystem types), which is relevant to some phenomenon or ecosystems of interest, such as coastal wetlands and their ecological functions and services. Landscape ecology provides the ideal theoretical framework for analyzing spatial patterns relative to ecological condition and risk when it is desirable to assess a vast area, such as the Great Lakes Basin.

We present the "landscape ecology" approach in this report as one of the techniques for developing indicators of coastal wetland condition, in an effort to solve the real-world problems of protecting and restoring these areas, while assisting in the formulation of solutions that are beneficial to the public.

Concepts and Acceptable Uses

For a variety of reasons, some regulatory agencies and research communities have found it a challenge to complete basinwide assessments of Great Lakes coastal wetland conditions (Consortium, 2004a). Some of the difficulty is related to the paucity of useful information, even in limited coastal areas, resulting in data for less than half of the ecological measures that have been identified by the 1998 State of the Lakes Ecosystem Conference (SOLEC) as important to monitor coastal wetland health. This fundamental shortage of comprehensive information about coastal wetlands is at the heart of the reason why there is no comprehensive long-term strategy for assessing the condition of Great Lakes coastal wetlands, an assessment of environmental impacts from development on coastal wetlands, or an assessment of the cumulative net (historical or projected) change of coastal wetlands. U.S. EPA is using the "landscape ecology approach" (Turner *et al.*, 2001; Brown *et al.*, 2004) to investigate and potentially resolve these outstanding questions about the status of coastal wetland resources in the Great Lakes, specifically by testing selected landscape metrics as potential indicators of ecological conditions in coastal wetlands.

Satellite and airborne remote sensing platforms, increasing available geospatial data products, improved accuracy assessment procedures, and a theoretical construct for the "landscape ecology approach" (Turner *et al.*, 2001; Brown *et al.*, 2004) has allowed for the characterization of landscape conditions and processes around the world.

Researchers have previously used the landscape ecology approach to conduct simple regional assessments of environmental conditions, using some of the assessment results to further their goals of determining the interaction between landscape patterns and the flow of water, energy, nutrients, and biota in the environment (EPA, 2001a). Data about the size, shape, and connectivity of ecosystems or human-built areas (Figure 7) have also been used to provide measurements that may be useful for indicating (i.e., by geospatial statistical inference) the condition of other things on the ground, for example, the condition of coastal wetlands in a particular region of the Great Lakes. Good indicators can reveal dominant ecological changes with the most efficient use of resources, but cannot be used to determine the ecological condition at very fine scales, for example, a specific coastal wetland reserve. Using geospatial statistical models and incorporating our existing knowledge (from empirical studies in coastal wetlands), measurements from the broad scale can be related to conditions in specific ecological resources, and used to verify that the landscape scale measurements are indeed an “indicator” of the ecological conditions on the ground. Thus, landscape metrics of ecological condition can provide a *basis* for assessments of ecological condition and can be substantiated using scientific methodologies. Caution should be exercised when contemplating the use of landscape ecological results to make decisions at scales other than that of the original input data.

Figure 7. The size, configuration, and connectivity of non-wetland areas within the landscape may provide important information about the condition of wetlands in the nearby vicinity; for example, those land cover and land use types immediately adjacent to or within several kilometers of the coastal wetlands shown in this oblique aerial view of the Great Lakes coastline (photograph courtesy of GLNPO and Sea Grant Minnesota).

Metrics and Indicators

The terminology used in this section is specific to ecological studies, and is important to review and understand prior to interpreting broad scale ecological research results.

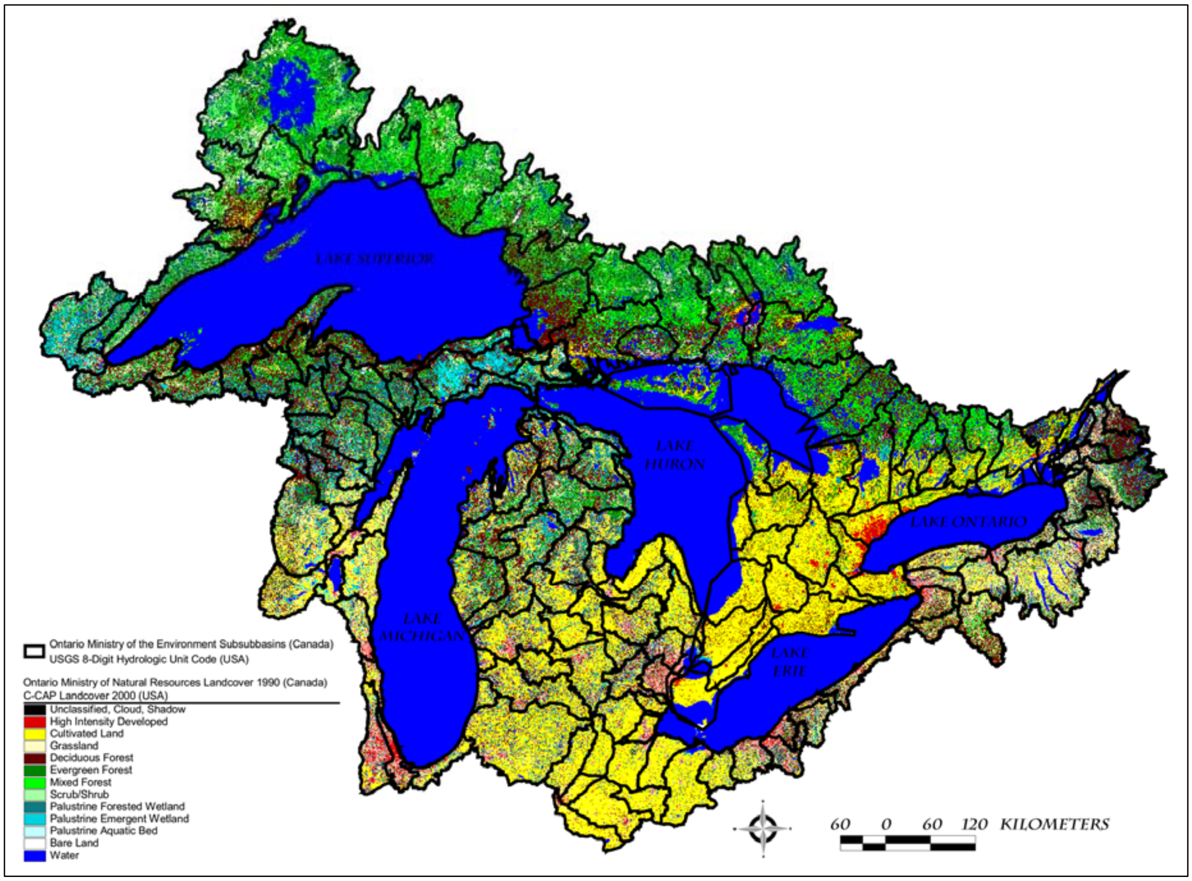
Standard measurements of ecological resources provide ecological *metrics.* When measured at a relatively broad (i.e., "landscape") scale (Forman, 1995), ecological metrics (such as the percent cover of cattail in a particular coastal wetland location) can be described as a *landscape metric*, i.e., a measurement that describes the condition of an ecosystem's critical components (O'Neill *et al.*, 1992). Calculation of landscape metrics (typically derived from information on spatial form or structural relationships) requires the use of spatial data, often displayed as a thematic map, and contained within a GIS. There are many formats of thematic maps, and several possible GIS platforms to select from. The primary uses of landscape metrics are the characterization of historical and current ecological condition, based on land cover information, with the possible extrapolation of current and past information (Figure 8) to make predictions about the future of environmental conditions. The combination and analyses of past, present, and future ecological conditions is referred to as ecological (or land cover) change analysis.

Indicators can be thought of as pieces of evidence, or clues, which give us information about the condition of some environmental feature of interest (GLNPO, 1999). Indicators have significance far beyond the actual values of the attribute measured. An indicator is a value calculated by statistically combining and summarizing relevant data. For example, doctors use human temperature and weight to gauge human condition, and economists use interest rates and unemployment to assess the status of economies. Economists make seasonal adjustments for these indicators with a model, and most look at several indicators together instead of just one at a time (Jones *et al.*, 1997). Similarly, environmental indicators provide pieces of information that may tell us something about the true condition of our surroundings. An *ecological indicator* is defined as a sample measurement, typically obtained by collecting samples in the field of an ecological resource (Bromberg, 1990; Hunsaker and Carpenter, 1990). For example, collecting plant material in a coastal wetland for further measurements in a laboratory spectrometer may provide information about the amount of trace metals in the soil of the wetland, indicated by the concentration of those trace metals in the leaf of the plant. The State of the Great Lakes Ecosystem Conference (SOLEC, 2000) defines an indicator as:

> *"a parameter or value that reflects the condition of an environmental (or human health) component, usually with a significance that extends beyond the measurement or value itself. Indicators provide the means to assess progress toward an objective."*

Landscape metrics can therefore be used to characterize the environment at a broad scale, and they can be used to develop verified *landscape indicators* (Jones *et al.*, 1997), including indicators of habitat quality, ecosystem function, and the flow of energy and materials within a landscape. Empirical ecological studies in coastal wetlands and other wetland ecosystems suggest that fundamental patch measurements (such as the size of wetlands) or processes (such as net primary productivity) may be suitable as landscape indicators of ecological condition in Great Lakes coastal wetlands.

It is important to remember at which scale a metric (ecological metric or landscape metric) is being applied so that the results of such analyses can be viewed in the context of actual conditions on the ground in coastal wetlands. Many land cover gradients are subtle, but the data used for the metric may not be appropriate for capturing such subtleties of the true gradient on the ground. For example, even



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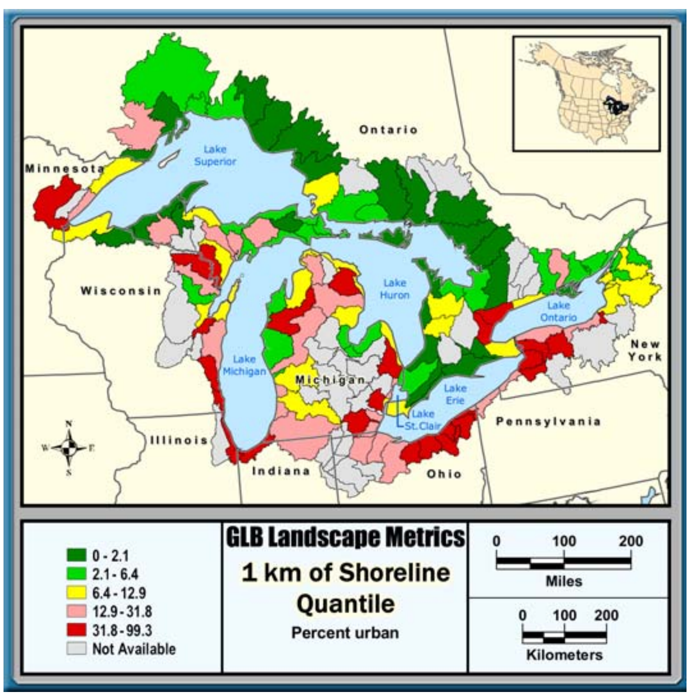


(b)

Figure 8. A general example of how (a) land cover derived from satellite remote sensing data has been used to produce (b) metric maps in the Great Lakes Basin. These metric maps can then be used to develop indicators of coastal wetland condition.

though plants may be good indicators of soil trace metal concentrations in wetlands, field collection of 20 plant samples throughout a coastal wetland (analyzed in the laboratory to determine the concentration of trace metals in the leaves of each) may be inadequate to determine the concentration gradient(s) of trace metals across an entire wetland. This is similar to the problem that occurs at broader landscape scales with GIS data. If land cover data is provided at a 1-kilometer pixel size, that resolution of GIS data may be too coarse to measure the true gradients on the ground (e.g., small wetlands may be missed). Thus, two important guidelines for effectively using landscape ecology metrics and indicators at relatively broad scales are: (1) select the most appropriate data for addressing the ecological process or "endpoint" of interest, and (2) select the geospatial model(s) that is (are) most appropriate for detecting or describing spatial or temporal change in the landscape. The selected landscape ecology endpoints and models can also be adjusted or modified to help interpret the measurements, and to better understand overall ecological conditions (Jones *et al.*, 1997) as improved data and understanding of ecological processes emerge.

Over time, landscape metric and indicator values can provide information on the trends in the condition of the ecosystem components. The information about trends helps to determine:

1) if it is necessary to intervene,
2) if so, which intervention will yield the best results, and
3) how successful interventions have been.

Landscape Scale and Gradients

The term *scale* is generally defined by the *extent* of information, and the *grain* of information. The *extent* of information is the spatial domain, or the size of the area studied for which data are available (McGarigal, 2002). The *grain* of information refers to the minimum resolution or size of the observation units, often identified as patches or digital picture elements (pixels). The pattern detected in any portion of the land is a function of scale. Landscape ecologists often consider the scale of the information they will use in their analyses and the gradients of land cover data or other biophysical data. In order to understand risks to ecological resources and humans, it is important to analyze the spatial patterns of environmental conditions on a variety of scales, e.g., ranging from a single plot in a wetland to a large region, such as the coast of Lake Michigan. Scientists may select metrics and indicators that reflect environmental conditions on a variety of scales in both space and time. In this report, "fine scale" refers to minute resolution, such as might be observed in a single plot at a particular wetland, and a "landscape scale" or "broad scale" refers to coarse resolution, such as images acquired by a satellite that might produce individual pixels that are 30 meters on a side. A landscape ecological investigation requires a definition of the scale of the input data (e.g., 30 m pixel size for land cover), and requires the user to understand what scale is appropriate for their particular application (e.g., animal species requirements). It is an important responsibility of the user to exercise caution when attempting to make decisions at, or among, different scales of landscape ecological outputs. For example, in this report, wetlands in the U.S. that are smaller than 900 m^2 (i.e., the minimum pixel resolution of the U.S. land cover GIS data) are too small to have been detected in the land cover classification process, and even slightly larger wetlands may be missed in the classification process because of factors related to the physics of the satellite sensor system used in the production of land cover data. Therefore, broad-scale monitoring of such small wetland areas may be difficult by directly observed landscape metrics (Lopez *et al.*, 2003).

It is important to select gradients (i.e., changes over space and/or time) of condition(s) that offer sufficient variability, and a sufficient number of field-sampling sites to compare among reporting units (Green, 1979; Karr and Chu, 1997, Lopez *et al.*, 2002), in the event that ecological metrics are to be used to develop landscape indicators. Landscape (e.g., land cover) gradients may be useful for the development of landscape indicators because the statistical relationships between landscape metrics and ecological metrics can give clues about how two (or more) elements of the landscape may interact, such as the relationship between agriculture in a watershed and the concentration of phosphorus in wetlands. In addition, the use of previously observed *in situ* correlations between biophysical measurements may help to guide the analyses of relevant parameters that may be good indicators of ecological vulnerability at moderate to coarse scales.

Prior to the advent of GIS, it was prohibitively expensive and time-consuming to calculate metrics of landscape composition and pattern at multiple (spatial and/or temporal) scales throughout a vast area of the landscape. Without a full understanding of the spatial and temporal patterns of landscape composition and pattern (Figure 9), the condition of coastal wetlands and the vulnerability of these resources to loss and degradation are limited. Landscape metrics can be correlated with ecological metrics collected in the field at a fine scale and, using statistical inference, these correlations can be used to determine the association between the broad scale data (the landscape metric) and the fine scale condition (the ecological metric). A determination of correlations between the broad scale (e.g., Riitters *et al.*, 1995; Jones *et al.*, 2000; Jones *et al.*, 2001), moderate scale (e.g., van der Valk and Davis, 1980; Roth *et al.*, 1996; Nagasaki and Nakamura, 1999; Faith *et al.*, 2000; Lopez *et al.*, 2002; Lopez and Fennessy, 2002), and fine scale (e.g., Peterjohn and Corel, 1984; Murkin and Kale, 1986; Ehrenfeld and Schneider, 1991; Willis and Mitsch, 1995; McIntyre and Wines, 1999a; Luoto, 2000) has not been completely explored. The current list of potential and operational indicators of condition for coastal wetlands (at several scales) of the Great Lakes Basin can be found in proceedings of the State of the Lakes Ecosystem Conferences (SOLEC).

Figure 9. An oblique aerial view of a coastal wetland complex. Coastal wetland complexes like this are important landscape elements and their ecological functions provide many human services such as water quality improvement and flood attenuation. Wetland complexes can be described in terms of its wetland, open water, upland, and other biophysical components. An area of the landscape, such as the area depicted in this image or the entire Great Lakes Basin, can be described as patches of ecosystems, vegetation associations, and patch metrics such as size, topographic position, interspersion, orientation, and relative proximity to components in the landscape.

Landscape Models

Because the landscape of the Great Lakes Basin is very complex, an initial focus on the relevant biophysical characteristics (i.e., excluding fewer relevant biophysical characteristics) is an important first step toward developing landscape indicators. GIS is a key tool that can be used to focus on relevant features of the landscape. For example, a GIS-derived landscape metric, such as percentage of cropland area among watersheds, can be correlated with water quality parameters at a location that is known to be the outlet of a watershed, and a geostatistical model can then be developed. The relationships might be analyzed as a causal (predictive) relationship, perhaps using a regression model with watershed condition as the independent variable(s) and water quality parameter(s) as the dependent variable(s). The causal relationships of these variables might be based on *a priori* knowledge acquired as a result of previously published *in situ* studies of similar variables, and ecological theory as a whole. Broad scale models founded on the ecological principals of *in situ* studies may be limited by a lack of detailed information about small areas, but can serve as a preliminary tool to assess large areas that would otherwise be impractical to assess in the field, or where full coverage of detailed GIS data is absent. A specific and contemporary example of how to use remote sensing, GIS, and field-based techniques in Great Lakes coastal wetlands is demonstrated in Chapter 4, which may be used to determine the potential causal relationships between landscape disturbance, as described with broad-scale landscape metrics (the independent variables), and the influx and spread of invasive and opportunistic plants (the dependent variables) in coastal wetlands. Other stressor variables may also be tested in this manner (e.g., water quality measurements, habitat characteristics, or wetland functional characteristics), depending on the objectives of the user, and the ecological endpoint of interest.

Selection and Use of Metrics and Indicators

Landscape metrics and landscape indicators (derived from the metric) may be used to assess progress toward one or more objectives (SOLEC, 2000). Thus, the selection and use of metrics and indicators should be guided by the purpose for which the information will be used, whether research oriented or policy oriented. Depending upon the use, the relative importance of quality, cost, and completeness of the coverage of the metric or indicator may differ for the user.

There is crossover between the goals of pure research landscape ecologist and the policy uses of the results. The crossover between landscape ecology science and policy is a result of the common *primary* goals of each perspective, which are essentially focused on identifying key indicators of ecological condition that can serve as sentinels of important change. Despite this common primary goal, the differences between the scientific and policy uses of landscape ecology can be profound, and is generally a result of differing secondary goals. The common primary goals of the research (red) and policy (blue) communities are summarized below (note: all topics are being addressed to some extent by both groups, although not always as a primary goal):

1) Assess changes in the condition of the ecosystems and the progress toward achieving management goals for its sustainable well-being.

2) Improve understanding of how human actions affect the ecosystems and determine the types of programs, policies, or regulations needed to address the environmental impacts.

3) Gain a clearer understanding of existing and emerging environmental problems and their solutions.

4) Provide information that assists the public and stakeholders in participating in informed decision-making.

5) Provide information that will help managers better assess the success of current programs, and provide a rationale for future ones.

6) Provide information that will help set priorities for research, data collection, monitoring, and cleanup programs.

Regulatory Support Uses (Policy Goals)

As environmental regulations were initially being developed in the United States, there was a focus on the established measures of environmental quality, such as those for drinking water and air quality. These measures reflected a traditional view of the environment and the potential for multiple factors that may contribute to environmental degradation (Jones *et al.*, 1997). Research that was supported by regulatory agencies addressed the need to make policy recommendations to decision-makers, but did not fully address the scientific (i.e., ecological research) community's goal of increasing our understanding of the interrelationships between abiotic and biotic parameters (Zandbergen and Petersen, 1995).

Thus, landscape indicators were initially developed as lists of physical and chemical measures to monitor improvements in water quality. Biological responses resulting from changes were not considered. Requirements for environmental impact statements led to development of procedures to evaluate habitat as the basis for environmental assessment. As government policies endeavored to protect both human health and the environment from the byproducts of an industrial economy, scientific research required a different approach to support these policies. Awareness of the scope of environmental problems increased and toxic substances became a concern. A variety of tissue, cellular, and subcellular indicators were developed as diagnostic screening tools or biological markers, to evaluate the physiological condition of an organism and to detect exposure to contaminants. The need to develop management strategies able to address interactions within ecosystems and the impacts of human activities upon those natural systems became another stimulus for the development of indicators.

The development and use of indicators that meet all of these needs is a learning process for both the scientists who develop them and for the policy makers who use them. Scientific knowledge itself is the outcome of a consensus-building process among scientists from different disciplines who require easily interpretable descriptions of ecological condition (Zandbergen and Petersen, 1995). Developing landscape indicators involves the collection and management of supporting data, the identification and use of selection criteria, the evaluation of indicators for their efficacy, and accounting for the influence of scale on the final product. Landscape indicators are an important input to a Decision Support System, which can be utilized by policy makers and environmental professionals who require the most up-to-date and accurate information for determining effective strategies for ecological monitoring, assessment, restoration, characterization, risk assessment, and management.

Ecological Research Uses (Science Goals)

The current ecosystem concept and approach to studying ecological interrelationships was conceived as a multidisciplinary, problem-solving concept with the goals of restoring, rehabilitating, enhancing, and maintaining the integrity of particular ecosystems. The answers to scientific questions posed within ecosystems have created a new list of scientific questions that focus on how these ecosystems interact with the surrounding biophysical environment, and thus have spurred a new area of investigation into the pattern of land cover and the implications of that land cover pattern on the ecosystems that are "embedded" within the land cover (e.g., a coastal wetland that is embedded in a larger landscape of agricultural crop land). None of these relationships have been fully field tested across a vast area, yet many landscape indicators have been conceptually proposed, i.e., developed from theoretical ecology (EPA, 2001a). Very few results are available that show comparisons of landscape metrics or metric performance at different scales (Cushman and McGarigal, 2004), but some of these relationships have been preliminarily analyzed, and several new patterns have just recently been explored throughout the entire Great Lakes Basin for coastal wetlands (Appendix A).

The indicators listed below are currently under evaluation by the Great Lakes Coastal Wetlands Consortium (GLCWC, 2004a) and include biophysical measurements that directly relate to ecological endpoints within coastal wetland of the Great Lakes. Many of these indicators are addressed at a landscape scale in Appendix A.

- Amphibian community condition
- Areal extent of wetlands by type
- Bird community condition
- Contaminant accumulation
- Extent of upstream channelization
- Fish community condition
- Gain in restored wetland area by type
- Habitat adjacent to wetlands
- Human impact measures
- Invertebrate community condition
- Land-use classes adjacent to wetlands
- Land-use classes in watersheds
- Phosphorus and nitrogen levels
- Plant community condition
- Proximity to navigable channels
- Proximity to recreational boating activity
- Sediment flow and availability
- Water level

The GLCWC also recommends the following six criteria (2004b) that should be applied when selecting landscape indicators that are applicable to Great Lakes coastal wetlands:

- Cost and level of effort to implement basinwide
- Measurability with existing technologies, programs, and data
- Basinwide applicability or sampling by wetland type
- Availability of complementary existing research or data

- Indicator sensitivity to wetland condition changes
- Ability to set endpoint or attainment levels

Acquisition of information about a number of indicators relating to physical characteristics of wetlands and their surrounding environment has previously been conducted by the GLCWC (Table 1 and Table 2), such that the data will provide integrated flora and fauna measurements, rather than be solely used as individual indicators of coastal wetland condition (GLCWC, 2004b). The indicator summaries (Table 1 and Table 2) can be useful in the initial conceptualization stages of developing landscape ecological indicators by ensuring that geospatial data will adequately address ecological endpoints. Field methodologies that are necessary to validate landscape gradients or to test landscape indicator sensitivity are included for flora and fauna (Table 1) and physical measurements (Table 2). Field methodologies may be modified to directly address the ecological endpoint of the specific sensitivity of the landscape metric/indicator, as needed. The GLCWC's effort includes collection of contemporary and historical data from existing monitoring stations, and can be used within a broad scale landscape assessment such as is described in this report. GLCWC data are also being used to explain current site-specific (i.e., fine scale) wetland conditions and to standardize conditional measurements around wetlands. Recent results of the GLCWC research are maintained at the following Internet URL: http://www.glc.org/wetlands.

Table 1. Summary of Great Lakes Coastal Wetland Consortium (2004) flora and fauna indicators and their methods.

Indicator (SOLEC ID)	Measurement Description	Method Summary
Invertebrate community health (*4501*)	Diversity indices, adult caddisfly presence/absence, and diversity.	Sweep nets, activity traps, backlighting, Hester-Dendy samplers. Need standardized processing. Need standardized habitat sampling. Repeat visits.
Fish community health and DELTs (*4502, 4503*)	Several diversity and abundance (fish per meter) measures, incidence rate of DELTs (deformities, eroded fins, lesions, and tumors).	Electroshocking along transects, fyke nets.
Amphibian diversity (4504)	Many possible population, diversity, and abundance measures. Compare with extensive measures. Species presence, abundance, and diversity.	From most intensive to most extensive– complete counts, capture-recapture, larvae sampling, drift fences or pitfall traps, funnel trapping, visual encounter surveys, Marsh Monitoring Program, and audio surveys.
Bird diversity and abundance (4507)	Intensive–many population, diversity, and abundance measures. Compare with extensive measures–species presence, abundance, and diversity.	Intensive–territory mapping, strip censuses, nest counts, site inventories. Extensive–MMP survey.
Plant community health (*4513)*	*From air photos*: % dominant vegetation types, % invasive types; *from floristic survey:* % wetland obligate species, % native taxa, floristic indexes; *from quantitative sampling:* % cover of invasives in dominant emergent, % floating/submersed cover of turbidity tolerant taxa, rate of change in invasive taxa.	Air photo compilation and interpretation, floristic survey, and quantitative sampling.
Contaminants (4506)	Contaminant levels or physical anomalies. *Further work is needed to develop this indicator.*	External survey of bullheads, DELTs, or other methods that provide useful biological contamination metrics.

Table 2. Summary of Great Lakes Coastal Wetland Consortium (2004) physical characteristics, and methods for obtaining these measurements in coastal wetlands.

Indicator (SOLEC ID)	Measurement Description	Method Summary
Water levels (4861)	Lake levels, wetland water levels, in/out-flows.	Data obtained from lake gauges.
Sediment flow (4516)	Suspended sediment unit area yield (tons/km^2 of upstream watershed).	Metric should be estimated from gauging stations upstream of wetland. Sediment core or turbidity measures.
Sediment available for coastal nourishment (8142)	Sediment budget, net accumulation/loss.	Metrics measured from streamflow and sediment gauging stations at mouths of major tributaries. Alternatives–geomorphic surveys of barrier bars/islands, air photo interpretation.
Storms and Ice	Possible metrics include wetland form factor, succession lag times, storm erosion of shore buffers; ice cover duration, ice thickness, ice jams.	Methods vary by metric.
Phosphorus and total nitrates (4860)	Total phosphorus and nitrates concentrations from May to July for correlation with other metrics. *Further work is needed to develop this indicator.*	Metric calculated from concentration and flow measures from gauging stations.

Data Variables

Decisions about which type of ecological information, remote sensing data, and GIS data to use to begin a landscape indicator development project are difficult because they require an optimization of three important factors: (1) the cost of data (i.e., acquisition, processing, and storage), (2) the availability of the necessary data, and (3) the quality of the data. In the planning of a landscape ecological assessment, whether for ecological research or for regulatory support, one has to decide, for example, between the use of an objective data source with high quality but many gaps in coverage, which would require a large portion of available resources to collect sufficient data, or the use of other data sources, with fewer gaps and less costly information, but requiring a reduction in reliability and comparability (Figure 10).

Availability, Cost, and Quality

Decisions about how to evaluate and monitor the ecological condition of Great Lakes wetlands must take into consideration the logistical challenges presented by large landscapes and the fact that assessment and monitoring schemes must be parsimonious. Although there are many benefits associated with exploiting existing data, there are costs (e.g., non-contemporaneous data incompatibility) that must be considered in accessing those data. Long-term or wide-area data are generally accessible through major data centers. Short-term or single-site data sets, generated to address focused scientific questions, are often available solely from the originating organization. Overall cost of any landscape assessment is affected by the availability of existing data, its source (whether from a public, nonprofit agency, or from private for-profit companies), and its quality.

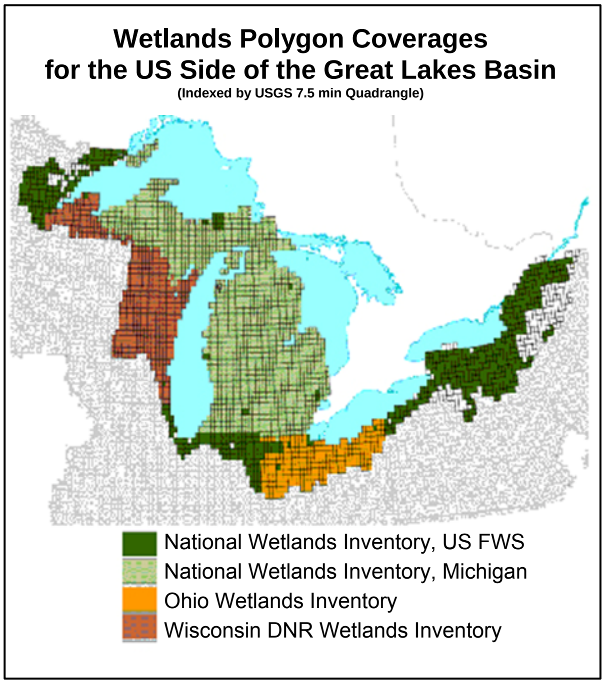


Figure 10. Wetland inventory data (shown solely) for the Great Lakes Basin is available to the public, but is variable in coverage completeness, class consistency, and is generally based on conditions in the 1980s. Digital wetland maps for Ontario, Canada, are pending but wetland maps may be available near some urban areas, at coarse resolutions, or in non-digital formats (map courtesy of the Great Lakes Commission and the Great Lakes Coastal Wetland Consortium).

Existing data are often fragmented and dispersed among many sources, depending on the geographic and environmental areas considered. This problem is especially relevant when local information is needed at a broad scale for land management tasks, such as coastal wetlands of the entire Great Lakes Basin. In addition, databases are created in several formats or geographic projections that may not be interoperable. These are important issues to understand prior to selection of the data and/or metric.

U.S. federal agencies are likely to be the primary lower cost sources for data that include maps of elevation, watershed boundaries, road and river locations, human population, soils, land cover, and air pollution. Sources include the U.S. Army Corps of Engineer; National Oceanographic and Atmospheric Administration; U.S. Geological Survey; the U.S. Environmental Protection Agency; the U.S. Department of Agriculture; the U.S. Census Bureau; and the Multi-Resolution Land Characteristics Consortium. Resources may consist of databases, raw or preprocessed remote sensing data, digitized maps, and GIS/statistical models or software. Data types that use standard methodologies, such as those that comply with the Federal Geographic Data Committee (FGDC), provide data for which reliability is high, availability assured, identified sources, and good comparability. In the absence of these data quality assurances, large quantities of data may be available at lower costs, but with an increased risk of noncomparability, low reliability, and uncertain future availability.

Key Data Types

The types of data that may be available for landscape indicator development include ecological information, remote sensing data, and geographic information. Ecologists have traditionally used historical maps, aerial photographs, and their understanding of spatial relationships between ecosystem patches to explore relatively broad scale ecological characteristics of the landscape (e.g., Miller and Egler, 1950; MacArthur and Wilson, 1967; Howard, 1970). Airborne digital data is useful for determining the abiotic conditions of Great Lakes coastal wetlands (e.g., Lyon and Drobney, 1984; Lyon and Greene, 1992; Lyon et al., 1995). The inherent complexity of wetland ecosystems and the particular ecological processes of coastal wetlands have also prompted development of, and research into, the use of specialized airborne and satellite sensors, and related processing techniques for these new data types. Within the past decade, environmental scientists have successfully integrated and applied the use of relatively sophisticated sensors (e.g., airborne hyperspectral, airborne multispectral, and satellite multispectral scanners), automated image processing software/techniques (e.g., ERDAS' Imagine, http://www.gis.leica-geosystems.com/; RSI's ENVI software, http://www.rsinc.com), and the computing power of GIS (e.g., ESRI's ArcView and ArcInfo, http://www.esri.com) to the study of ecology. However, most of these tools are relatively new, and the application of multiple sensors and techniques to wetland detection and analysis has not fully matured.

Ecological Information

It is possible to sample ecosystem components, such as the water, soil, air, plants, and animals, but it is impossible to survey (i.e., fully measure all of these components throughout the entire ecosystem). Thus, any ecological study must consider what components of an ecosystem to answer the question, "Which ecological indicators are the best surrogates of overall ecosystem condition?" A traditional ecologist might consider a good coastal wetland indicator as one that can be explained in its component parts, is known *a priori* to be directly linked to the functional status of coastal wetlands (e.g., hydrology), and has a demonstrable and repeatable linkage with the functional status of the wetland. A landscape ecologist might additionally consider a good coastal wetland indicator as one that reflects conditions across multiple coastal wetlands, multiple watersheds, multiple lake basins, or at other more broad scales. Environmental policy experts may be additionally interested in selecting ecological indicators that have the greatest likelihood of answering the following related questions:

1) What indicators characterize and measure ecological sustainability?

2) What indicators best show changes caused by human impacts?

3) How can indicators developed in one place and time be used in other places and times?

To some extent, different measures and monitoring designs are needed to answer all of these questions, and to answer them at local, watershed, regional, national, and basinwide scales. While local or watershed assessments may include fairly complete monitoring of stresses and impacts, such direct assessment is not practical over large regions, such as the Great Lakes Basin. But there are opportunities to harmonize assessments across spatial scales by including, together with field monitoring, advanced and less expensive assessment methods that utilize remote sensing data.

Remote Sensing Data

Because of the vast areas involved, and the complexity of information that is required to assess the ecological functions within the Great Lakes Basin, remote sensing technologies have been developed to provide an additional source of information to develop indicators of coastal wetland condition. However, our ability to interpret landscape spatial patterns and identify the materials on the ground can be a challenge because of the limits of the spectral (e.g., detectable energy wavelengths) and spatial (e.g., minimum pixel size) properties of the sensor. Remote sensing data are often mistakenly thought to be less useful than observations that are made on the ground within ecosystems of interest. However, field-based measurements (e.g., 1,000 sample points within a wetland) are not as comprehensive as remote sensing data and thus may be relatively less effective at determining the true type, number, and distribution of some of the key elements of an ecosystem (e.g., wetland plant species distribution). Remote sensing data can supplement the inability of investigators to effectively sample a wetland by providing “wall to wall coverage” (e.g., a complete coverage; a full image that assesses a wetland from edge to edge of the ecosystem).

The inherent tradeoff of having a full coverage of remote sensing data, rather than a field sample, is being distant from the wetland and consequently having the (satellite or airborne) image picture elements (pixels) at sizes that are coarser grain than field-based observations, but having a complete coverage of these data. This is the reason why remote sensing data (or derived geospatial data) should be thought of as a supplement to field-based information, and not as a replacement for field-based information.

It is important to determine the scale of ecological information that is necessary to assess the ecological condition of coastal wetlands prior to determining which types of remote sensing data are required for the assessment. For example, if the goal is to measure simple spectral characteristics (e.g., measuring for the presence and area of large open water areas), then it is not necessary to have fine scale spectral or spatial resolution information, and satellite (e.g., MODIS or Landsat) data should suffice. If the goal is to measure more complex characteristics of coastal wetlands (e.g., the presence and location of all emergent vegetation, combined), then it may be necessary to acquire data with higher spatial resolution for those areas of vegetation (e.g., a 50-meter-wide patch of cattail on the edge of a marsh) and can still be used to cost-effectively cover a vast area, such as the entire coastline of the Great Lakes Basin (e.g., Landsat Thematic Mapper data with 30 meter pixel resolution). The appropriate spatial resolution of remote sensing data is thus determined by the ecological investigator deciding what the minimum conceivable level of spatial information is necessary to adequately assess coastal wetlands and then determining the optimal pixel size that provides that information, in the context of the cost and availability factors. The spectral resolution necessary for the landscape assessment is determined similarly by the ecological investigator deciding what the minimum conceivable level of spectral information (e.g., how much information must be directly extracted from the reflectance of plant leaves) is necessary to adequately assess the condition of coastal wetlands, and to address the ecological endpoints. The ecological investigator should also determine whether there is a need for temporal data analyses in the future, and at what frequency the remote sensing acquisition might be required to adequately assess the condition of coastal wetlands. All remote sensing platforms (e.g., airborne or satellite equipment) have differing return (i.e., repeated overflight) rates, ranging from approximately daily, to once every several weeks.

Because the characteristics of land cover or land use in the vicinity of coastal wetland may determine the condition of the coastal wetland, and these conditions may change over time, it is often desirable to assess these features repeatedly over time using remote sensing. Stresses related to land cover and land use may be those directly caused by humans, such as agricultural, urban, and industrial development. Other human-induced disturbances in coastal wetlands include those associated with upland development, shoreline development, deforestation, changes in upland agricultural practices, road construction, dam construction, or other hydrologic alterations. These changes or activities can be directly observed or inferred using remote sensing. Aerial photographs (generally 1-meter spatial resolution) or airborne digital imagery (generally a 1-5 meter spatial resolution) is often available for specific areas and can be used to correlate land-use changes with wetland alterations (Figure 11).

Figure 11. Airborne multispectral imagery (e.g., Positive System's 1-meter spatial resolution, 4-band "ADAR" data) is available for specific areas and may be used to correlate land-use changes with wetland alterations, at local to regional scales, such as is shown in the Wildfowl Bay region of Saginaw Bay (Lake Huron).

Land use and land cover data are most often derived from some type of overhead remotely sensed imagery, such as aerial photographs, airborne digital data, or satellite digital data. Data collected by satellites are most often used to map land cover over vast areas like the Great Lakes Basin and have been used to measure changes over time. With a few exceptions, most of the sensors carried on satellites measure light reflected from the Earth's surface. Because different surfaces reflect different amounts of light at various wavelengths, it is possible to identify general vegetational change (Figure 12) or broad land cover types (Figure 5) from satellite measurements of reflected light. Examples of how land cover maps, derived from satellite multispectral data, are shown in Chapter 3, and can be used to develop landscape indicators of coastal wetland condition.

Remote sensing data are the source for much of the derived land cover and land use data sets that are used for GIS analyses and modeling. Generally, GIS products are derived by either manual remote sensing data interpretation or semi-automated image processing. The examples in this report include indicator development, using a variety of high and intermediate (Chapter 4), and low (Chapter 3) spatial and spectral resolution digital remote sensing data.

Geographic Information (Geospatial Data)

Geographic information describes the locations of landscape entities and can be interpreted so that the spatial relationships between these entities are understood. Most of the broad-scale geographic information produced today resides with national and state governmental groups, but is frequently produced at fine-to-moderate scales by local governments, individuals, corporations, and other

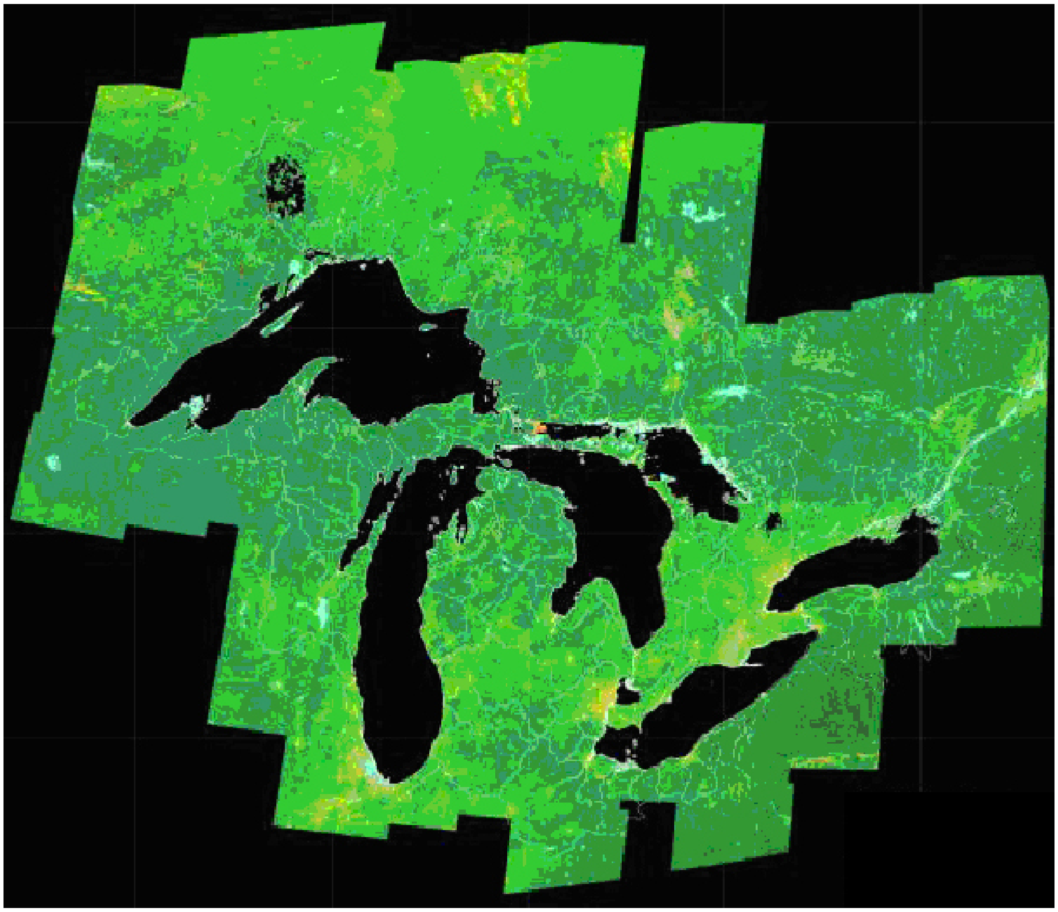


Figure 12. Satellite-based sensors can measure light reflected from the Earth's surface and may be used to identify general vegetational characteristics, such as relative greenness of plants (mid-1980s), based on chlorophyll content of living parts of the plants on the ground in the Great Lakes Basin. Imagery courtesy of Dr. Bert Guindon, Canada Centre for Remote Sensing.

nongovernmental organizations. All of the geographic information products from the U.S. that are used in this report can be readily downloaded to your personal computer by visiting the Web site URLs that are listed in the tables, figures, and text of this report, and which are contained within the metadata of Appendix A. A computer and GIS software are required to process and analyze these digital geographic data sets (e.g., using Geographic Resources Analysis Support System, http://grass.baylor.edu/; or Environmental Science Research Institute's ArcInfo or ArcView software; www.esri.com).

The categories of geographic information cover a wide range of parameters that have been mapped (in what is sometimes referred to as a "thematic map") at a variety of scales and may include information about topography, human population, land cover, land use, oceans, rivers, streams, lakes, wetlands, roads, important political boundaries (e.g., counties or townships), and features of importance (e.g., national parks, monuments, and landmarks). The level of detail described for each parameter within a map (e.g., type of wetland vegetation: herbaceous and woody plants, or by plant species) is dependent upon the spatial and spectral characteristics of the remote sensing data, from which the geographic information or geospatial model was derived.

In a typical thematic map, data are digitally stored as a series of numbers that produce a map of these values associated with each pixel in the map. These maps can be thought of as checkerboards, where each grid pixel represents a data value for a particular landscape characteristic or “theme” (e.g., a map’s topographic theme with a point elevation value and pixel value of “2451,” which defines that particular pixel at 2451 feet above sea level). A GIS can be used to view and measure landscape metrics or indicators, using a variety of methods. One method called “overlaying” simply examines several different themes to extract information about the spatial relationships among the themes. For example, by overlaying maps of land cover and topography, the analyst can look at the occurrence of agriculture on steep slopes, using an overlay of land cover (which includes agriculture locations) on topography (which includes elevational change, i.e., slope, across the entire landscape). These relationships can be digitally stored as a new map, which combines the information from the original set of thematic maps. Another method called “spatial filtering” can be thought of as using a “window” to calculate values within small areas that are part of a larger map. Spatial filtering can be used to create surface maps of metric or indicator values that help to visualize the spatial patterns of metrics or indicators in more detail than is provided, for example, by watershed scale summaries (Jones *et al.*, 1997).

Because landscape ecological research involves the use of several GIS data sets, a thorough understanding of how these GIS data sets can be integrated and managed is important during the early stages of the research. With the rapid growth in GIS software and applications, the environmental scientist’s capability for storing, manipulating, and visualizing geographic information is becoming commonplace for understanding ecological data, which has shifted some of the emphasis of landscape ecology from the GIS applications and manipulations (described in the prior paragraph) to the statistical analysis of the geospatial data. Such improved geospatial data analyses of the relationships between landscape condition and the ecological functions of coastal wetlands can be enhanced by targeted (i.e., non-extensive) site-specific assessments, allowing for a broader-scale spatial analysis, given a well-designed field, remote-sensing, and GIS mapping approach (see Chapter 4 case study for a specific example of site-specific approaches to developing indicators of coastal wetland condition). Statistical procedures can improve the understanding of the broad-scale relationships between landscape condition and the condition of coastal wetlands that reside, thereby allowing for larger data sets to be analyzed using analytical techniques that allow for the inclusion of data that might otherwise cause analysis difficulties. Such geospatial statistical techniques have demonstrated initial significant relationships between coastal wetland parameters and other mapped geographic data in the vicinity of these wetlands, but the strengths of the relationships can be variable, and the causal relationships are uncertain at this time (Lopez and Nash, manuscript in review).

The potential limitations of using mapped geographic data to assess wetlands are directly related to the capability of linking GIS-based assessments to relevant field-based assessments of wetlands (Whigham *et al.*, 2003), an important component of determining the accuracy of landscape indicators of coastal wetlands in the Great Lakes Basin. This report demonstrates the initial steps in producing broad-scale basinwide metrics of landscape condition (Chapter 3), and includes a case study that demonstrates how to use a landscape approach to map potential landscape disturbance receptors within coastal wetlands of the Great Lakes (Chapter 4).

Metric Measurability, Applicability, and Sensitivity

After reviewing data availability, the next step in a landscape assessment is the selection of landscape metrics, which requires considering three important questions:

1) Are the available data capable of adequately measuring the (metric) parameters, and do they address the ecological endpoint(s) of interest?

2) Are the metrics to be derived during the landscape ecological analyses applicable to the ecological endpoint(s) of interest, and do these results answer the questions of the audience for the analyses?

3) Are the metrics to be derived during the course of the landscape ecological analyses likely to be sensitive enough to provide information about the ecological endpoint(s) of interest?

Evaluation of measurability of a landscape metric must include a primary review of the expertise, training, and methodologies used to acquire and process the remote sensing data, input and analyze the derived GIS data, and synthesize the results of such analyses. These four measurability-related steps require the input from individuals that have expertise in remote sensing, computer science, geography, GIS, wetland ecology, general ecology, environmental science, chemistry, hydrology, geology, and other relevant specialized fields. Evaluating measurability also involves an early review of prior techniques, and determining how they may be modified to accomplish the particular goals of a landscape scale coastal wetland assessment. It is often tempting to repeat some of the same techniques applied in other geographic locations or in other ecosystem types, but many of the techniques in GIS and remote sensing work do not apply to wetland assessments. One of the principal differences between landscape-scale wetland assessments and assessments of other ecosystem types is that wetlands are, by definition, a transitional zone between upland and open water ecosystems. Thus, there is a mixture of upland and open water conditions, at different times in wetlands, which may lead to confusion if solely upland or solely open water methodologies are applied to wetland ecosystems. Additionally, coastal wetlands have very unique hydrodynamic conditions, as compared to other wetland types, and thus caution should be exercised when merely transferring methodologies from other landscape-scale general wetland studies to assess conditions in *coastal* wetlands of the Great Lakes.

The applicability of a landscape metric (or indicator, derived from that metric) is also a critical step that a research team should address prior to beginning the landscape assessment process. SOLEC has compiled several lists of operational and proposed measurements that are applicable to landscape assessments and that can be used to develop landscape indicators (Table 1 and Table 2). Not all of these measurements have been completed at a broad scale and some have been completed solely at selected sites around the Great Lakes. Additional information about these measurements can be used to ensure the applicability of landscape scale metrics for the development of landscape indicators (see Internet URL: http://cfpub.binational.net/home_e.cfm).

Landscape metrics and metric-derived indicators must demonstrate that they are sensitive to (spatial and temporal) changes that occur in coastal wetlands if they are to provide information to the relevant audiences, determined in the “measurability” evaluation. Because all ecological systems change, metric and indicator sensitivity must be gauged at a relevant spatial and temporal scale that makes sense for the ecological endpoint, determined in the “applicability” evaluation. Metric sensitivity can be evaluated by field verification and then further evaluated (as a landscape indicator) by validating a response by the metric to known (and validated) drivers within, or in the vicinity of a coastal wetland ecosystem. For example, a landscape metric that approximates nutrient conditions in coastal wetlands of two different watersheds can be field tested using a statistically valid field sample of coastal wetland soil and water chemistry in those two watersheds, and then could further be tested as an indicator by field validating the relative proximity of agricultural land to those wetlands throughout each of the watersheds.

The field-based validation of the landscape metrics/indicators is a vital (often neglected) step that requires a statistically sound methodology prior to entering the field to conduct sampling. A typical way of determining if a landscape metric/indicator is sensitive is to hold it to a predetermined standard of acceptability (e.g., for a linear regression or ANOVA, a significance level of $\alpha = 0.05$), but this standard is not always the same for every metric, geography, ecosystem, and relevant audience. This step relies on the *a priori* knowledge and expertise of the research team and is a standard method for designing a hypothesis test. Thus, a critical analysis step is for the research team to agree on the level of sensitivity that is required to satisfy the various research or policy goals of the project, prior to the commencement of field validation; however, this method is not the preferred methodology (for the reasons outlined above). The sensitivity of a landscape metric can also be assessed by comparing the results and distribution of the metric with the results of other studies and is insufficient for fully developing a landscape indicator and should be avoided if possible.

Availability of Complementary Research

The Great Lakes Consortium, U.S. EPA, and the members of SOLEC have several interests in the investment of additional resources for the assessment, restoration, and understanding of the processes of coastal wetlands of the Great Lakes. Thus, these groups sponsor complementary research that involves the collection and processing of a tremendous amount of remote sensing and GIS data. Each of these groups also conducts detailed field studies at a variety of locations throughout the Great Lakes Basin. Each of the groups compiles much of these data at the end of each project so that cross-site comparisons can be made, and the assessment of the Great Lakes Basin can proceed efficiently. A basinwide examination of coastal wetlands using remote sensing techniques is recognized as a common goal of these groups. Thus, the integration of sampling and analytical protocols and benchmarks for implementing an effective binational and basinwide monitoring program, which is capable of tracking and assessing the existing status and projected integrity of Great Lakes coastal wetlands, is warranted. Collaborations between the members of these groups are overlapping and offer many opportunities for complimentary research that, individually, may be quite different. Complementary work under the guidance of the Consortium includes the development of a monitoring database, implementing a monitoring plan, and coordinating implementation with Consortium member organizations (Consortium, 2004a). Thus, a key step for a landscape ecology research team is to assess the present and past studies of Great Lakes coastal wetlands so they can avoid duplication of data acquisition and processing, and to build upon the work of prior studies. Presently, assessments of coastal wetlands throughout the entire Great Lakes Basin are being conducted by the contributors to this report (i.e., U.S. EPA's Office of Research and Development, U.S. EPA's Great Lakes National Program Office, and the Great Lakes Coastal Wetland Consortium). Other similar research is being conducted by the Great Lakes Environmental Indicators Project, which is a multiagency effort funded by the U.S. EPA's STAR Program (http://glei.nrri.umn.edu/default/default.htm).

Data Synthesis and Presentation Techniques

Inferring Ecological Condition

A landscape ecological assessment is a determination of the condition of an area with regard to specific ecosystems and their surroundings. This may involve the general summary of conditions, a determination of suitability of habitat for specific plants or animals, a determination of the health risks for humans (e.g., water quality), or the determination of vulnerability for specific plants and animals (i.e., the ecological vulnerability). Such determinations require a basis of comparison (a benchmark), which might be based on the least-disturbed condition that is known or is desired for the ecosystem. The condition of the assessment area, or a portion therein, can be compared to the benchmark condition (sometimes called a "reference condition") to establish specific criteria against which proposals for change or modifications might be presented. Although past impairments may preclude restoration of any given ecosystem to natural conditions, the perceived natural condition must be understood in order to define the target condition and guide ecosystem improvement. That is, for coastal wetlands in the Ohio coastal area (for example) it is impossible to find wetlands that are currently in the condition that they might have been found in the early-1800s (i.e., pristine), but this is not to say that natural wetland conditions that may be desirable, but are not currently present in the landscape, cannot be used as a reference condition to compare to the current conditions found throughout the landscape. Thus, reference conditions are frequently thought of as the "least impacted" area or conditions for a specific geographic region. Understanding specific impairments to physical, chemical, and biological conditions is a precursor to determining appropriate improvements. Movement from any current condition toward a reference condition would be considered an improvement; movement away from the reference condition might be considered harm or degradation.

Habitat Suitability and Vulnerability

Habitat information about plants and wildlife species is frequently represented by scattered data sets collected during different seasons and years, and from different sites throughout the range of a species. A GIS-based model of habitat suitability (i.e., based on the physiological and sociobiological requirements of a species or taxa) and habitat vulnerability (i.e., potential for degradation) can present this broad database in a formal, logical, and simplified manner. Habitat models are a formalized synthesis of biological and habitat information and include many assumptions about the organization of the model components. Thus, such models should be regarded as hypotheses of species-habitat relationships, and not as a statement of proven cause and effect relationships, unless the metric model has been thoroughly tested using a valid statistical design. Habitat models may have merit in planning wildlife habitat research studies about a species, as well as providing an estimate of the relative suitability of habitat for that species (Rogers and Allen, 1987; Lopez *et al.*, 2003).

Data needs for developing and using a GIS habitat suitability or vulnerability model include bathymetric and topographic maps, aerial photographs, categorized satellite imagery, surface water area, streamflow, river stage, species-specific habitat requirements, historical precipitation, air or water temperature data, and potential for future precipitation and temperature. Vulnerability can be assessed by comparing habitat quality, availability, or distribution with historical and projected future conditions.

Water Quality and Hydrologic Impairment

Coastal wetlands of the Great Lakes have many of the same functions that all wetlands have, but their unique position in the landscape makes them a particularly important ecosystem for intercepting, transforming, and accumulating chemical constituents that flow from upland areas to the open water areas of the lakes. As the runoff passes through and/or is stored, coastal wetlands often transform and retain nutrients (e.g., nitrogen and phosphorus), some pollutants (e.g., pesticides or components of road runoff), and reduce the amount of sediment that might otherwise be transported beyond the coastal areas to open water areas.

Coastal wetlands in the Great Lakes may also function to ameliorate the erosional forces of waves, seiches, and other hydrologic changes in upland areas of the Great Lakes Basin. Changes in the hydroperiod of the lakes and coastal wetlands (that is, altered patterns of water levels and flows in and out of the wetlands) can quickly lead to a change in the vegetated communities of wetlands, which can, in turn, change the habitat structure of wetlands and potentially alter the flow of material in and out of the wetlands. Thus, the geomorphology or the hydrodynamics of coastal wetlands can be used to infer ecological conditions in the wetlands, primarily because of *in situ* research studies of processes and results.

Although a major factor in the assessment of coastal wetland condition in the Great Lakes, hydrologic alteration (i.e., impairments to the natural hydrologic regime) is not the sole factor controlling ecosystem functions. Thus, hydrologic regime is a dominant factor that should be used when designing a landscape ecological assessment of coastal wetlands because it is a master variable that drives variation in many other components of the ecosystem, for example, fish populations, vegetation composition, and nutrient cycling (Richter *et al.*, 2003). Because the linkages between hydrologic impairment and ecosystem impairment are well established (Bunn and Arthington, 2002), such linkages may be useful for inferring coastal wetland condition derived from remote sensing and GIS data that often contain spatial and temporal hydrologic information.

Effectively Completing and Conveying Ecological Assessments

A landscape ecological analysis can take many different forms, but may need to address very specific needs and audiences. Thus, a cost-effective technique for conveying landscape ecological assessment results is desirable and can be achieved by:

1) Selecting the minimum necessary metrics to address the basic questions of the research and/or regulatory goals.

2) Determining the key "next steps" that might be taken if additional funding is forthcoming, and which metrics might be the preliminarily assessed during the initial analyses stages of the project.

3) Reviewing and synthesizing the ecological, remote sensing, geostatistical, and other theory bases that might be necessary to explain the assessment results.

The culmination of the landscape ecological assessment requires a decision about what the best format for conveying the results of the study is, considering the research and policy goals of the audience. U.S. EPA's Office of Research and Development has developed the "Landscape Atlas" concept (Jones *et al.*, 1997; Lopez *et al.*, 2003), which communicates the complex analyses of remote sensing, GIS, and field-based information to a variety of users. The breadth and complexity of landscape ecological information may hinder some audience members when they are in need of immediate answers to their issues or in need of immediate information to convey to local and regional stakeholders. A landscape atlas integrates broad scale analysis results into a format that reduces the volume of data to a series of preselected maps, with standardized legends. The landscape atlas format can thus offer a series of informative maps that give the reader a general picture of the variety of ecological parameters across a common region, and pinpointing specific areas of interest depending on the audience.

It is also possible to explain ecological endpoints at a broad scale with greater ease by grouping the maps by common geographies or metric/indicator types. The atlas format allows for looking at assessment results among scales, and based on different important topics that relate to ecological vulnerability, among different maps, and it offers a way for the reader to compare metrics in a way that is most useful for particular needs (Lopez *et al.*, 2003). The maps are designed to give the reader an idea of the spatial distribution of ecological conditions relative to specific environmental values, at multiple scales, and/or during different historical periods.

A relatively recent advance in landscape atlases is the application of CD-based, digital video disk (DVD)-based, and Internet-based decision support tools, which incorporate the above-described maps in a format that is readily accessible to those using a personal computer with a CD drive, DVD drive, and an Internet connection, respectively. The advantage of these enhanced modes of data access is enabling the user to view large volumes of data, simulate analyses of the data, and download the data associated with maps so that they can perform their own analyses. Because data sets for the entire Great Lakes Basin require a tremendous amount of storage space and a tremendous amount of processing capability, it is preferable to prepare all of the possible metric maps for an area, and then deliver them to the public in one of these formats. As data become more uniform across the Great Lakes Basin or as specialized collaborations develop, the use of Internet-based (e.g., Internet-based mapping applications) decision support tools are likely to become more practical. A demonstration of using the CD format in the Great Lakes Basin is provided in Appendix A of this report, and will soon be incorporated on the U.S. EPA Web site (http://www.epa.gov/nerlesd1/land-sci/staff/lopez.htm).

Chapter 3

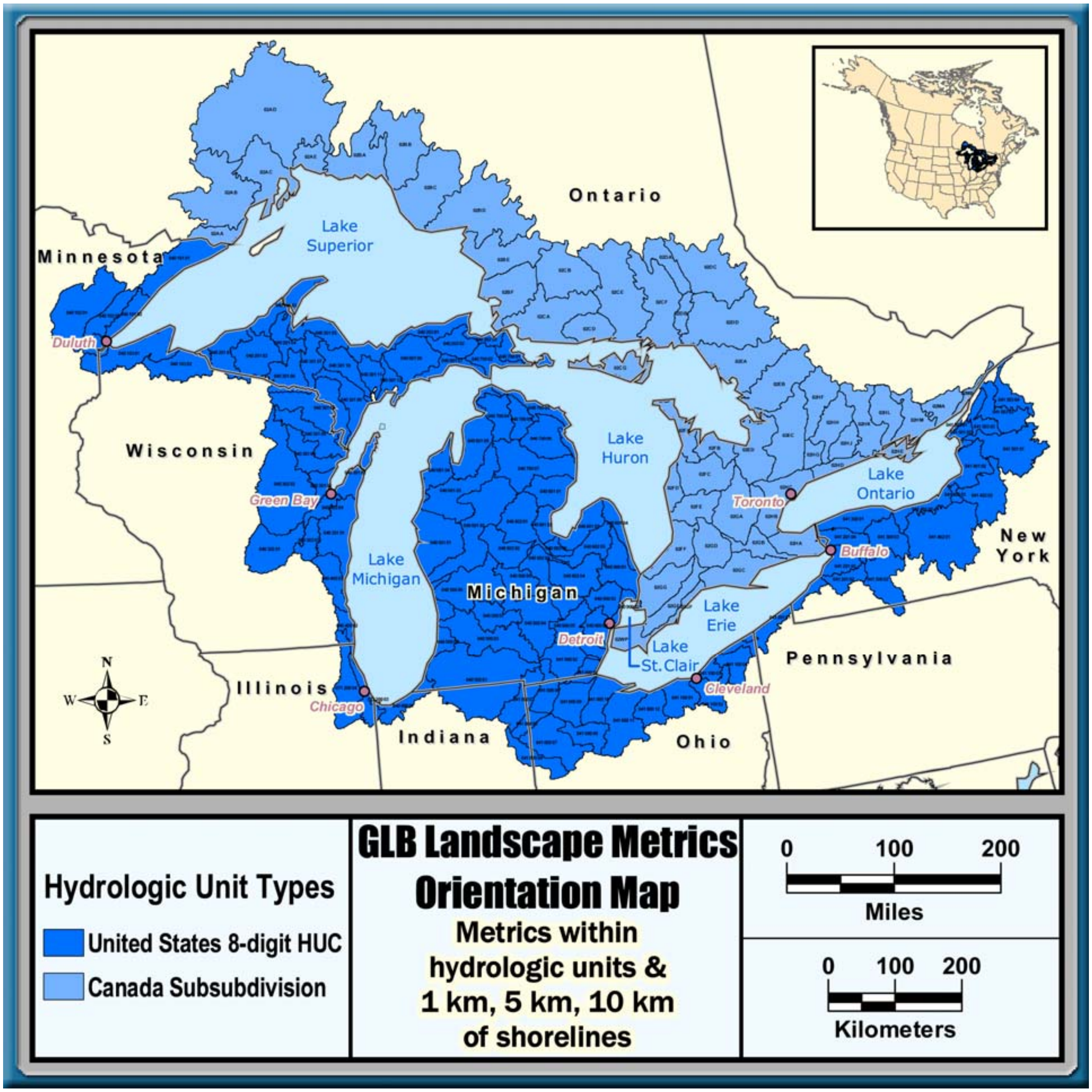
Using Landscape Metrics and Indicators in Great Lakes Coastal Wetlands

Additional metrics and information that could be used to address coastal wetland (and other ecosystem) assessment topics in the Great Lakes are provided in this report as a CD browser (Appendix A). Additional information and analyses of landscape metrics and landscape indicators are periodically updated and can be accessed by visiting the following Internet URL: http://www.epa.gov/nerlesd1/land-sci/wetlands.htm.

Study Area Description

The Great Lakes Basin (United States and Canada) was mapped using the landscape ecology approach described in the previous chapters (Figure 13). Landscape ecology metrics were mapped and interpreted among 8-digit Hydrologic Unit Codes in the United States and within hydrologic sub-subdivisions in Canada. Because there is a narrow strip of area on the perimeter of the Great Lakes where coastal wetlands exist, some landscape characteristics within this coastal strip are particularly important to quantify within the strip. Consequently, three coastal regions were selected to report relevant landscape metrics: (a) a 10-kilometer coastal region, most likely encompassing all of the coastal wetlands in the basin, and a large portion of the inland landscape that may influence these coastal wetlands; (b) a 5-kilometer coastal region, encompassing most all of the coastal wetlands in the basin, and a moderate portion of the inland landscape that may influence these coastal wetlands within the basin; and (c) a 1-kilometer coastal region, encompassing many, but not all of the larger coastal wetlands in the basin, and a minimal portion of the inland landscape that may influence these coastal wetlands. Although the 1-kilometer coastal region may not entirely capture all of the costal wetlands within the basin, it is most useful for inferring the potential for disturbance of some of the landscape metrics that describe land cover that can directly affect wetlands (e.g., road density and agricultural land cover metrics). The 1-kilometer coastal region is also included to provide information as per the recommendations of the State of the Lakes Ecosystem Conference and U.S. EPA's Great Lakes National Program Office, which heretofore have assessed the condition of the Great Lakes Basin within the 1-kilometer coastal region. Each of the coastal regions where landscape metrics are reported is also divided among the different hydrologic units of the Great Lakes Basin so that the calculations can be easily viewed and compared among them. Because the relatively narrow coastal regions are indistinguishable at the broad scale, and difficult to portray using a full-basin map (Figure 13), each of the metrics for coastal regions (where applicable) is reported by coloring the full hydrologic unit associated with that length of coastal area (see Chapter 3).

Thus, all maps of coastal and full hydrologic unit metrics are directly comparable, but the user must pay close attention to the legend to identify the scale of analysis, to which the map refers (Figure 14). Most of the maps in Chapter 3 describe landscape metrics within the full hydrologic unit (metrics related to water quality) and the 1-kilometer coastal region (metrics related to land cover). The metrics in the 1-kilometer coastal region in Chapter 3 are thus directly comparable, but additional analyses within the 5-kilometer and 10-kilometer coastal regions are available in Appendix A and may be useful for comparison among scales of analyses.


Ontario
Lake Superior
Minnesota
Duluth
Wisconsin
Lake Huron
Lake Ontario
Toronto
Green Bay
Buffalo
New York
Lake Michigan
Michigan
Lake Erie
Detroit
Lake St.Clair
Pennsylvania
Illinois
Chicago
Cleveland
Indiana
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Hydrologic Unit Types
United States 8-digit HUC
Canada Subsubdivision
GLB Landscape Metrics Orientation Map
Metrics within hydrologic units & 1 km, 5 km, 10 km of shorelines
0
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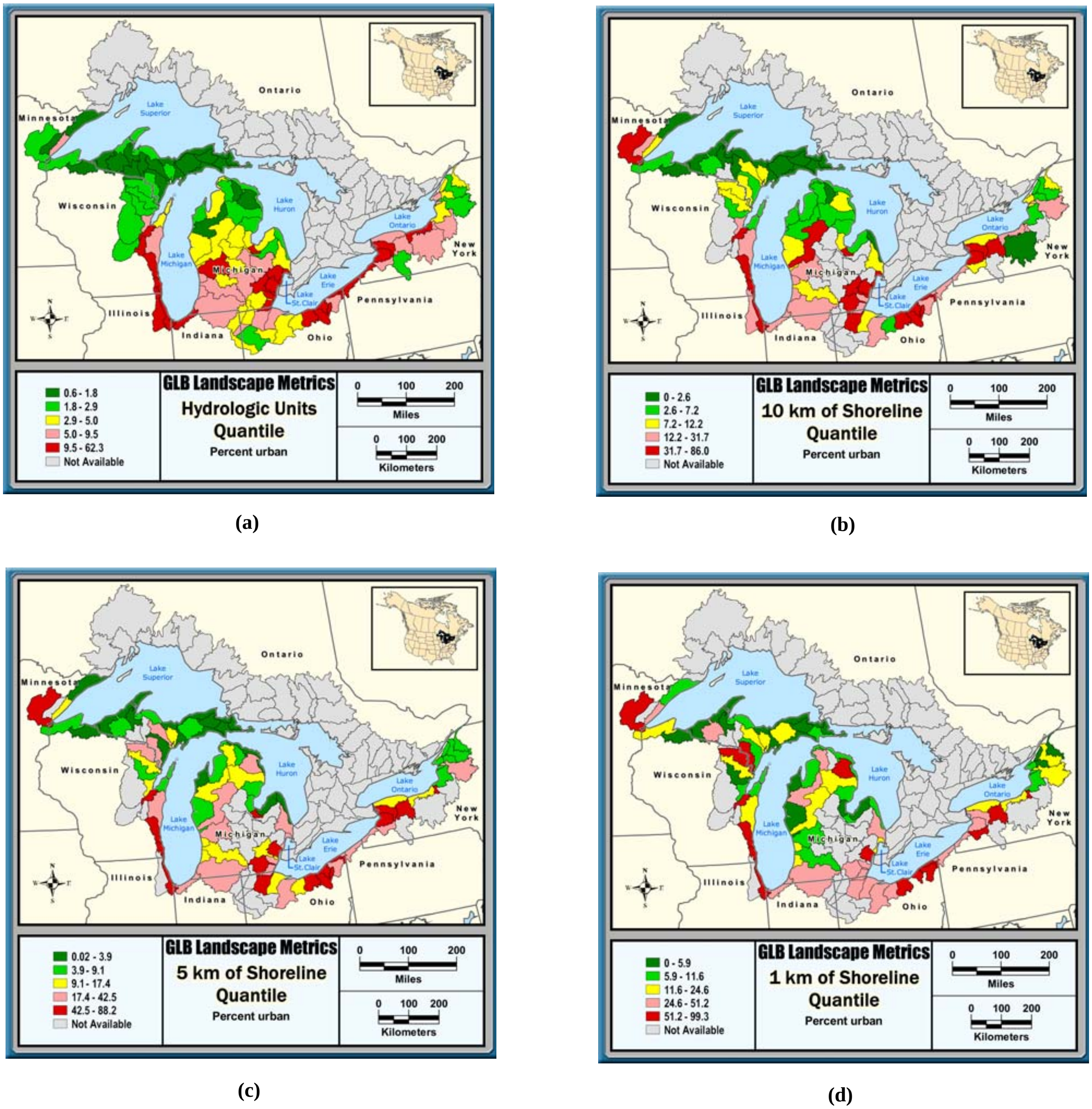


Figure 14. Regions within each of the (a) full hydrologic units, (b) 10-kilometer, (c) 5-kilometer, and (d) 1-kilometer regions of the Great Lakes Basin (shown solely here for the United States) are mapped in Chapter 3 and Appendix A of this report. Because the relatively narrow coastal regions are indistinguishable at the broad scale, and difficult to portray using a full-basin map, each of the metrics in this report (where applicable) is reported by coloring the full hydrologic unit associated with that length of coastal area per the legend color described for each metric.

Ecological Vulnerability of Great Lakes Coastal Wetlands

Coastal wetlands of the Great Lakes Basin are vulnerable to loss or degradation as a result of the interaction of naturally occurring conditions and human activities in the Great Lakes Basin (Table 3). Wetlands that are degraded as a result of conditions within the Great Lakes Basin may continue to function, but at a reduced functional level. Not all wetlands remain after these functional changes occur with some coastal wetlands losing their ecological functions quickly, and some ceasing to function altogether (i.e., wetland loss). Wetlands may flourish in conditions that fluctuate in their conditional state; for example, some coastal wetlands depend on periodic changes between standing water and exposed soil, which tends to increase the diversity of plants, which in turn supports wetland-independent animal habitat. Thus, periodic wetland disturbances may allow for the formation of relatively small, interconnected metapopulations, where gene flow between plant patches or wetlands maintains the genetic diversity that might otherwise decline in relatively large inbred populations. When such populations become unable to bridge the gaps between populations, at the advanced stages of patch isolation, entire populations may become locally extinct (Opdam, 1990). Water-level fluctuations also promote the interaction of aquatic and terrestrial ecosystems, and can result in higher quality habitat and increased productivity.

Environmental changes that can directly influence coastal wetland condition (such as dredging, filling, draining, and species invasion) originate in the wetland itself and are therefore easier to pinpoint than indirect environmental changes. Direct environmental changes in coastal wetlands are often human-induced, highly visible, and can result in rapid changes to wetlands. Indirect environmental changes are often less pronounced, potentially causing changes in wetland function and vegetation communities over a longer period of time. Indirect environmental changes are physically removed from a wetland, and thus it may be difficult to pinpoint the exact source of the environmental change. Indirect environmental changes include urban and agricultural runoff. Indirect environmental changes are relatively difficult to control, due to their diffuse and variable sources (Environment Canada, 2002). Human-induced environmental change factors described in this report are based on previously observed positive correlations between ecosystem degradation and amount of land cover conversion during road construction, road maintenance, and other human-activities (e.g., Connell and Slatyer, 1977; van der Valk, 1981; Ehrenfeld, 1983; Johnston, 1989; Scott *et al.*, 1993; Johnston, 1994; Poiani and Dixon, 1995; Jenning, 1995; Wilcox, 1995; Ogutu, 1996; Stiling, 1996; Heggem *et al.*, 2000; Lopez *et al.*, 2002; Lopez and Fennessy, 2002).

The spatial configuration of coastal wetlands (i.e., size, shape, and interspersion within the larger landscape) is an important consideration, since larger wetlands may be relatively more likely to persist in the face of environmental changes. Wetlands of various sizes also attract different species, and a range of sizes may increase the diversity of habitat types across a broad area. For example, some birds (e.g., black tern, Forster's tern and short-eared owl) may require a sufficiently large size before they will make use of it for nesting (Environment Canada, 1998). Mitsch and Gosselink (2000) have described wetlands as spatially and temporally dynamic habitats, and thus the boundaries of coastal wetlands could be affected by the combined geological and hydrological processes associated with erosion and deposition, changing biological processes in the process. Wetland size and proximity metrics used in this report and Appendix A are based on previously observed trends regarding the effects of patch size, patch shape, and the interspersion of ecosystems within the broader landscape for specific taxa, in many different regions (e.g., MacArthur and Wilson, 1967; Simberloff and Wilson, 1970; Diamond, 1974; Forman *et al.*, 1976; Pickett and Thompson, 1978; Soule *et al.*, 1979; Hermy and Stieperaere, 1981; van der Valk, 1981; Simberloff and Abele, 1982; McDonnell and Stiles, 1983; Harris, 1984; McDonnell, 1984; Moller and Rordam, 1985; Brown and Dinsmore, 1986; Dzwonko and Loster, 1988; Gutzwiller and Anderson, 1992; Opdam *et al.*, 1993; Hamazaki, 1996; Kellman, 1996; Bastin and Thomas, 1999; McIntyre and Wiens, 1999a; McIntyre and Wiens, 1999b; Twedt and Loesch, 1999; Jones *et al.*, 2000; Lopez *et al.*, 2002; Lopez and Fennessy, 2002).

Table 3. Environmental conditions in the Great Lakes Basin and some of the potential affects upon coastal wetlands.

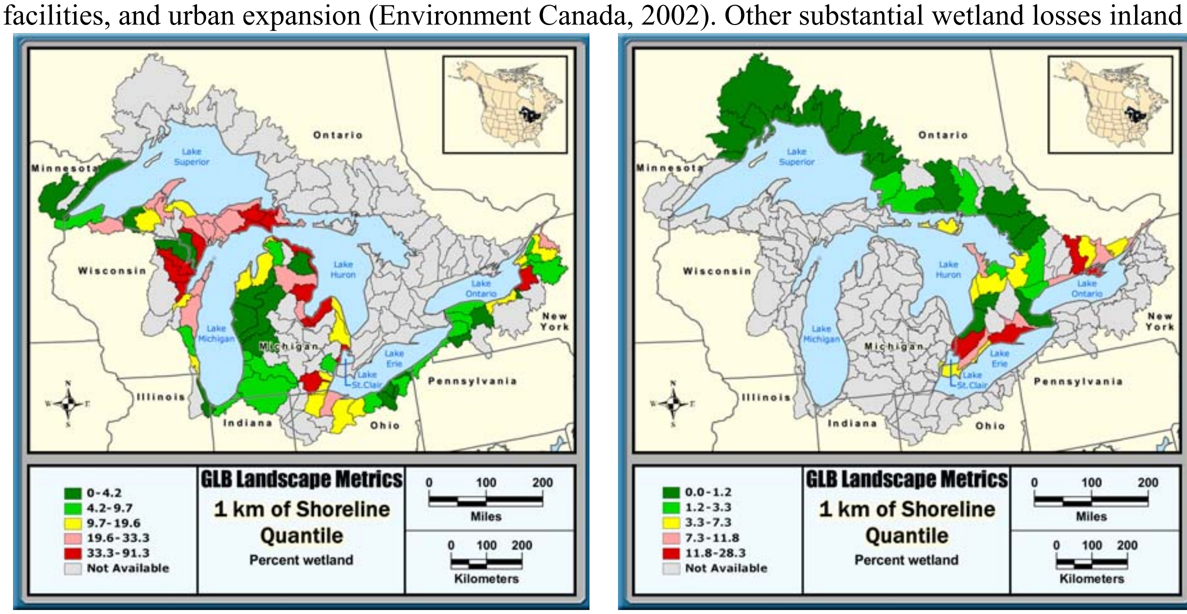
GLB Environmental Condition	Potential Coastal Wetland Affect(s)
Adjacent urbanization	Peak flows of runoff from paved urban areas may rapidly pulse through wetland and increase the amount of metals, oils, salts, or other contaminants into, or flowing out of, wetlands to open lake areas
Change in magnitude and/or duration and/or frequency of water levels	Changed competitive or successional processes that may result in changed species diversity in fish, amphibian, bird, plant, or other community structure
Change in wetland vegetation, e.g., change in proportion of wetland open water and emergent vegetation	Loss of optimum habitat for some species of fish, waterfowl, and other marsh birds
Chemical/oil spill	Death of wetland organisms
Dredging	Deepening water and removal of sediments can result in loss of wetland habitat
Early ice breakup, early peaks in spring runoff, change in the timing of stream flow, and increased intensity of rainstorms	Fewer viable breeding sites, especially for amphibians, migratory shorebirds, and waterfowl; northern migratory species (e.g., Canada geese) winter further north; increased flooding frequency in coastal areas
Habitat loss and fragmentation	Decrease in the available aquatic habitat for organisms, especially affecting species with limited dispersal capabilities (e.g., amphibians and mollusks)
Mechanical clearing of wetland vegetation	Creation of impassable areas for some species, thus isolating populations and increasing likelihood of extirpation
Over-harvesting of resources	Depletion of recreationally or commercially valuable species
Reduced summer water levels	Reduction in the total area of wetlands, resulting in poorer water quality and less habitat for wildlife
Removal of tree cover and shoreline vegetation	Increased runoff into wetland from adjacent land
Runoff and pollutants from agricultural areas, sewage treatment outflows, stormwater outputs, urbanized areas, industrial outfalls, and other sources in watershed	Increased loading of nutrients, sediments, and toxic chemicals in downstream wetlands; reduced water clarity
Shoreline modification; wetland filling or drainage	Physical destruction or reduction in protection of coastal regions to erosion
Species invasion and spread (e.g., carp, zebra mussel, common reed, purple loosestrife)	Feeding, spawning, and nesting behavior of animals may interfere with plant photosynthesis/growth; nonnative animals may prey upon native animal species or outcompete them for food and habitat; plants may not provide suitable forage, nesting, reproduction
Storms and seiches	Damage to vegetation due to high winds and waves

The spatial configuration of coastal wetlands within the larger landscape is also important because wetland vulnerability (i.e., the risk of wetland loss or degradation) can be initially evaluated by investigating these spatial interrelationships. Measurement of the spatial configuration of coastal wetland size, shape, inter-wetland spacing, proximity to non-wetland land cover, and variations of these metrics are important because these metrics may foretell the likelihood that a particular wetland will rebound after a disturbance. That is, an *a priori* understanding of wetland ecosystem characteristics, and specific landscape metrics can be used to address ecological endpoints that predict habitat degradation as a result of wetland destruction, fragmentation, or degradation. Accordingly, we begin this overview by describing wetland area, followed by a sample of the other wetland metrics that are described in detail in Appendix A.

Areal Extent of Great Lakes Coastal Wetlands

The extent of coastal wetlands (i.e., wetlands within 1-kilometer of the coastline of the Great Lakes) is shown in Figure 15. Relatively large coastal wetlands may extend further inland than 1-kilometer. Thus they are mapped within a 5-kilometer coastal region in Appendix A; however, this may include non-coastal areas too. The differences between coastal wetland areal coverage among watersheds and coastal region areas can be used to interpret other metrics and to prioritize all of the Great Lakes coastal areas for more detailed analyses.

Prior to European settlement, the extent of wetlands in the Great Lakes Basin spanned large areas from the western edge of Lake Erie, across Ohio and Indiana, and covering the southern portion of the Province of Ontario. It is estimated that two-thirds of Great Lakes coastal wetlands have been lost since European settlement. Many of these areas have been drained or reclaimed for land development, farmland, harbor facilities, and urban expansion (Environment Canada, 2002). Other substantial wetland losses inland from



(a) (b)

Figure 15. Areal extent of coastal wetlands is mapped here as percent of 1-kilometer coastal region among coastal watersheds in the United States (a) and Canada (b). Percent coastal wetland is calculated by dividing the number of wetland land cover cells in the coastal region of each watershed (i.e., the reporting unit) by the total number of land cover cells in the reporting unit minus those cells classified as water. This measurement has potential for measuring and comparing wetland contribution among watersheds and may be used to indicate potential for wetland removal or reduction in the amount of pollutants entering the Great Lakes. The relative extent of coastal wetlands may also be developed into a quantitative indicator of habitat for a wide variety of plant and animal species.

the coast of the Great Lakes may contribute to the degradation of coastal wetlands as a result of sub-urbanization, dam construction, stream alteration, and the construction of flood control structures that alter the hydrology of contributing watersheds (Cox and Cintrón, 1997).

Between the 1780s and the 1980s, the largest reductions of coastal wetlands occurred in Ohio (U.S. EPA 2001b). Urban development along the shores of the Great Lakes generally reflects the history of human decision-making processes that necessitated safe and efficient harbors for the distribution of natural resources, such as timber and mineral ores. As a result of these decisions, the areal extent of coastal wetlands has been dramatically reduced by the conversion to, and to some extent by the indirect effects of, urban and agricultural land use (U.S. EPA, 2002a).

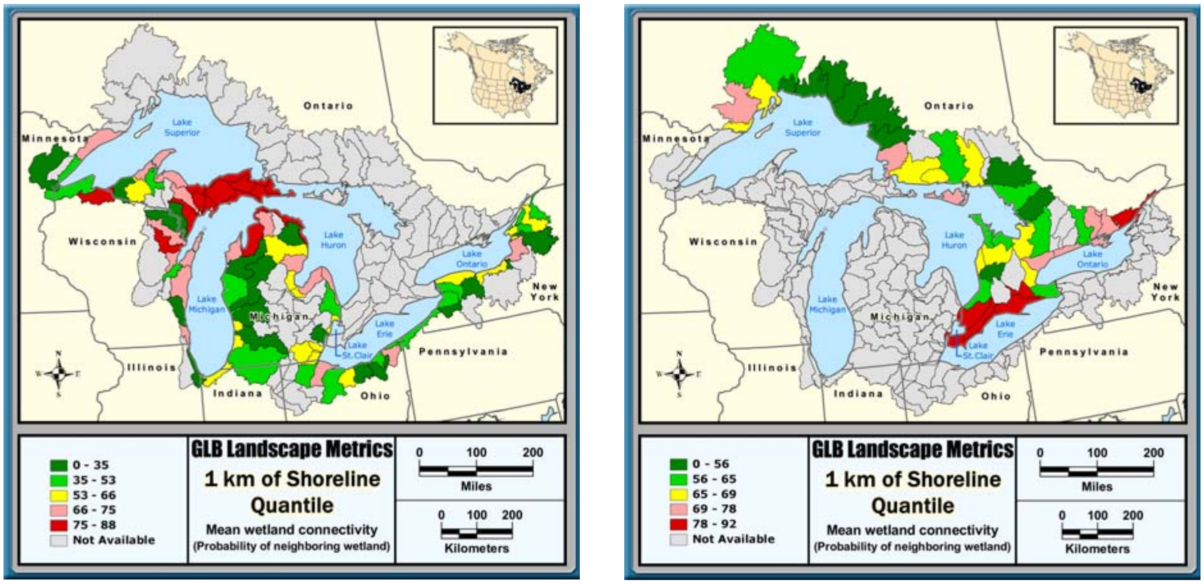
Inter-Wetland Spacing and Landscape Integration

Interconnected wetland patches function as a network (e.g., within a watershed or migratory bird flyway), and have the cumulative functional capability of all the individual wetlands. A collection of wetlands in the landscape may be particularly important for providing a vital ecological unit for some animals, while other animals may require a mixture of wetland and upland areas for different portions of their life cycle or their daily activities (e.g., a species that reproduces in wetlands and forages in upland areas). The absence of such wetland complexes or integrated upland and wetland conditions may completely interrupt or degrade the reproduction rates, survival rates, and overall fitness of some plant and animal species.

Fragmentation of the landscape may result in the isolation of coastal wetlands, with the remnants of the formerly larger interconnected wetland complexes being replaced by less heterogeneous landscapes that are dominated by either agricultural land, urban or rural human habitations, and industrial land. Such conversions of wetland to other land cover types may reduce the functional capability of coastal wetlands and may have also increased the likelihood that the remaining wetlands are further affected by the new land cover type (Tiner *et al.*, 2002). Thus, as the general concept of ecosystem integrity describes, the capability of coastal wetlands to continue to function and provide ecological services to the residents of the Great Lakes (e.g., improving and maintaining clean water; providing critical habitat for plants and animals; and shoreline stabilization and protection) is dependent upon the effects of the surrounding landscape.

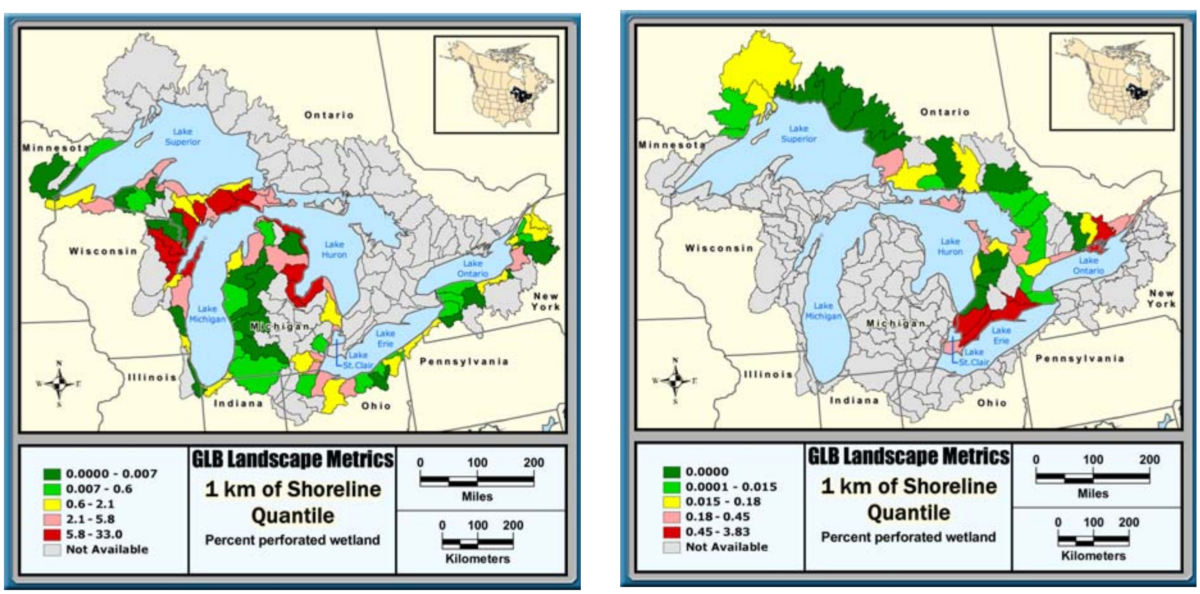
Wetland interconnectivity is one way of measuring the fragmentation of coastal wetlands in Great Lakes coastal regions (Figure 16). A standard and uniform method for measuring wetland interconnectivity in the coastal region (e.g., within 1-kilometers of the shoreline) is to determine the probability of wetland area cell having a neighboring wetland, using a “moving window” over a GIS data set (i.e., a 9 pixel x 9 pixel area in Figure 16). Thus, the boundaries between all pixel pairs, where at least one pixel is wetland, were examined in the moving window. The interconnectivity metric is the number of boundaries where both pixels are wetland, divided by the total number of wetland boundaries (regardless of neighbor land cover type). This metric gives a measure of how well the wetland is connected within the window sample area, with high values being better connected than low values.

The relative percentage of “perforated” wetland is another measurement of ecosystem fragmentation (Turner *et al.*, 2001), and is calculated here by using a moving 270-meter-square window (i.e., 9 pixel x 9 pixel) across the GIS land cover data set (Figure 17). When the percent wetland in the window is greater



(a) (b)

Figure 16. Mean wetland connectivity in a 1-kilometer coastal region of the Great Lakes Basin (probability of neighboring wetland), which is the mean (for a reporting unit) probability of a wetland cell having a neighboring wetland cell, calculated using a moving 270-meter-square window (9 pixels x 9 pixels) across the GIS land cover data set. Because these analyses use two differing land cover data sets, results for (a) the U.S. and (b) Canada may not be directly comparable.



(a) (b)

Figure 17. Percentage of perforated wetland, in a 1-kilometer coastal region of the Great Lakes Basin, is calculated using a moving 270-meter-square window (9 pixels x 9 pixels) across the land cover, and generally indicates if center upland area(s) are present in a wetland. Because these analyses use two differing land cover data sets, results for (a) the U.S. and (b) Canada may not be directly comparable.

than 60%, and greater than the window's mean wetland connectivity value (Figure 16), the wetland cell in the center of the window is categorized as perforated. The number of perforated wetland cells in the reporting unit is then divided by the reporting unit's total land area (i.e., the total number of cells in the reporting unit boundary minus those cells classified as water) to derive the percentage of perforated wetland. Perforated wetland generally consists of a patch of wetland with center upland area(s), such as would occur if small clearing(s) were made within a patch of wetland, or if an area of wetland contained an interior upland region. Perforated wetlands may be fragmented in this fashion to such an extent that they do not provide suitable interior habitat for some wetland species. However, the interspersion of upland and wetland conditions in perforated wetlands may provide suitable habitat for some specialized plants and animals that require fluctuating wetland conditions and isolated upland areas. Thus, high perforation values may be considered as detrimental for some ecological functions and species and advantageous for others.

Fragmentation of coastal wetlands may lead to increased inter-wetland distances because of the increases in the incidence and extent of other land cover types developing in the intervening spaces (e.g., farm land or human habitations). Accordingly, mean distance to closest like-type wetland (Figure 18) is an important metric because it may indicate the likelihood of nearby similar wetland habitat (e.g., neighboring emergent-emergent wetlands for migratory bird resting and foraging or neighboring forest-forest wetlands for migratory song bird resting and foraging). The mean (for a reporting unit) minimum distance to closest wetland patch, e.g., the distance from each wetland patch to its nearest neighboring wetland patch, should be measured from one patch edge to another patch edge, and may consist of multiple measures (e.g., mean of three nearest patches). This metric is useful in determining relative wetland habitat suitability at scales that are ecologically meaningful for specific plant and animal taxa, and demonstrates the importance of establishing the ecological endpoint(s) of interest prior to full development of this indicator.

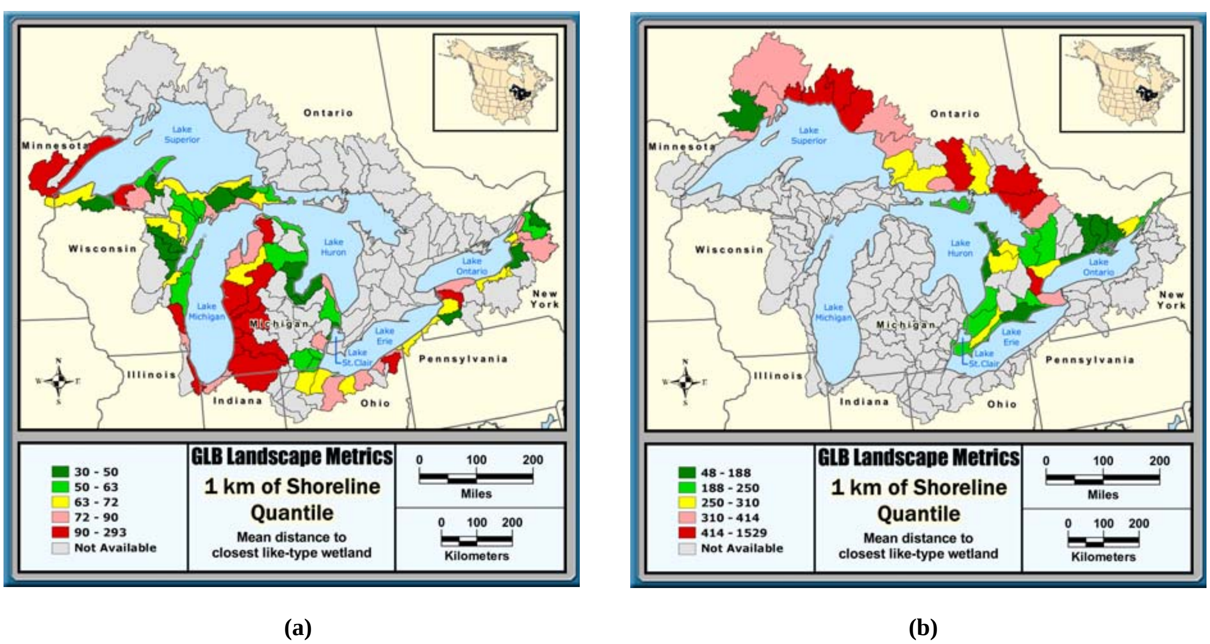
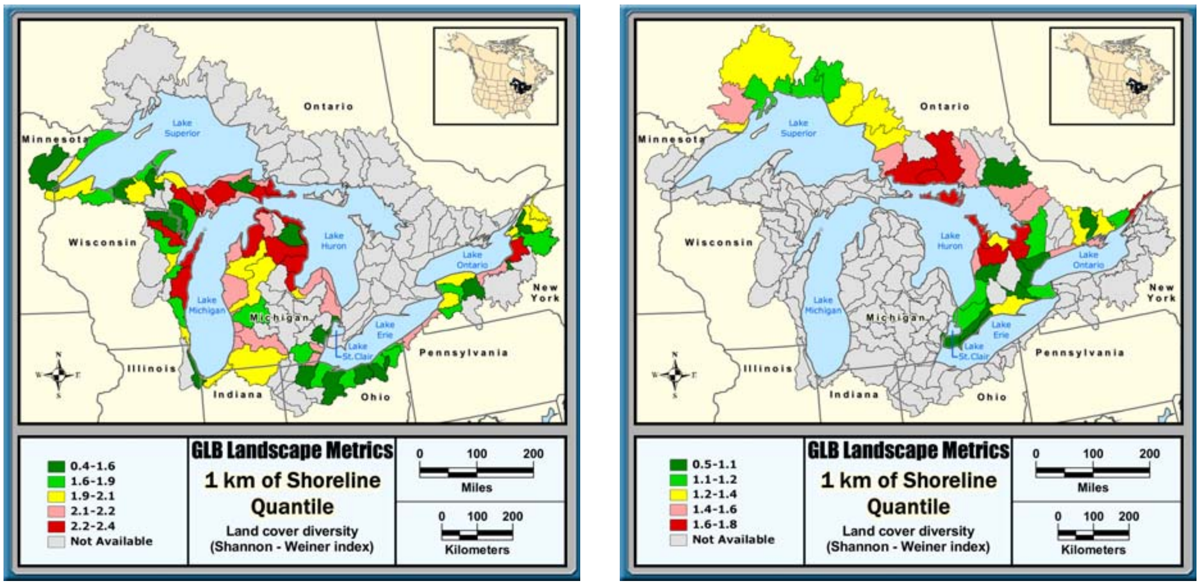


Figure 18. Mean distance to closest like-type wetland, in a 1-kilometer coastal region of the Great Lakes Basin, is the mean minimum distance to closest wetland patch, for the 1-kilometer shore area, within each hydrologic unit. Distances were measured from edge to edge and are reported in meters. This metric is useful in determining relative wetland habitat suitability at scales that are ecologically meaningful for specific plant and animal taxa. Because these analyses use two differing land cover data sets, results for (a) the U.S. and (b) Canada may not be directly comparable.

The Shannon-Wiener index and Simpson's Index are two different ways of measuring the diversity and distribution of land cover types within a specific area of the landscape. The Shannon-Wiener Index of land cover type diversity (Figure 19) is calculated as:

$$H = -\sum_{i=1}^{m} P_i * \ln P_i$$

, where P_i = the proportion of land cover type i.



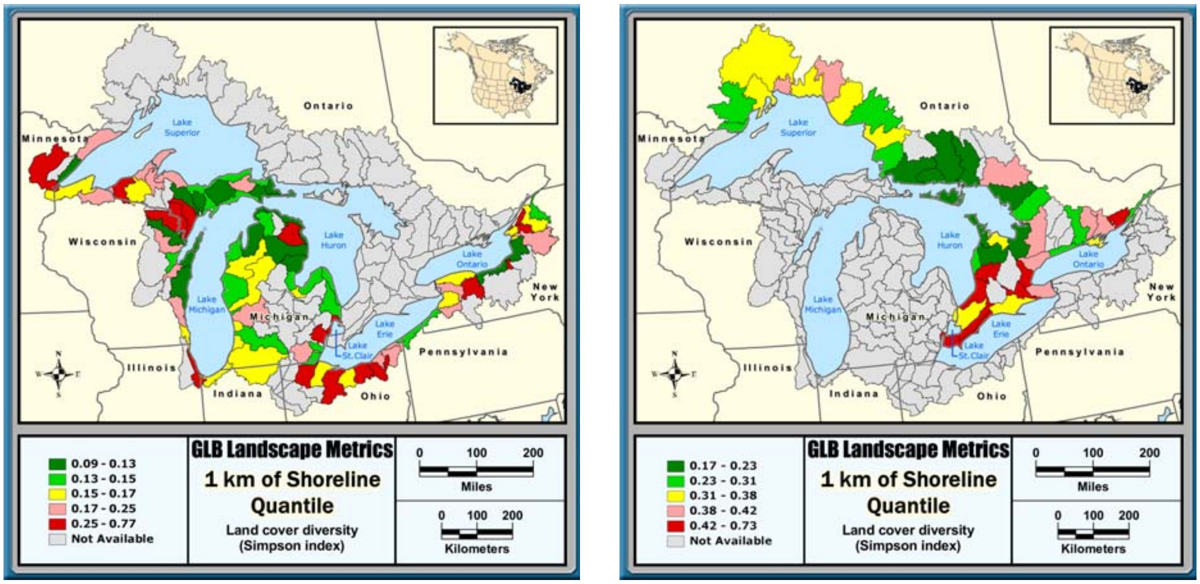
(a) **(b)**

Figure 19. The Shannon-Wiener Index, in a 1-kilometer coastal region of the Great Lakes Basin, is one of several ways to measure the diversity of land cover types within a specific area of the landscape. The Shannon-Wiener Index value increases as the number of land cover types within the reporting unit increases. Because these analyses use two differing land cover data sets, results for (a) the U.S. and (b) Canada may not be directly comparable.

Shannon-Wiener Index values increase as the number of land-cover types within the reporting unit increases, with higher value coastal areas having more diverse land cover (i.e., more diversity) than areas with lower values. Because higher Shannon-Wiener diversity in coastal areas does not always indicate greater opportunities for variety of species (i.e., land cover diversity includes agriculture and urban), Simpson's Index (Figure 20) can be used to better describe the distribution of the land cover in a coastal region. Simpson's Index is a quantitative measure of the evenness of the distribution of land-cover classes and is most sensitive to the presence of common land-cover types within a reporting unit. Simpson's Index values range from 0 to 1, with 1 representing perfect evenness of all land cover types within a reporting unit. Simpson's Index is calculated as:

$$C = 1 - \sum_{i=1}^{m} P_i^{\,2}$$

, where P_i = the proportion of land cover type i.



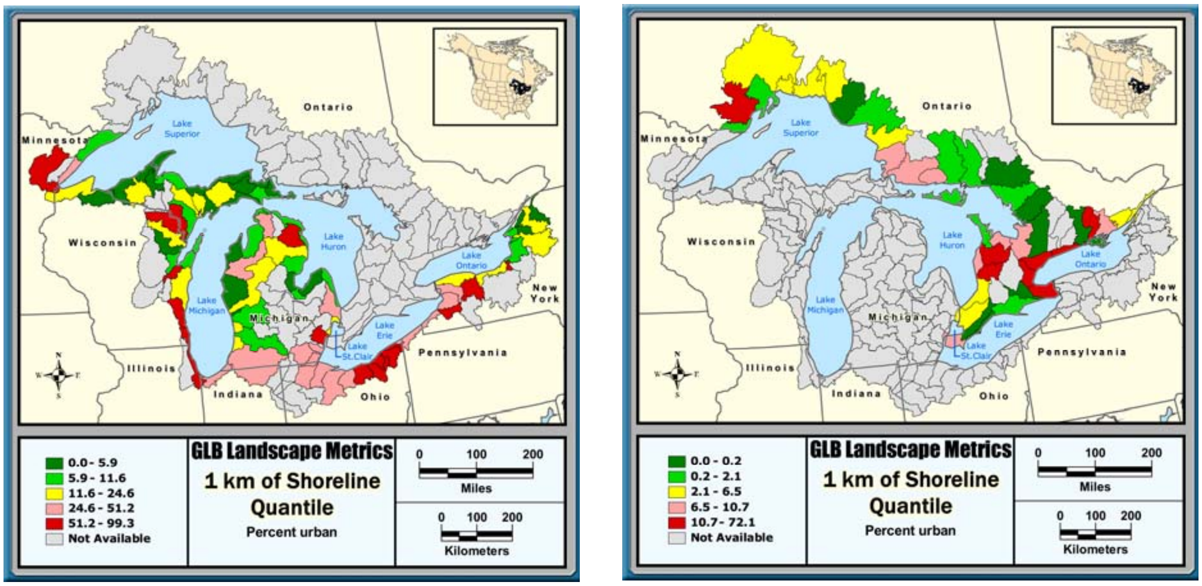
(a) **(b)**

Figure 20. Simpson's Index, in a 1-kilometer coastal region of the Great Lakes Basin, is a measure of the diversity of land-cover types within a specific area of the landscape. Simpson's Index is a measure of the evenness of the distribution of land-cover classes. Because these analyses use two differing land cover data sets, results for (a) the U.S. and (b) Canada may not be directly comparable.

Proximity of Land Cover and Land Use to Coastal Wetlands

The coastal region of the Great Lakes has been an attractive location for development during the history of settlement and expansion of societies. The shorelines are a focus of human activities because they are near water, which provides unique transportation functions, resources for manufacturing, recreational opportunities, residential uses, and drinking water resources. The transportation services in combination with the close proximity to productive farmland, raw materials, and an ever-growing inland infrastructure makes the coastal areas an unparalleled area to economically exploit. Thus, there may be conflicts between preserving the remaining coastal wetlands and developing these areas for additional commercial and societal needs. Coastal wetland areas that are close to urbanization (Figure 21) or human population centers (Figure 22) may be sensitive natural areas and affected by human land use associated with urban and suburban activities.

An example of the effects of coastal wetland disturbance is an increased expansion of invasive or opportunistic plants into landscape gaps (i.e., within and between wetlands), which may be the result of increased land-cover fragmentation (Forman, 1995). The patch dynamics (i.e., either increases or decreases in extent) of invasive and opportunistic plant species (Lopez and Nash, manuscript in review) in disturbed Great Lakes coastal areas may be facilitated by the extent and intensity of wetland patch disturbance that results from human fragmentation of the landscape, resulting in hydrologic alteration (e.g., road construction). Because species-level assessments may not be possible using satellite, or other coarse scale remote sensing data (i.e., spatial or spectral resolution data), it may be necessary to map invasive or opportunistic species using finer scale remote sensing data (see Chapter 3, remote sensing data types). Chapter 4 provides a specific example of how to implement a broad scale coastal wetland assessment, using a combination of hyperspectral and fine-scale airborne multispectral data, GIS, and detailed field-based sampling. This mapping approach is the preliminary step necessary to determine



(a) **(b)**

Figure 21. The percentage of urban land cover, in a 1-kilometer coastal region of the Great Lakes Basin, is calculated by dividing the number of urban land-cover cells in the reporting unit by the total number of land-cover cells in the reporting unit minus those cells classified as water (i.e., total land area). High amounts of urban land indicate substantial modification of natural vegetation cover and may affect the condition of wildlife habitat, soil erosion, and water quality in coastal areas. Because these analyses use two differing land cover data sets, results for (a) the U.S. and (b) Canada may not be directly comparable.

potential causal relationships between landscape disturbance (determined from landscape metrics describe in this chapter) and the receptor variables, e.g., the influx and spread of invasive and opportunistic plants in coastal wetlands.

Data about the land cover and land use that is in the vicinity or directly adjacent to coastal wetlands may be important indicators of the level of disturbance within a wetland. For example, paved surfaces (e.g., roads; Figure 23) increase the impermeability (Figure 24) of land surfaces and may increase the amount of runoff to streams, lakes, and wetlands, and potentially increase the transport of road salts or other chemicals from paved surfaces (e.g., trace metals and hydrocarbons). Roads also fragment habitat and may act as barriers to animal movement (e.g., amphibians or large mammals).

Land use in a particular watershed may also have a significant influence on the flow of runoff and sediments toward coastal areas, and may be indicative of the amount of runoff that is intercepted by coastal (and other) wetlands. The capability of such wetlands to accumulate, transform, and/or store pollutants that are transported in the runoff from the inland areas of the watershed is an important mechanism for maintaining and improving the water quality of the Great Lakes. Wetlands that are adjacent to other habitats and that provide connections between other habitats in the watershed are also more likely to maintain their normal hydrologic regime, which may moderate the amount of water, sediment, and chemical constituents that are directly input into the open water areas of the lakes. Thus, areas that are relatively more developed and intensively used for agriculture may have increased rates of runoff and sediment loading to the Great Lakes. However, if coastal wetlands, situated between upland urban or agricultural areas, are present the runoff and sediment loading may be reduced. However, wetlands in close proximity to urban or agricultural land (Figure 25) may be at greater risk of loss or degradation as a result of hyper-eutrophication or pollution. Wetlands that are adjacent to urban land cover (Figure 26) may also provide poor animal habitat relative to wetlands adjacent to natural land cover, such as forests.

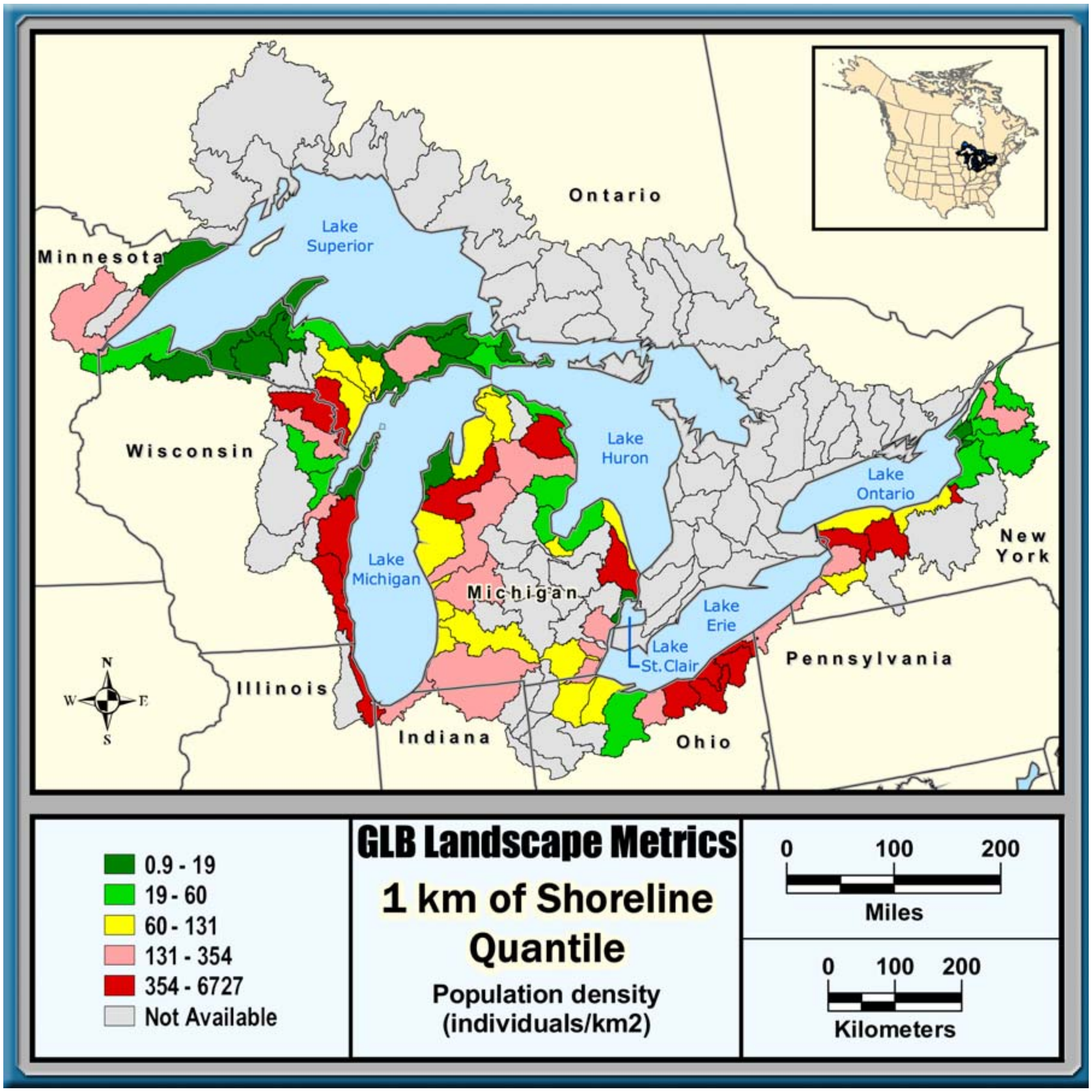


Figure 22. Human population density (individuals/km^2) approximated in the 1-kilometer coastal region of the Great Lakes Basin. Population density is calculated by summing the number of people living in the reporting unit and dividing by the reporting unit area. Where census units are not completely contained within the reporting unit, population is apportioned by area. High population densities are generally well correlated with high amounts of human land uses, especially urban and residential development. Large areas of development often involve substantial modification of natural vegetation cover that may have substantial effects on wildlife habitat, soil erosion, and water quality.

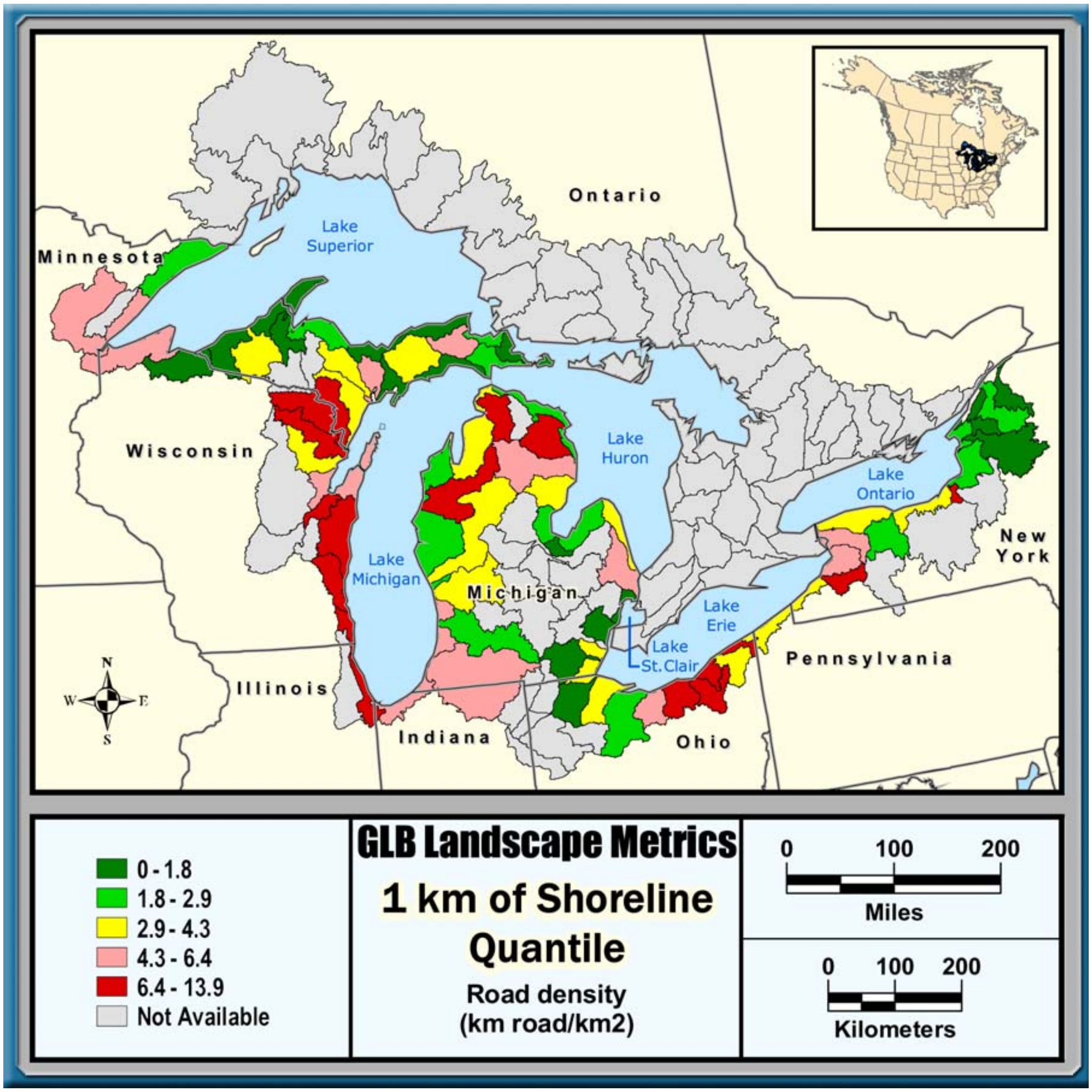


Figure 23. Road density (km road/km^2) in a 1-kilometer coastal region of the Great Lakes Basin. The density of roads is calculated by summing the length of roads and dividing by the area of the reporting unit. Values are reported as length of all road types (i.e., freeways, highways, surface streets, rural routes, and other roadways) per reporting unit area. High total road densities are generally well correlated with high human population and urban development in the coastal region.

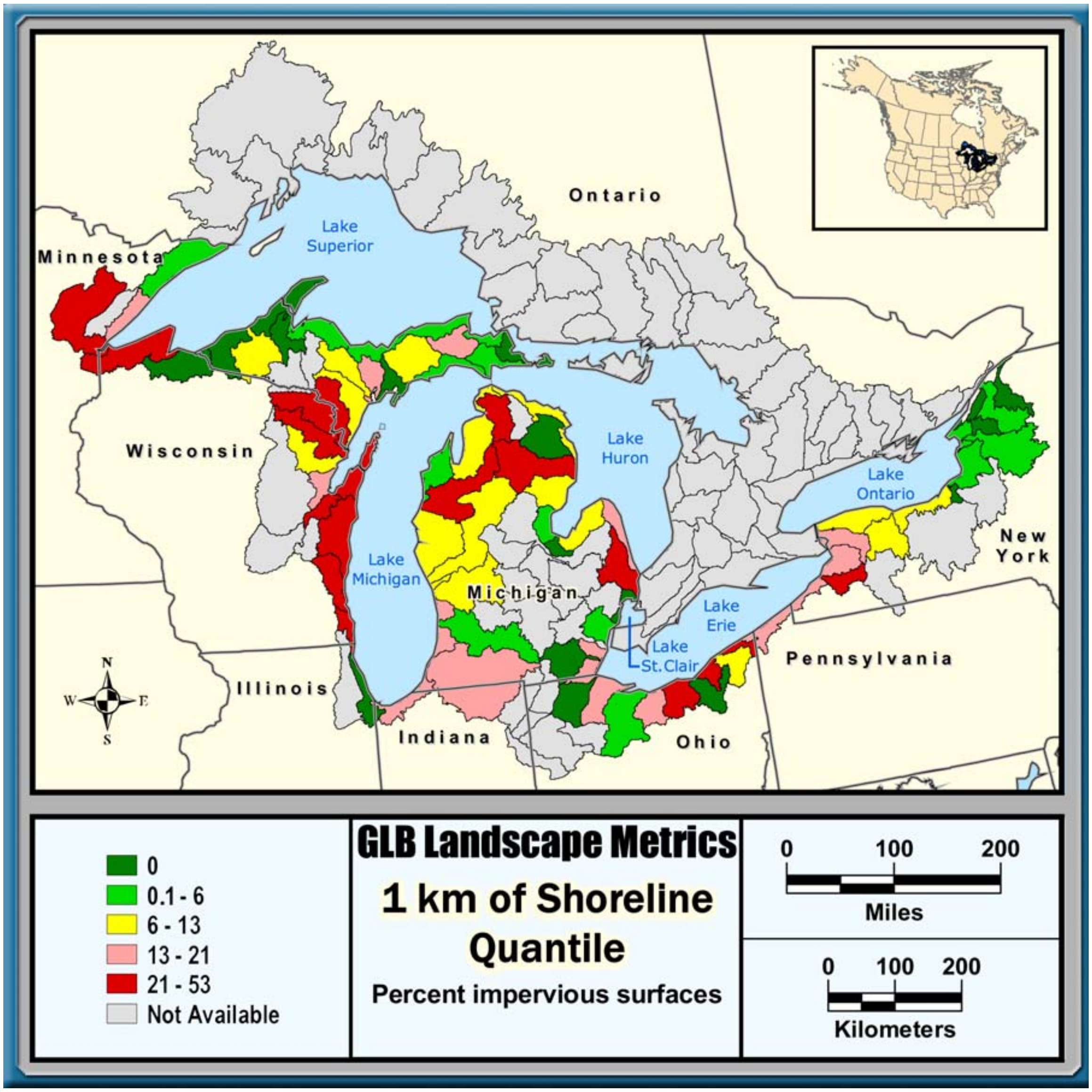


Figure 24. Percent impervious surfaces are mapped within a 1-kilometer coastal region of the Great Lakes Basin (U.S. side). The percent of total impervious area is calculated using road density as the independent variable in a linear regression model (May *et al.*, 1997).

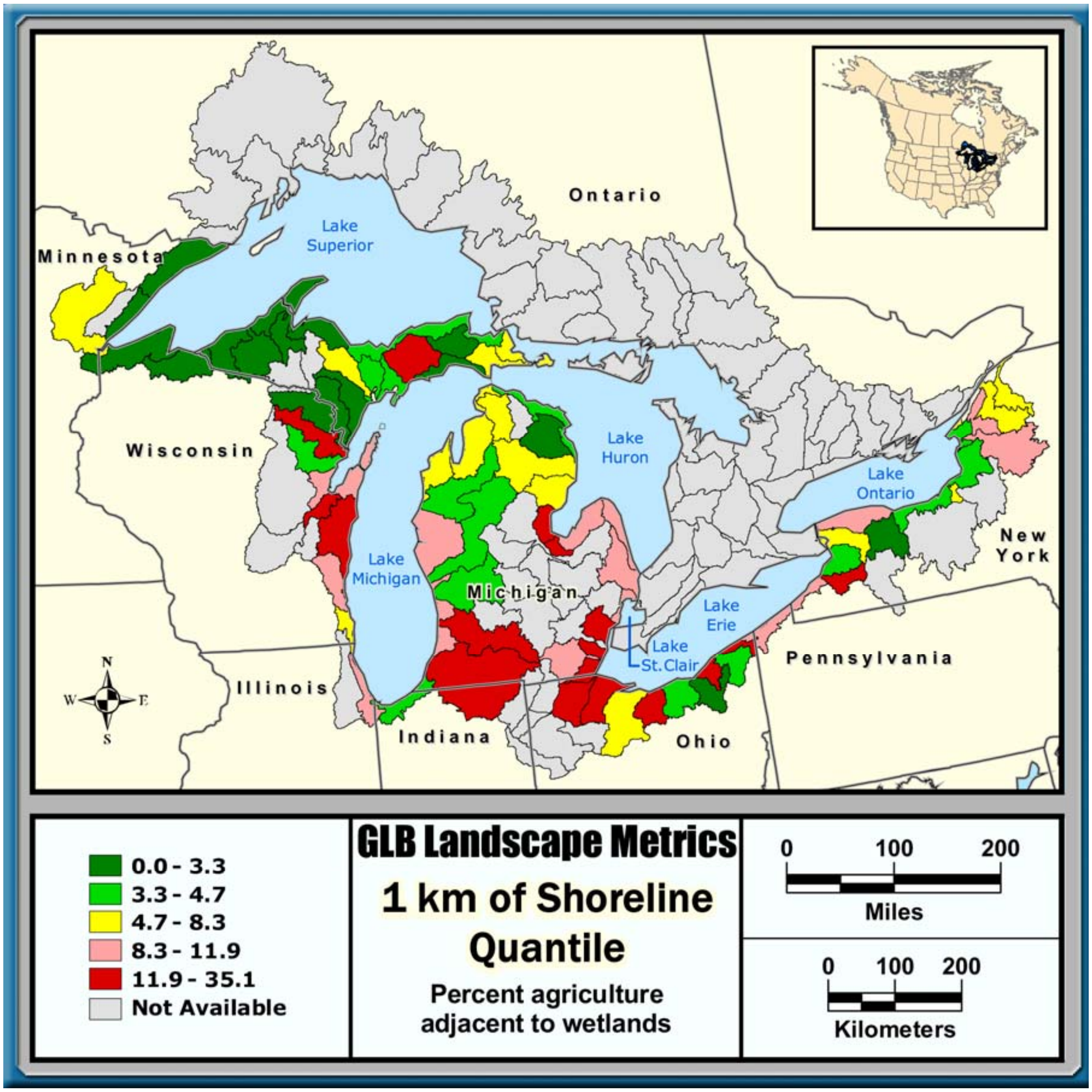


Figure 25. Percent agriculture adjacent to wetlands is mapped within a 1-kilometer coastal region of the Great Lakes Basin (U.S. side). The percentage of all agricultural land cover adjacent to wetlands is calculated by summing the total number of pasture and cropland land-cover cells directly adjacent to wetland land-cover cells in the reporting unit and dividing by wetland total area in the reporting unit.

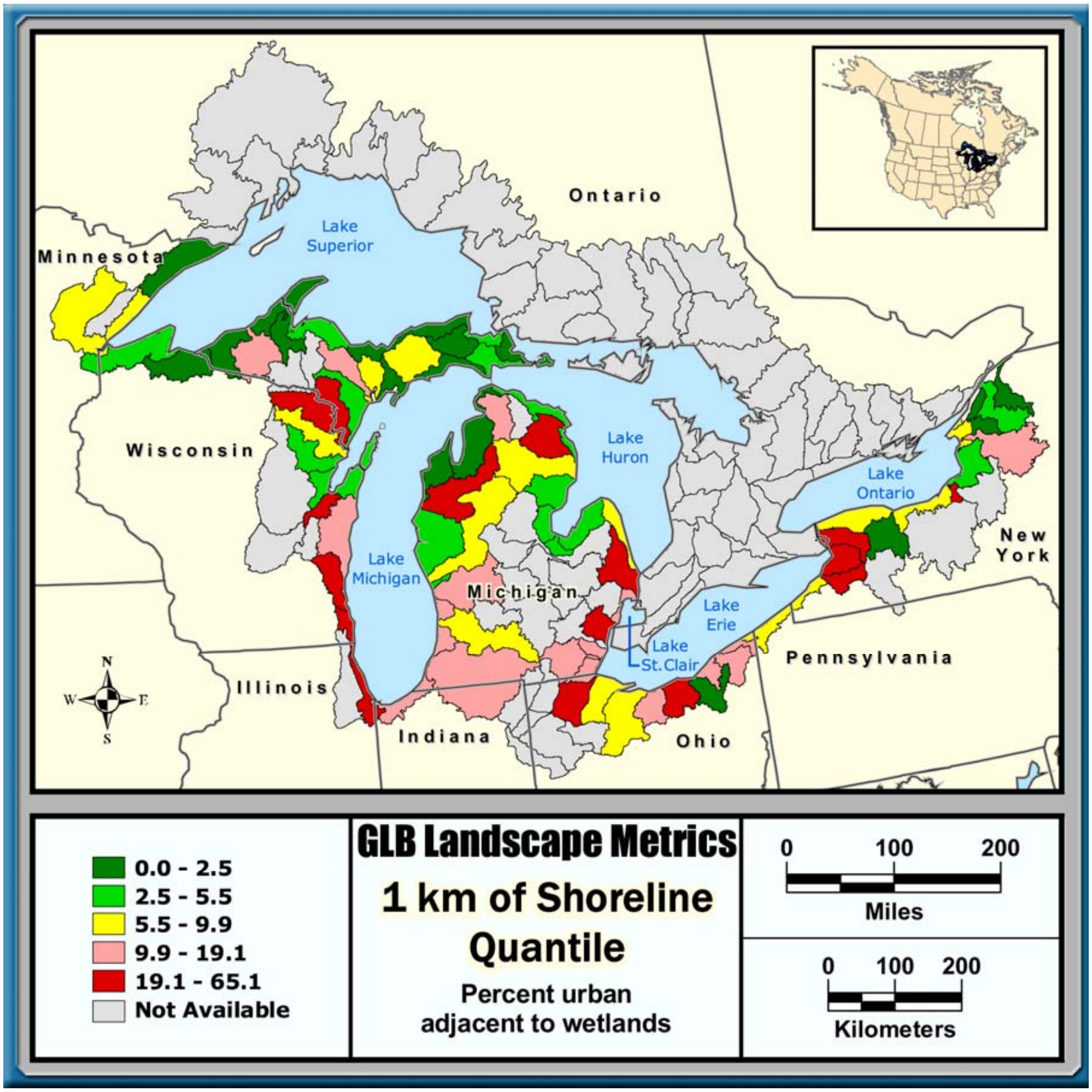


Figure 26. The percentage of urban land cover adjacent to wetlands is mapped within a 1-kilometer coastal region of the Great Lakes Basin (U.S. side). Percent urban is calculated by summing the total number of urban land-cover cells directly adjacent to wetland land-cover cells in the reporting unit and dividing by wetland total area in the reporting unit.

Water Quality Metrics Related to Coastal Wetlands of the Great Lakes Basin

Wetlands play an integral role in the hydrologic cycle. They provide important ecosystem functions and services that include flood storage during periods of high water and can act to improve the quality and safety of water resources in the Great Lakes. Coastal (and other) wetlands in the Great Lakes watershed can cleanse surface and ground water before it enters the shore waters (Lake Huron Center, 2000) by accumulating and transforming contaminants that are contained within soil particles that travel in runoff from upland areas toward the open waters. An increase in soil erosivity (Figure 27) or erodibility (Figure 28) may indicate an increase in the amount of the runoff to streams, lakes, and wetlands that may contain sediment and chemical constituents associated with sediment (e.g., phosphorus). Excessive amounts of sediment, nutrients, or other chemicals in runoff may degrade surface water, ground water, wetlands, and open water areas of the Great Lakes. Some watersheds in the Great Lakes have less sediment runoff than others. An increase in soil permeability (Figure 29), i.e., a decrease in soil impermeability, may indicate a decrease in the amount of runoff that may contain sediment, road salts, or other compounds, which eventually flow from uplands, to streams, through wetlands, to the Great Lakes.

An increase in surface roughness (Figure 30), a function of land cover and soil physical characteristics, may indicate a decrease in the amount of runoff (that can contain sediment, road salts, or other compounds) to streams, lakes, and wetlands. In addition to the soil and general land-cover characteristics, the presence of wetlands (by virtue of specialized vegetation and highly organic and clay soils) can have a tremendous influence on the reduction of sediment runoff to the open water of the Great Lakes. Wetlands slow down the movement of sediment, and thereby trap pollutants in the vegetation's tissues. Thus, chemicals like nitrogen and phosphorous (commonly associated with agricultural runoff) and pesticides are taken up by the root systems of wetland vegetation, which incorporates them into plant tissue, subsequently incorporating these constituents into the organic and clay soils, potentially for very long periods of time (Environment Canada, 1995). In areas where surface roughness is low, this cleansing may be critical in preventing eutrophication, which is a major human health and nuisance issue, as well as a threat to aquatic plants and animal species.

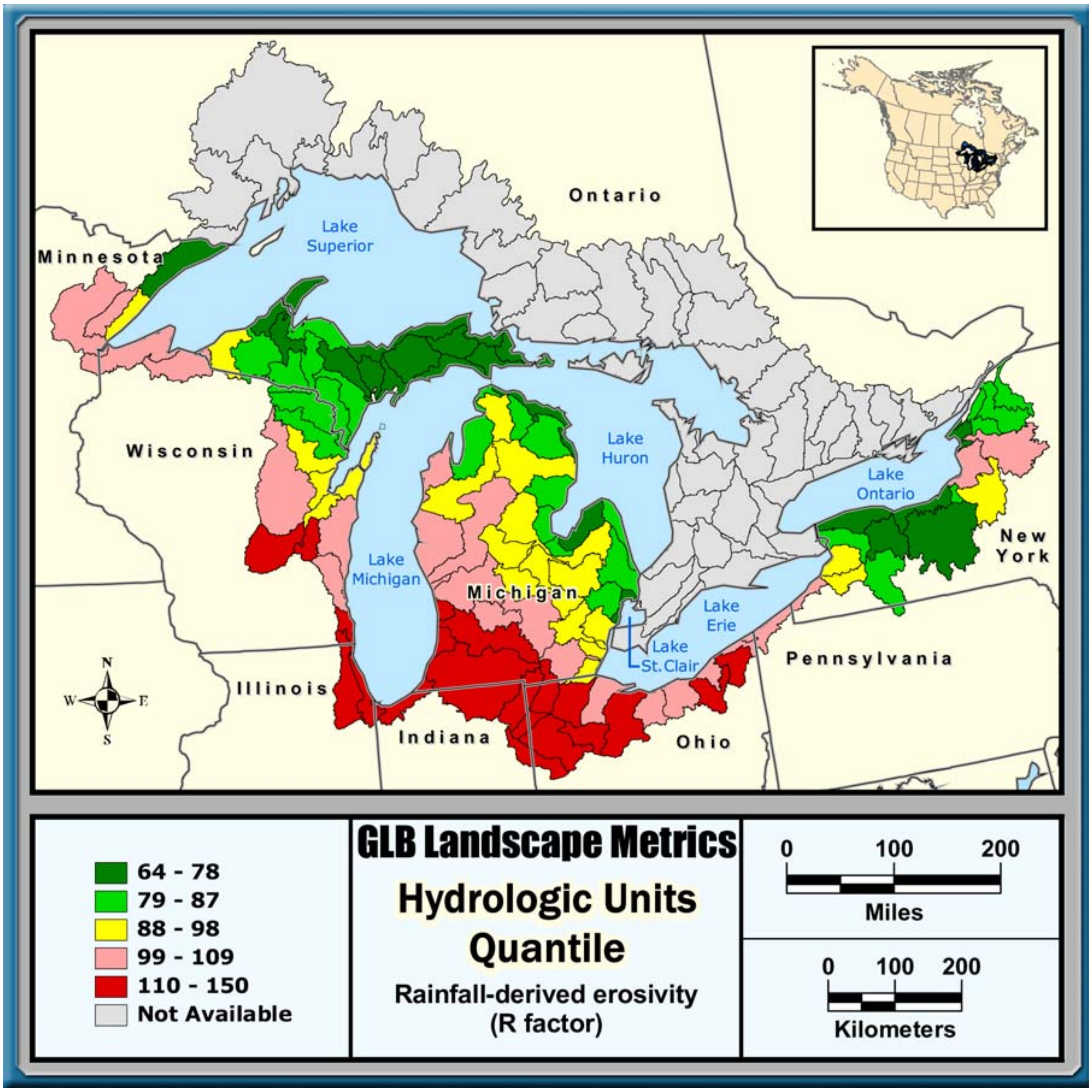


Figure 27. Rainfall-derived erosivity (R factor) within the Great Lakes Basin (U.S. side). This metric is a RUSLE weighted-average rainfall-derived erosivity metric, which is derived from a PRISM 2-km grid, and is computed on a cell-by-cell area basis.

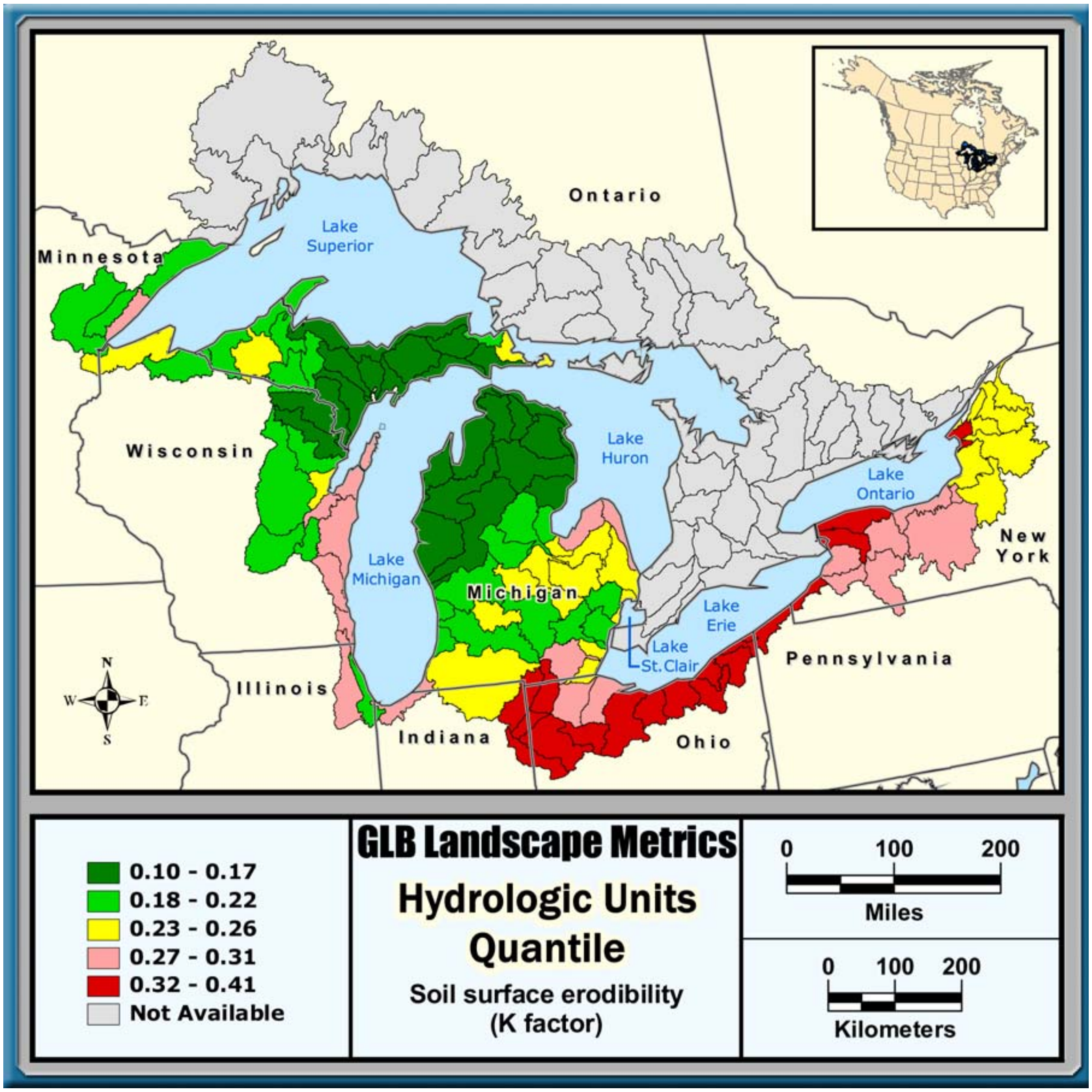


Figure 28. Soil surface erodibility (K factor) within the Great Lakes Basin (U.S. side). This metric is a RUSLE weighted-average effect of inherent soil surface erodibility (K factor), which is from STATSGO data, and is computed on a cell-by-cell area basis.

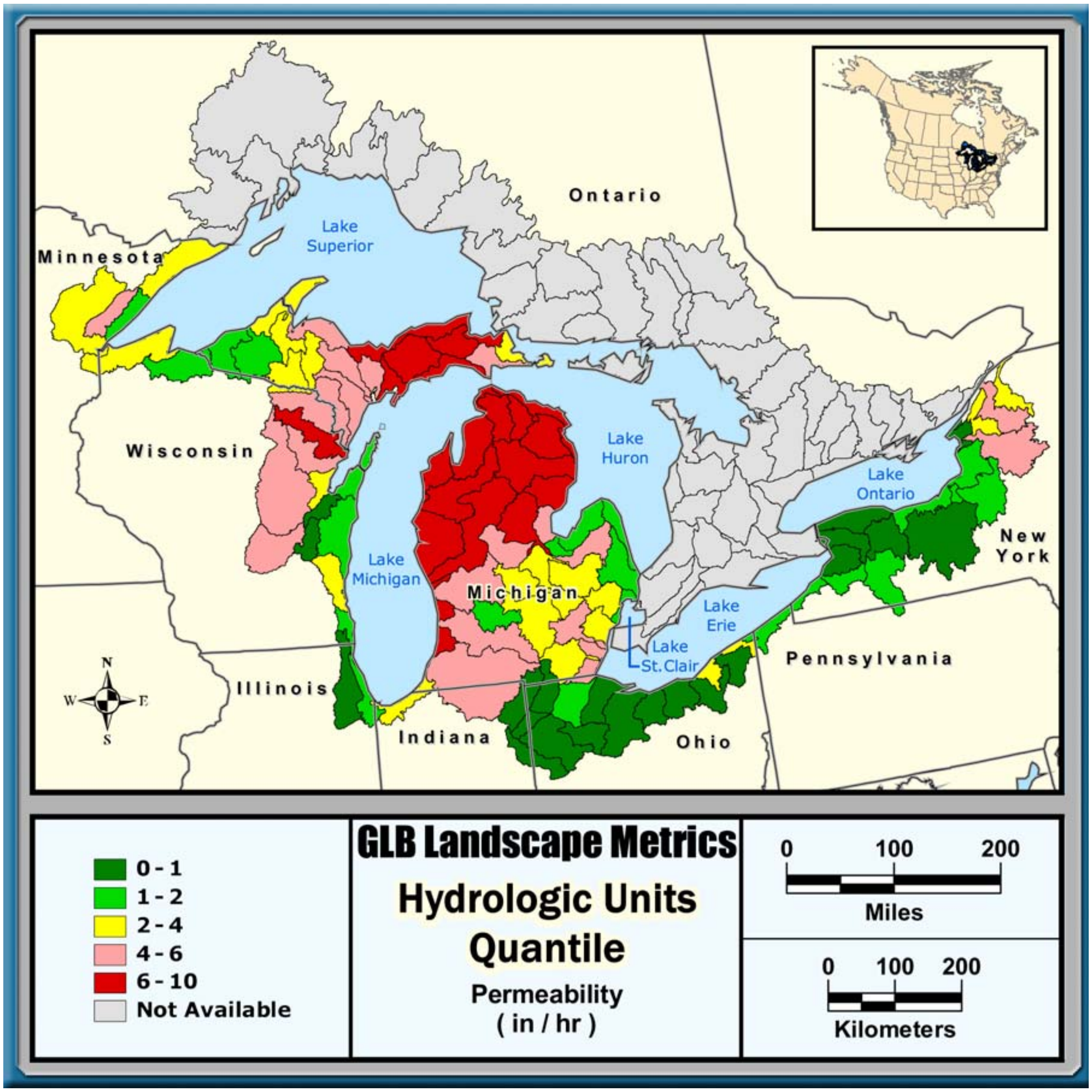


Figure 29. Soil permeability (in./hr.) within the Great Lakes Basin (U.S. side). This metric is derived from a STATSGO weighted-average soil permeability rate, measured in inches of water flow through soil layers per hour.

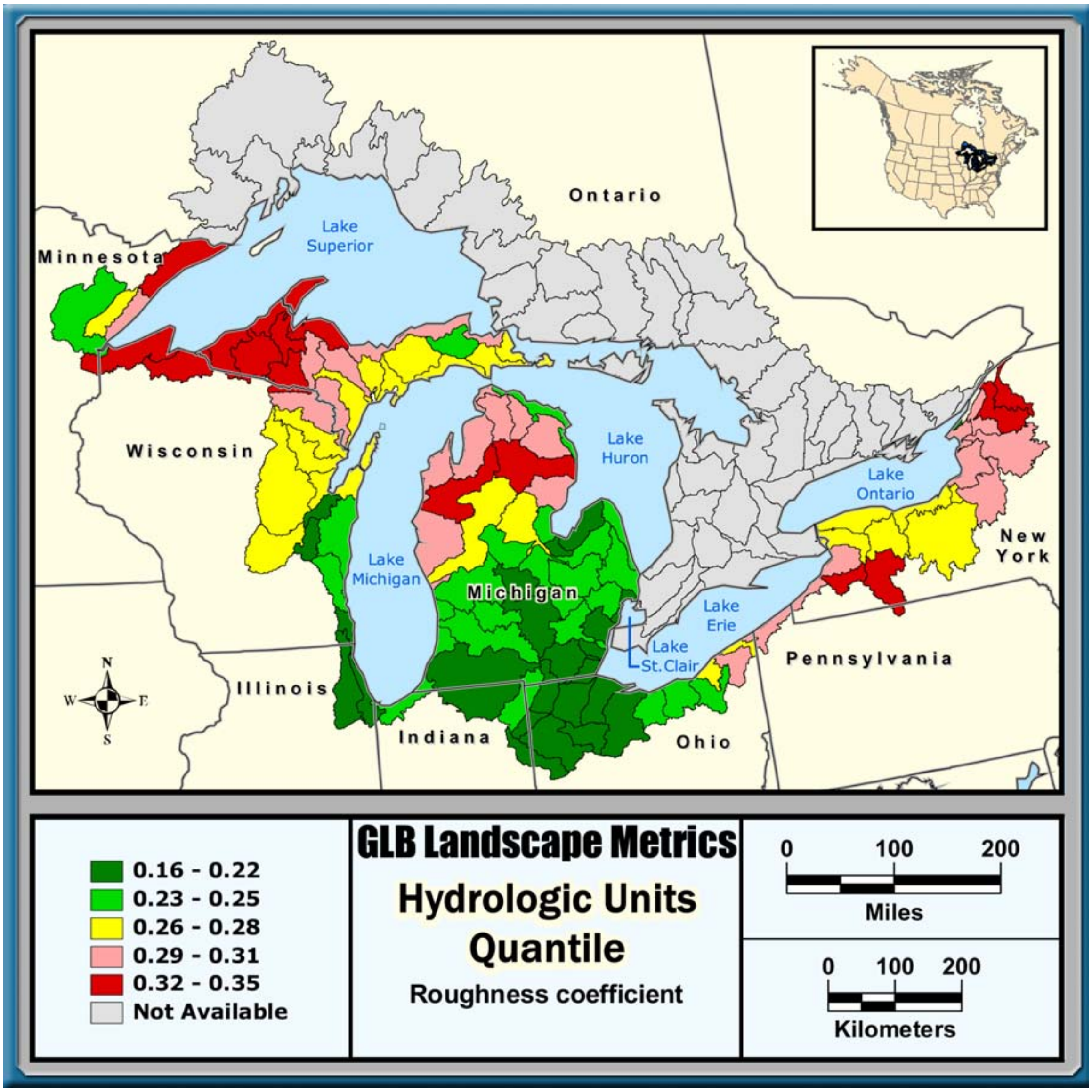


Figure 30. Surface roughness coefficient within the Great Lakes Basin (U.S. side). This metric is a SEDMOD weighted-average "Mannings' n" surface roughness coefficient, which may indicate the relative slowing of runoff as a result of friction with the land surface.

Chapter 4

Using a Landscape Approach for Monitoring Invasive and Opportunistic Plant Species in Great Lakes Coastal Wetlands

This is a case study describing in detail the application of the landscape ecological approach to map invasive and opportunistic plant species, using common reed *(Phragmites australis)* as an example. In combination with the broad-scale landscape metrics described in this report, an integrated landscape ecology approach can be used to simultaneously conduct cost-effective monitoring and determine the potential effects of landscape disturbance on the influx and spread of species throughout the entire Great Lakes Basin.

Invasive and Opportunistic Plant Species Impacts on Coastal Wetlands

Coastal wetlands and "invasive species" have been identified as important indicators of ecological integrity within the Great Lakes (SOLEC, 2000). Although coastal wetlands of the Great Lakes have potential for tremendous biological diversity and productivity (Figure 31), their plant communities are extremely sensitive to impacts from local landscape conversion, which may directly or indirectly cause the loss or the degradation of this diversity and productivity. The loss of biological diversity in coastal wetlands often coincides with the increase in presence and dominance of invasive (i.e., nonnative and opportunistic) or native opportunistic plants (e.g., certain species of cattails or common reed).

Figure 31. Some coastal marshes in the Great Lakes contain a relatively diverse vegetational community with high structural heterogeneity (both vertically and longitudinally), as shown in this Lake Erie diked coastal wetland (Lucas County, Ohio). This wetland (from background to foreground) contains row crop agricultural land (not visible in the distance), upland forest, forested wetland (far distance), emergent wetland (intermediate distance), floating leaved vegetation (near), and submersed aquatic vegetation (near). At the transitional region, between each vegetation type, there exists a mixture of each vegetation type.

Combining Remote Sensing, Field-Based Measures, and GIS to Map *Phragmites australis*

Remote sensing technologies offer a unique capability for measuring the extent of invasive/opportunistic plant species, over a large area. In this section, we demonstrate the use of ground-based vegetation sampling and airborne remote-sensing data to map the presence and distribution of these plants within a selected coastal wetland in western Lake Erie, which is a similar technique used to assess seven other wetlands in the Great Lakes coastal zone (Lopez and Nash, manuscript in review). These analyses along the entire coastal area of the Great Lakes are currently being used to test for broad-scale relationships between wetland disturbance (see Chapter 3) and invasive/opportunistic plant species in the 1-kilometer coastal region of the Great Lakes. Maps of invasive/opportunistic plants on a wetland site basis can help specific wetland managers throughout the Great Lakes region to target regions within a wetland for control procedures (e.g., spraying of herbicide). Such maps could provide regional environmental managers (e.g., EPA Region 5 Environmental Specialists) with a practical and cost-effective tool for monitoring the progress of wetland rehabilitation and restoration projects.

Phragmites australis (Figure 32) is a flowering perennial monocot that is native to North America but often dominates the vegetation of coastal wetlands. *Phragmites australis* reproduce by rhizome or stolon, and produce copious amounts of seed that is predominantly sterile (Voss, 1972). In general, *Phragmites australis* is a resource generalist that has a life history and physiological characteristics that enable it to rapidly invade new areas and flourish under environmentally stressful conditions, where other plant species cannot. Thus, *Phragmites australis* is often found to dominate wetland plant communities, and its spread in coastal wetlands may be a benchmark for observing the potential effects of landscape disturbance with remote sensing because it forms large, relatively homogeneous patches that typically reach sizes in the range from 1 to 50 hectares. The expanding populations of *P. australis* within Great

(a)

(b)

Figure 32. (a) A St. Clair Delta coastal marsh (St. Clair County, Michigan) and (b) an eastern Lake Michigan coastal marsh (Oceana County, Michigan), each containing stands of *P. australis*. Patches of *P. australis* grow in many Great Lakes coastal wetlands. This dense and tall, aggressively growing opportunistic plant species may reach heights of up to 3.1 meters, stem densities of up to 52 stems per square meter, and up to 71 percent cover in the canopy (Lopez and Nash, manuscript in review), depending on the location and the environmental conditions of the wetland in which the plant is growing.

Lakes coastal wetlands may be the result of increased opportunities for the migration of individuals (or genets) from small initial populations to newly opened gaps in the landscape.

Studies of genus *Phragmites* in other regions support a patch disturbance hypothesis that the level of disturbance may be an important factor in the process. For example, die-back of *Phragmites* in relatively undisturbed temperate European regions and expansion of *Phragmites* in European areas of climatic extremes (van der Putten, 1997) suggest that periodic disturbance may increase the rate and extent of expansion, such as has occurred in some coastal areas of the Great Lakes. Periodic stress may actually allow for the formation of relatively small, interconnected metapopulations, where gene flow between patches maintains the genetic diversity that might otherwise decline (i.e., in relatively large inbred populations). When such populations become unable to bridge the gaps between populations at the advanced stages of patch isolation, entire populations may become locally extinct (Opdam, 1990).

Case Study: Mapping *P. australis* at the Pointe Mouillee Coastal Wetland Complex

The purpose of this case study was to demonstrate the landscape ecological approach for determining the presence and distribution of *P. australis* in an entire coastal area, with minimal field activities. Ground-based wetland sampling was solely used to calibrate airborne hyperspectral data, to develop spectral signatures of the native opportunistic plant species, and to accuracy assess GIS maps. Eight coastal wetlands underwent this process, with case study results and techniques described at one of them (Pointe Mouillee, Figure 33).

Typically, *Phragmites* communities form large monospecific "stands" that may predominate in wetland plant communities, supplanting other plant taxa (Marks *et al.*, 1994). Compared to other more heterogeneous plant communities, *Phragmites* stands are less suitable as animal habitat and reduce the overall biological diversity of wetlands. From a Great Lakes coastal wetland resource perspective, *Phragmites* is difficult to manage because it is persistent, produces a large amount of biomass, propagates easily, and is very difficult to control with mechanical or chemical techniques. A combined field and remote-sensing-based approach was used to develop a semi-automated detection and mapping technique to support *Phragmites* monitoring and assessment efforts. Relevant ecological field data provided an important measurable link between airborne sensor data and information about the physical structure of *Phragmites* stands, soil type, soil moisture content, and the presence and extent of associated plant taxa.

The 13 coastal wetland study sites were selected from a group of approximately 65 potential sites along the coastal margins of western Lake Erie, Lake St. Clair, Lake Huron, and Lake Michigan (Figure 33). Sites were selected using aerial photographs, topographical maps (1:24,000-scale), wetland inventory maps, National Land Cover Data (NLCD), input from local wetland experts, and published accounts of coastal wetland studies in the areas (Lyon, 1979; Herdendorf *et al.*, 1986; Herdendorf, 1987; Stuckey, 1989; Lyon and Greene, 1992). Site selection criteria mandated that sites (i) generally spanned the gradient of current landscape conditions along the coastline of the lakes, (ii) were emergent wetlands (Cowardin *et al.*, 1979), and (iii) included both wetlands that are open to lake processes and wetlands protected from lake processes, e.g., diked wetlands or drowned river mouths (Keough *et al.*, 1999). Sites were selected so that proportions of adjacent LC generally varied among landscapes in the vicinity of the 13 sites. NLCD and aerial photographs indicated that site LC adjacent to all of the study sites included active agriculture, old-field agriculture, urban areas, and forest, in varying amounts. Each of the 13 selected wetland sites was known *a priori* to contain at least one of the targeted taxa of interest.

Figure 33. Thirteen wetland study sites in Ohio and Michigan coastal region, lettered A-M. Sites were sampled during July-August 2001. Magnified view (inset image) of Pointe Mouillee wetland complex (Site E). White arrows indicate general location of two field-sampled *Phragmites australis* stands. Field-sampled site location legend: Pa = *Phragmites australis*; Ts = *Typha* spp.; Ls = *Lythrum salicaria*; Nt = nontarget plant species; Gc = ground control point.

Remote Sensing

The PROBE-1^{TM} is a hyperspectral scanner system with a rotating axe-head scan mirror that sequentially generates cross-track scan lines on both sides of nadir to form a raster image cube. Incident radiation is dispersed onto four 32-channel detector arrays. The single scene of PROBE-1^{TM} data was visually examined for missing or noisy bands. After the missing and noisy bands were removed, the resulting 104 bands of data were subjected to a minimum noise fraction (MNF) transformation to determine the inherent dimensionality of image data, segregate noise in the data, and to reduce the computational requirements for subsequent processing (Boardman and Kruse, 1994). The MNF transformations, as modified from Green *et al.* (1988), are cascaded principal components transformations. The first transformation, based on an estimated noise covariance matrix, decorrelates and rescales the noise in the data. This first step resulted in transformed data in which the noise had unit variance and no band-to-band correlations. The second step was a standard principal components transformation of the “noise-whitened” data. Then, the inherent dimensionality of the data was determined by examining the final

Eigen values and the associated images from the MNF transformations. The data space was then divided into two parts, (i) one associated with large eigen values and coherent eigen images, and (ii) a complementary part with near-unity eigen values and noise-dominated images. By using solely the coherent portions, the noise is separated from the data, thus improving spectral processing results (RSI, 2001).

A supervised classification of the PROBE-1^{TM} scene was then performed using the ENVI^{TM} Spectral Angle Mapper (SAM) algorithm, an automated processing technique for comparing image spectra to a spectral library. Because the PROBE-1^{TM} flights occurred three weeks after field sampling, there was a possibility that trampling from the field crew could have altered the physical structure (thus, the reflectance characteristics) of *Phragmites*. For this reason, and due to inherent georeferencing inaccuracies of the data within the two *Phragmites* stands, PROBE-1^{TM} spectra were collected from a 9-pixel (i.e., 3 pixel x 3 pixel) area, centered on the most homogeneous field-verified area within each vegetation stand. The SAM algorithm was then used to determine the similarity between the spectra of homogeneous *Phragmites* and every other pixel in the scene by calculating the spectral angle between them (spectral angle threshold = 0.07 rad). SAM treats the spectra as vectors in an *n*-dimensional space equal to the number of bands (i.e., a 104-dimension space).

The SAM classification resulted in the detection of 18 image endmembers, each with different areas mapped as potentially homogeneous regions of *Phragmites*. Visual examination of the 18 endmembers involved determining if mapped areas generally coincided with areas of *Phragmites* observed in black and white aerial photos (1999) and field data collections (2001). Additional validation of mapped areas of *Phragmites* was also aided by using the ENVI^{TM} Mixture Tuned Matched Filtering (MTMF) algorithms. Visual interpretation of the MTMF "infeasibility values" (noise sigma units) versus "matched filtering values" (relative match to spectrum) further aided in the elimination of potential endmembers. The matched filtering values provide a means of estimating the relative degree of match to the *Phragmites* patch reference spectrum and the approximate sub-pixel abundance. Correctly mapped pixels had a matched filter score above the background distribution and a low infeasibility value. Pixels with a high matched filter result and high infeasibility were "false positive" pixels that did not match the *Phragmites* target. At the end of the endmember selection process, three *Phragmites* maps were created, one from the northernmost stand and two from the southernmost stand (Figure 33). For the purposes of determining adequately sized areas of mapped *Phragmites,* the three endmember maps were combined as a polygon theme, with a minimum area threshold of 75 m^2 (i.e., 3 pixels), using ArcView^{TM}.

Field Sampling

Vegetation was sampled at Pointe Mouillee on August 7-8, 2001. Prior to vegetation sampling, aerial photographs (1999) were used, along with on-site assessments to locate large target species stands. Six stands were sampled, including two stands of each target species and two nontarget vegetation stands, for comparison to target-species stands (Figure 33). Digital video of each vegetation stand was recorded to fully characterize the site and for reference during image processing. Each vegetation stand was mapped by a field sketch, noting the general location and shape of vegetation stands, key landmarks that might be recognizable in the remote sensor images, and other information about the site that might be useful when trying to reconcile ground data with remotely sensed data. Transects within each of the stands and on the perimeter of target-species stands were recorded using a real-time-corrected GPS for sampled target species (Figure 34). Each of the two nontarget stands of vegetation was delineated with a minimum of four GPS points, evenly spaced around the perimeter. Five GPS ground control points were collected at Pointe Mouillee, triangulating on sampled areas at that wetland. GPS location points were recorded with either a single digital photograph (edge quadrats and nontarget vegetation stand) or multiple digital photographs (ground control points) to provide several angles of each sample location. A written description of each ground control point was recorded to assist in the georeferencing of the remote sensor images.

Within each target-species stand, a nested quadrat sampling method was used to sample herbaceous plants, shrubs, tree species, and other characteristics of target-species stands (Mueller-Dombois and Ellenberg, 1974; Barbour, 1987). Depending on the size of the stands, from 12 to 20 (nested) 1.0 m^2 and 3.0 m^2 quadrats were evenly spaced along intersecting transects (Figure 35). The approximate percent

(a) **(b)**

Figure 34. Field sampling activities were an important part of calibrating the hyperspectral data: (a) dense *Phragmites* canopy and (b) dense *Phragmites* understory layer in the northernmost stand. The edges of the stand and the internal transects were mapped using a real-time-corrected global positioning system.

cover and taxonomic identity of trees and shrubs within a 15-m radius was also recorded at each quadrat. Depending on the size of the stand, a transect might either cross the entire stand or penetrate deeply into the stand of vegetation. Thus, where appropriate, the terminal quadrat was placed outside of the target-species stand perimeter to characterize the immediately adjacent LC. The perimeter of each stand and identified corner of each 1-m^2 quadrat was recorded with a GPS. All GPS locations were recorded with a real-time-corrected (OmniSTAR USA, Inc., Houston, TX) GPS (Trimble Navigation Ltd., Sunnyvale, CA), with a nominal spatial accuracy of 1.0 m. Non-spectral data collected along transects in the vegetation canopy and understory (Figure 35) are listed in Table 2.

The northernmost *Phragmites* stand sampled at Pointe Mouillee was bounded on the eastern edge by an unpaved road, with two patches of trees/shrubs to the north (dogwood and willow) and to the south (willow). The eastern edge of the stand was bounded by a mixture of *Lythrum salicaria* and *Typha* spp. Soil in the *Phragmites* stand was dry and varied across the stand from clayey-sand, to sandy-clay, to a mixture of gravel and sandy-clay near the road. Litter cover was a constant 100% across the sampled stand. Nontarget plants in the understory included smartweed (*Polygonum* spp.), jewel weed (*Impatiens* spp.), mint (*Mentha* spp.), Canada thistle (*Cirsium arvense* L.), and an unidentifiable grass. Cattail was the sole additional plant species in the *Phragmites* canopy. Thus, the northernmost *Phragmites* stand was relatively heterogeneous, with quadrat-4 located in the most homogeneous region of *Phragmites*, based on the ecological characteristics of the stand (Figure 35).

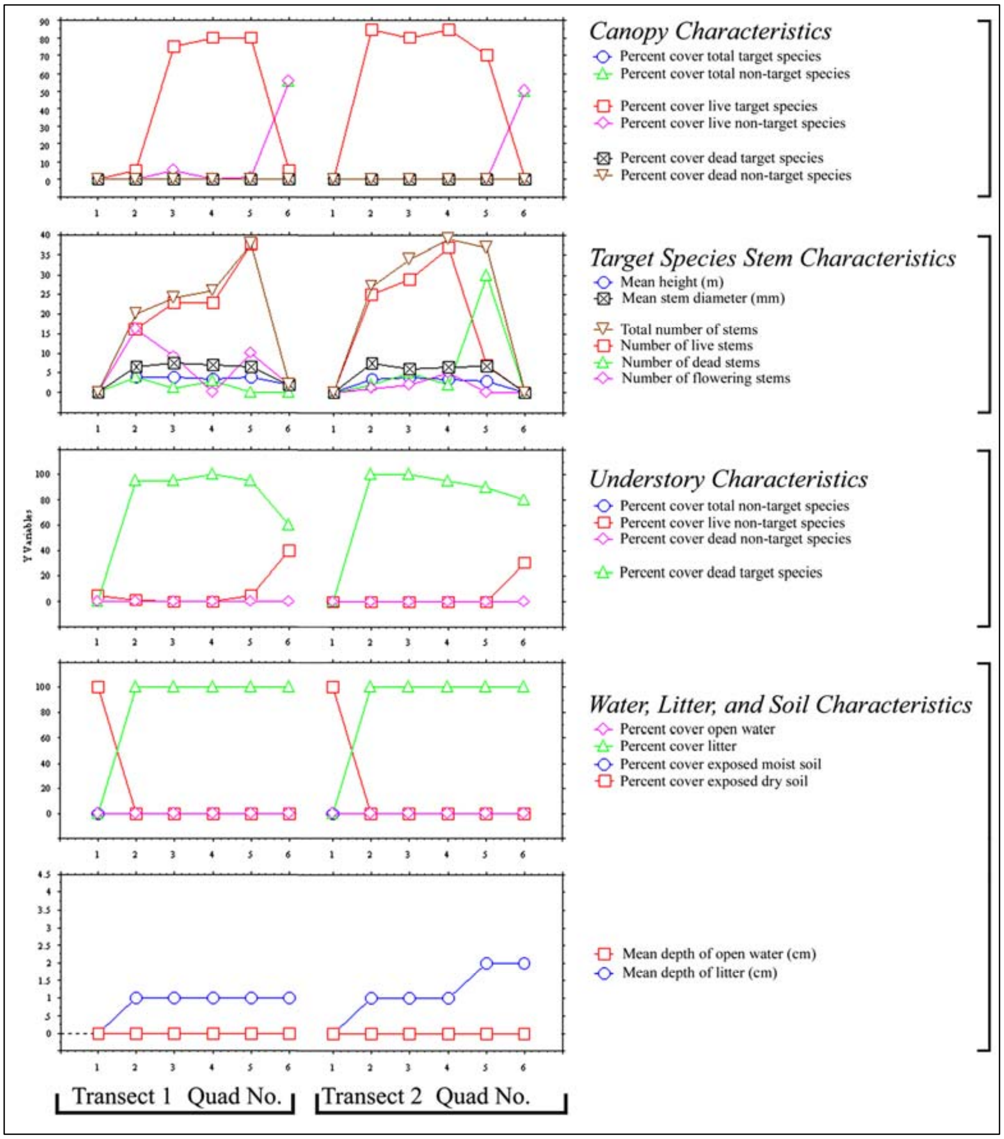


Figure 35. The heterogeneity of canopy, stem, understory, water, litter, and soil characteristics in *Phragmites australis* stands was used to calibrate the PROBE-1^{TM} data for the purpose of detecting *P. australis* at Pointe Mouillee (field data from the northernmost *Phragmites* stand sampled). The most, relatively, homogeneous area of *Phragmites* in the northernmost stand is in the vicinity of transect-1, quadrat-4. Pixels in the vicinity of transect-1, quadrat-4 were used in the Spectral Angle Mapper (supervised) classification of PROBE-1^{TM} reflectance data.

As described, the locations of the most homogeneous regions of *Phragmites* within sampled vegetation stands were determined by examining field transect data to determine which had the greatest cover of non-flowering live plants and greatest stem density. *Phragmites* is a facultative-wetland plant and usually occurs in wetlands, but occasionally occurs in non-wetlands (Reed, 1988). Thus, it can grow in clayey soil, varying from moist to dry substrate conditions. We did not have a *Phragmites* field sample in a moist-soil area at this site, but considering the great density of vegetation in the canopy and the high stem density, spectral endmember maps of field samples were sufficient to detect relatively homogeneous areas of *Phragmites* at a large number of locations.

GIS Mapping and Accuracy Assessment

SAM-supervised classification of the Pointe Mouillee PROBE-1^{TM} image resulted in a vegetation map indicating the locations of other relatively homogeneous *Phragmites* stands (Figure 36). Several of these areas are located in the diked areas of the wetland complex, areas that are typically populated by large stands of *Phragmites* in other Lake Erie wetlands.

A three-tiered approach to accuracy assessment of semi-automated vegetation maps at Pointe Mouillee was followed and is ongoing at the remaining 12 sites. The accuracy assessment approach is, as follows: (1) testing of target plant species presence/absence using a comparison of semi-automated vegetation maps to recent stereo aerial photographs; (2) testing of target plant species presence/absence using random field samples of the mapped areas; (3) testing of target plant species percent cover and structural composition using random field samples of mapped areas.

At Pointe Mouillee, tier-1 accuracy assessment (prior to field validation sampling) compared vegetation maps to 1:15 840-scale black and white stereo aerial photographs (September 1999) and field notes (May-August 2001). Tier-1 accuracy assessment results indicate that approximately 80% of the areas mapped as *Phragmites* are located within true *Phragmites* stands. Field sampling to complete tier-2 and tier-3 accuracy assessment was performed in August 2002. Comparison of field samples with the semi-automated vegetation maps of *Phragmites* resulted in a 91% user's accuracy (*n*=86). Tier-2 accuracy assessment of *Typha* spp. and *Lythrum salicaria* at the other wetland study sites, and tier-3 accuracy assessment at Pointe Mouillee is ongoing.

Ongoing Landscape Indicator Research in the Great Lakes

Disturbance theory suggests that the intensity and duration of disturbance within an ecosystem is a key factor in the loss of ecological integrity (Connell and Slatyer, 1977; Rapport, 1990; Keddy, *et al.* 1993; Opdam *et al.*, 1993). One of the potential mechanisms for the loss of ecological integrity may be the decline in biological diversity of an ecosystem, through the invasion of opportunistic species (Odum, 1985). The loss of plant biological diversity in coastal wetlands of the Great Lakes has been widely described as a result of increased dominance of opportunistic plant species (e.g., Stuckey, 1989).

Research suggests that the influx and spread of such invasive and opportunistic plant species may be the result of overall wetland ecosystem "stress" (Odum, 1985). Losses of biological diversity may be related to changes in the frequency of landscape disturbance within coastal wetlands or on the edges of coastal wetlands, such as fragmentation (Forman, 1995) that results from the construction of roads, the conversion/proximity of wetlands to agriculture, or hydrologic alterations that occur in coastal wetlands (e.g., ditching or diking). Attempts to control these plant species in Great Lakes coastal marshes (e.g., by flooding, by drawing down water levels, by plowing vegetation, by spraying vegetation, or by mowing vegetation) may bolster the population resiliency by increasing the proportion of "management resistant" characteristics in the plant populations (Diamond, 1974), acting to further select for invasive genotypes at managed wetland sites.

The potential drivers of this biological diversity loss and the landscape conditions in and around coastal wetlands can be described using metrics, as demonstrated in Chapter 3. Some of the potential landscape-scale ecological parameters that are correlated with the extent and pattern of invasive/opportunistic plant species in coastal wetlands are currently being tested for substantive relationships, using the landscape metrics described in this report and in the Appendix A. The landscape metrics described in the Appendix

A is an important step toward understanding the distribution of phenomena within coastal regions of the Great Lakes and within the entire Great Lakes Basin. The browser in Appendix A is also designed to present some key ecological metrics to the public and research communities at a landscape scale, which can be used to familiarize oneself with environmental conditions, or to plan a variety of other ecological analyses, respectively.

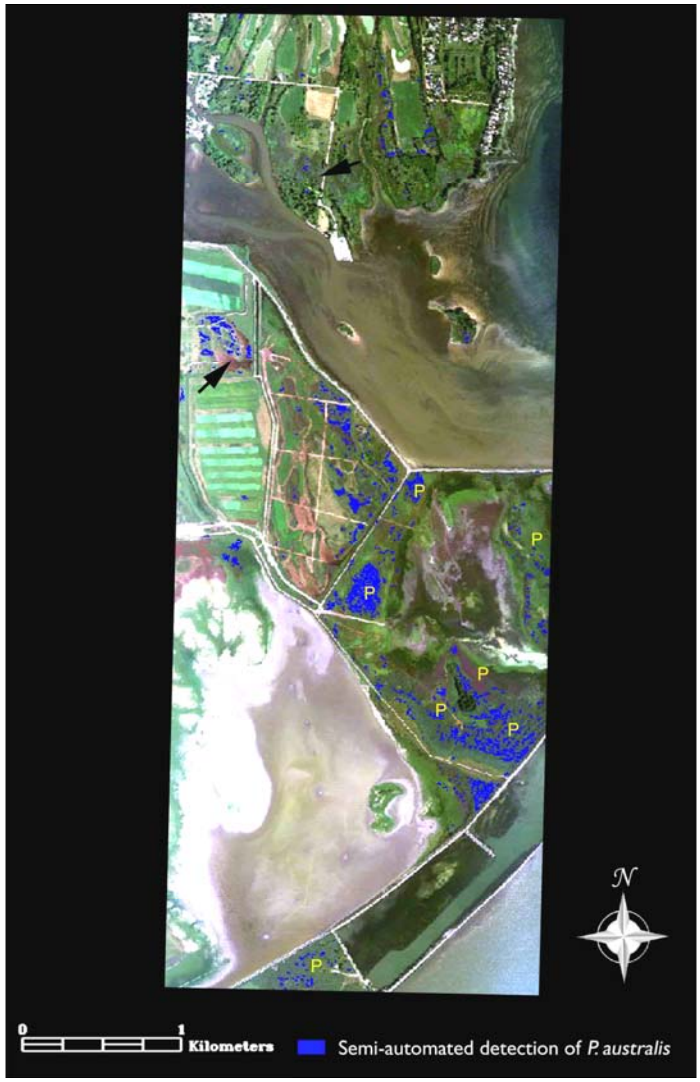


Figure 36. Results of a Spectral Angle Mapper (supervised) classification, indicating likely areas of relatively homogeneous stands of *Phragmites australis* (solid blue), using PROBE-1^{TM} data and field-based ecological data. Field-sampled patches of *Phragmites* are shown by black arrows. Areas of mapped *Phragmites* are overlaid on a natural-color image of Pointe Mouillee wetland complex (August 2001). Yellow "P" indicates the general location of known areas of *Phragmites,* validated with aerial photographs, field notes, and 2002 accuracy assessment data.

Glossary

Airborne hyperspectral data: A remote sensing data type that contains a relatively large number of spectral bands (typically more than 20) and is acquired by a sensor that resides on an airplane, at either a low or high altitude.

Airborne multispectral data: A remote sensing data type that contains a relatively small number of spectral bands (typically less than 10) and is acquired by acquired by a sensor that resides on an airplane, at either a low or high altitude.

ANOVA: Analysis of Variance test.

Anoxic: Condition which lack oxygen, typical of wetland soils.

C-CAP : The U.S. National Atmospheric and Oceanographic Administration's Coastal Change and Analysis Program.

Decision support: A set of software and/or database applications that are intended to allow users to search large amounts (e.g., in a clearinghouse) of information for specific reporting that can result in making (e.g., environmental) management decisions.

GLNPO: U.S. EPA's Great Lakes National Program Office.

System: An assemblage of interrelated elements or components that comprise a unified whole. An ecological system (ecosystem) is one type.

Ecological processes: The flow of energy and nutrients (including water) through an ecosystem.

Ecosystem: An interacting system consisting of groups of organisms and their nonliving or physical environment, which are interrelated.

Ecosystem approach: An approach to perceiving, managing and otherwise living in an ecosystem that recognizes the need to preserve the ecosystem's biochemical pathways upon which life within the ecosystems depends (e.g., biological, social, economic, etc.).

Ecological indicator: A characteristic of the environment that is measured to provide evidence of the biological condition of a resource (Hunsaker and Carpenter, 1990). Ecological indicators can be measured at different levels, including organism, population, community, or ecosystem. The indicators in this volume are measures of ecosystem level characteristics, at a broad scale (Jones *et al.*, 1997).

Ecosystem integrity: The inherent capability of an ecosystem to organize (e.g., its structures, processes, diversity) in the face of environmental change.

Endpoint: Describes a characteristic of an ecosystem of interest and should be an ecologically relevant measurement. An endpoint can be any parameter, from a biochemical state to an ecological community's functional condition.

EPA: The United States Environmental Protection Agency.

Extirpation: The elimination or disappearance of a species or subspecies from a particular area, but not from its entire range.

Foot: 0.305 meters.

GIS: Geographic Information System(s).

HGM: Hydrogeomorphic (methodology).

Hyper-eutrophication: The undesirable overgrowth of vegetation and algae as a result of high concentrations of nutrients in wetlands; eutrophication greater than the typically higher levels of nutrients found in wetland relative to lakes, streams, and rivers.

Indicator: In biology/ecology, any biological or ecological entity that characterizes the presence or absence of specific environmental conditions, as demonstrated by statistical correlations of ecologically meaningful relationships between the entity(ies) and the environmental condition(s).

Kilometer: 0.62 miles.

Land cover: A biological and/or physical description of the Earth's surface. It is that which overlays or currently covers the ground. This description enables various biophysical categories to be distinguished, such as areas of vegetation (trees, bushes, fields, lawns), bare soil, hard surfaces (rocks, buildings), and wet areas and bodies of water (watercourses, wetlands).

Landsat: The satellite-based U.S. National Aeronautics and Space Administration project that, in the late 1960s and early 1970s, endeavored to observe land features from space. The program has evolved by the launching of a total of several satellites to date. Landsat imagery is used for a variety of Earth observations.

Land use: A social or economic description of land cover. For example, an "urban" land cover description can be described as a land use if particular information about the activities that occur in the urban area can be discerned, such as residential, industrial, or commercial uses. It may be possible to infer land use from land cover, and the converse, but situations are often complicated, and the links to land use are not always evident; unlike land cover, land use is difficult to infer from remote sensing imagery, or over vast areas of the landscape. For example, it is often difficult to decide if grasslands are used or not for agricultural purposes. Distinctions between land use and land cover and their definition have impacts on the development of classification systems, data collection, and geographic information systems in general.

Landscape: A complex concept encompassing several definitions. For the purposes of this report, a landscape is an area containing a mosaic of land cover "patches," i.e., distinct areas that can be defined or mapped.

Landscape metrics: A measurement of a component or components (e.g., patches of forest) within the landscape, which is used to characterize composition and spatial configuration of the component within the landscape (e.g., forest size, fragmentation, proximity to other land cover types).

Landscape unit: A reference unit (usually of area) that is being measured, mapped, or described.

Landscape: The traits, patterns, and structure of a specific geographic area including its biological composition, its physical environment, and its anthropogenic or social patterns.

Landscape characterization: The process of documenting the traits and patterns of the essential elements of the landscape.

Landscape ecology: The study of the distribution patterns of communities and ecosystems, the ecological processes that affect those patterns, and changes in pattern and process over time and space.

Landscape indicator: A measurement of the landscape, calculated from mapped or remotely sensed data, used to describe some other spatial or temporal pattern(s) of land use or land cover across a geographic area.

Liter: 1.057 quarts.

Meter: 3.28 feet.

Metric: Any measurement value.

Mile: 1.61 kilometers.

Model: A representation of reality used to simulate a process, understand a situation, predict an outcome, or analyze a problem. A model is structured as a set of rules and procedures, including spatial modeling tools that relate to locations on the Earth's surface (Jones *et al.*, 1997).

MODIS: The satellite-based "Moderate Imaging Spectroradiometer." A project undertaken by the U.S. National Aeronautics and Space Administration that endeavored to improve our understanding of global dynamics and processes occurring on the land, in the oceans, and in the lower atmosphere.

ORD: U.S. EPA's Office of Research and Development.

Patch: A discrete land cover unit; for example, a "patch of forest" is a specific 25-acre wooded area in Hardin County, Ohio.

Perforated: The condition of a patch where gaps in the patch exist, such as a gap in a forest patch, which may contain shrub, grass, or other non-forest land cover.

PRISM: Parameter-elevation Regressions on Independent Slopes Model.

RUSLE: Revised Universal Soil Loss Equation.

Satellite hyperspectral data: A remote sensing data type that contains a relatively large number of spectral bands (typically more than 20) and is acquired by a sensor that resides on an Earth-orbiting platform.

Satellite multispectral data: A remote sensing data type that contains a relatively small number of spectral bands (typically less than 10) and is acquired by a sensor that resides on an Earth-orbiting platform.

Scale: The spatial or temporal dimension over which an object or process can be said to exist as in, for example, the scale of forest habitat. This is an important factor to consider during landscape ecology assessments because measured values often change with the scale of measurement. For example, coarse scale maps have less detailed information than fine scale maps and thus exclude some information, relative to fine scale maps.

Seiche: Temporary displacement of water in a large lake owing to high winds or atmospheric pressure. The short-term water-level oscillations that result from a seiche are functionally analogous to ocean tides.

Spatial database: A collection of information that contains data on the phenomenon of interest, such as forest condition or stream pollution, and the location of the phenomenon on the Earth's surface (Jones *et al.*, 1997).

Spatial pattern: Generally, the way things are arranged on the Earth's surface, and thus on maps. For example, the pattern of forest patches can be described by their number, size, shape, or proximity to other entities. The spatial pattern exhibited by a map can be described in terms of its overall texture, complexity, or by other landscape metrics.

STATSGO: State Soil Geographic (database).

Thematic map: A map that shows the spatial distribution of one or more specific "data themes" (e.g., percentage of agriculture or human population).

U.S. EPA: United States Environmental Protection Agency.

Watershed: A region or area shown in a map as a bounded area that might be actually bounded (on the ground) by ridge lines or other physical divides, which drain ultimately to a particular watercourse or body of water (Jones *et al.*, 1997).

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Appendix A: CD Browser of Landscape Metrics for the Great Lakes Basin

Also accessible online at URL:

http://www.epa.gov/esd/land-sci/glb_browser/GLB_Landscape_Ecology_Metric_Browser.htm

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