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Integrated Measures of Anthropogenic Stress in the U.S. Great Lakes Basin

Nicholas P. Danz · Gerald J. Niemi · Ronald R. Regal · Tom Hollenhorst · Lucinda B. Johnson · JoAnn M. Hanowski · Richard P. Axler · Jan J. H. Ciborowski · Thomas Hrabik · Valerie J. Brady · John R. Kelly · John A. Morrice · John C. Brazner · Robert W. Howe · Carol A. Johnston · George E. Host

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Abstract Integrated, quantitative expressions of anthropogenic stress over large geographic regions can be valuable tools in environmental research and management. Despite the fundamental appeal of a regional approach, development of regional stress measures remains one of the most important current challenges in environmental science. Using publicly available, pre-existing spatial datasets, we developed a geographic information system database of 86 variables related to five classes of anthropogenic stress in the U.S. Great Lakes basin: agriculture, atmospheric deposition, human population, land cover, and point source pollution. The original variables were quantified by a variety of data types over a broad range of spatial and classification resolutions. We summarized the original data for 762 watershed-based units that comprise the U.S. portion of the basin and then used principal components analysis to develop overall stress measures within each stress category. We developed a cumulative stress index by combining the first principal component from each of the five stress categories. Maps of the stress measures illustrate strong spatial patterns across the basin, with the greatest amount of stress occurring on the western

N. P. Danz (✉) · G. J. Niemi · T. Hollenhorst ·
L. B. Johnson · J. M. Hanowski · R. P. Axler ·
V. J. Brady · G. E. Host ·
Center for Water and the Environment,
Natural Resources Research Institute,
University of Minnesota Duluth,
5013 Miller Trunk Highway,
Duluth, Minnesota 55811, USA
E-mail: ndanz@nrri.umn.edu

R. R. Regal
Department of Mathematics and Statistics,
University of Minnesota Duluth,
10 University Drive, Duluth
Minnesota 55811, USA

J. J. H. Ciborowski
Department of Biological Sciences,
University of Windsor, 401 Sunset Avenue,
Windsor, Ontario N9B 3P4, Canada

T. Hrabik
Department of Biology,
University of Minnesota Duluth,
10 University Drive, Duluth
Minnesota 55811, USA

J. A. Morrice · J. R. Kelly
Mid-Continent Ecology Division,
U.S. Environmental Protection Agency,
6201 Congdon Boulevard,
Duluth, Minnesota 55804, USA

J. C. Brazner
Inland Waters Ecoservices,
29 Powers Dr., Herring Cove
Nova Scotia B3V 1G6, Canada

R. W. Howe
Department of Natural and Applied Sciences,
University of Wisconsin Green Bay,
2420 Nicolet Drive,
Green Bay, Wisconsin 54311, USA

C. A. Johnston
Center for Biocomplexity Studies,
South Dakota State University,
Brookings, South Dakota, USA

shore of Lake Michigan, southwest Lake Erie, and southeastern Lake Ontario. We found strong relationships between the stress measures and characteristics of bird communities, fish communities, and water chemistry measurements from the coastal region. The stress measures are taken to represent the major threats to coastal ecosystems in the U.S. Great Lakes. Such regional-scale efforts are critical for understanding relationships between human disturbance and ecosystem response, and can be used to guide environmental decision-making at both regional and local scales.

Keywords Great Lakes · Coastal ecosystems · Anthropogenic stress · GIS

Introduction

Integrated, quantitative expressions of anthropogenic stress over large geographic regions can be valuable tools in environmental research and management. Fundamental questions such as “How do human activities influence ecosystem responses?”, “What areas are most vulnerable in a region?”, and “What can be done to reverse environmental degradation?” require summaries of environmental problems that operate over large spatial extents (Hunsaker and others 1990; O’Neill and others 1997). Regional summaries of stress may provide the spatial context necessary for environmental decision-making at many scales (Smith and others 2000). Despite the fundamental appeal of a regional approach, development of integrated regional measures of stress remains one of the most important current challenges in environmental science (Wickham and others 1999).

Broad-scale environmental pressures such as acid deposition, agriculture, point-source pollution, climate change, and land-use change overlap in space and time, requiring that stress measures incorporate assessments of cumulative impacts across multiple stressors and multiple resources (Beanlands and others 1986; Shoemaker 1994). Multiple stressors can have independent, synergistic, or antagonistic effects on ecosystems, presenting many theoretical and technical challenges to the development of stress indices (Niemi and others 2004), including 1) obtaining and processing data that can be used to represent stress (Smith and others 2000), and 2) integrating the information from various sources into an overall quantitative expression (Locantore and others 2004).

Although it is rarely possible to acquire enough data to fully characterize stressors over a region (Bryce and others 1999), a top-down approach can be used to identify the major mechanisms of degradation at broad scales (Karr and Chu 1999). Measures of human activity at broader spatial scales tend to encapsulate the effects of stressors at finer scales because many stressors have common causes and similar spatial domains (Boughton and others 1999). For many regions of the continental United States, there is a wealth of spatially explicit data from monitoring and reporting programs related to human activities. Although existing data may have been collected for diverse reasons and may directly represent a variety of human activities, disturbances, stressors, or resource distributions, there are promising avenues for cost-effective integration of these data into regional stress indices (Locantore and others 2004). Methods to integrate spatial stress data range from relatively simple rank or scoring based methods (Bryce and others 1999) to multivariate statistical methods used in combination with a geographic information system (GIS) (Tran and others 2003; Tran and others 2004).

Despite differences in complexity, all integrated measures involve compromises regarding cost, resolution, and the level of integration (Fore 2003). Decisions regarding such compromises influence the ultimate utility of a stress measure. Finely resolved measures that are not highly integrated will tend to better represent individual stressors or individual stressor types rather than cumulative human influence. Measures of stress that integrate multiple variables at multiple (or broad) spatial scales can meet multiple objectives, including diagnosing major sources of impairment (Bryce and others 1999), calibrating ecological indicators (Kerans and Karr 1994), designing stratified sampling designs (Danz and others 2005), or identifying reference areas (Host and others 2005). Because biological assemblages are simultaneously subjected to multiple stressors, they are likely to be especially important sentinels of environmental conditions (Karr 1995; Niemi and McDonald 2004); thus, they may be more sensitive to the combined effects of stress than to single stressors. Empirical relationships between stress variables and biological variables will provide important insights into the net effects of human activities on ecosystem condition.

The objectives of this article are to develop and interpret integrated measures of anthropogenic stress across the U.S. Great Lakes basin. We illustrate the spatial distribution of stresses and show how the stress measures allow interpretation of relationships between human activity and ecosystem condition.

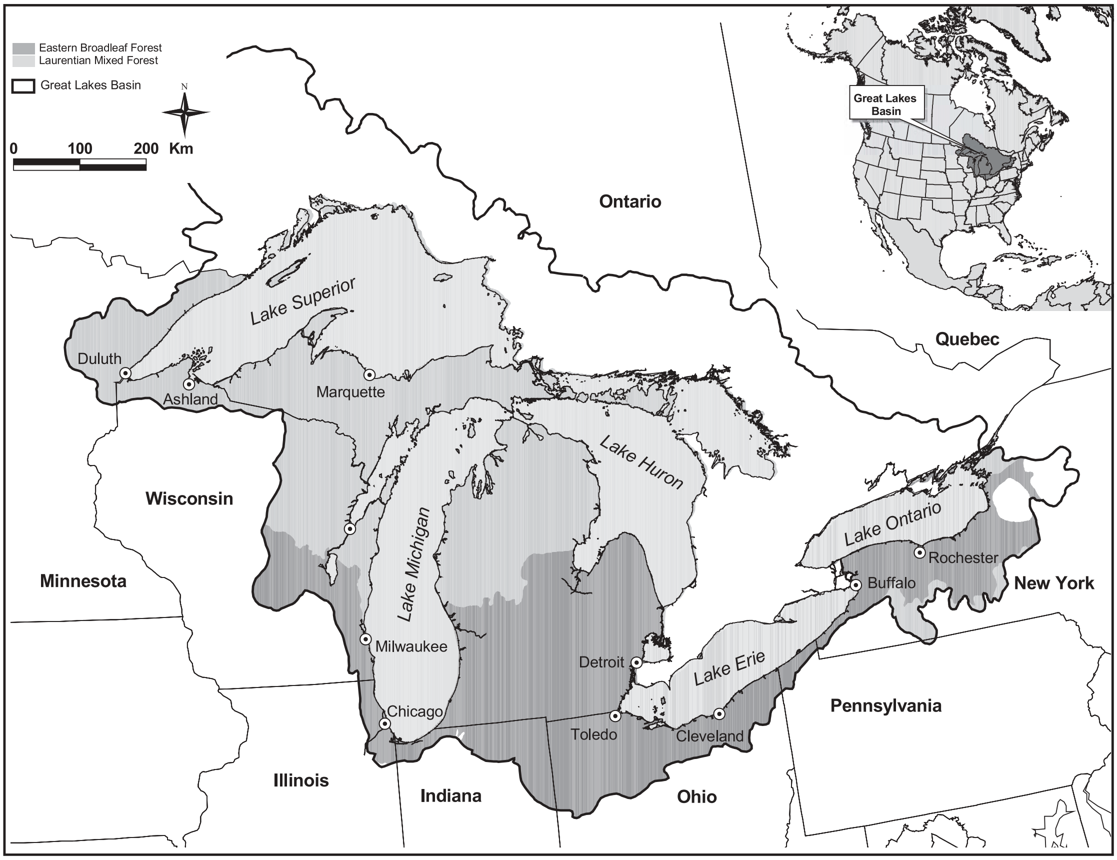


Fig. 1 The U.S. Great Lakes basin

Methods

Study Area

The Great Lakes basin encompasses more than 765,000 km^2 and 17,000 km of shoreline, bordering eight states and the Canadian province of Ontario (Fig. 1). The basin is within one of the most industrialized regions of the world and contains about 10% of the U.S. population and 30% of the Canadian population. Nearly 25% of Canadian agricultural production and 7% of American farm production are located in the basin (Government of Canada and U.S. EPA 1995). A boundary in climatic and physiographic features divides the U.S portion of the basin into two regions of nearly equal size occurring in the Laurentian Mixed Forest (LMF) and Eastern Broadleaf Forest (EBF) ecoprovinces (Bailey 1989) (Fig. 1). General patterns of human activity and land use in the basin differ between ecoprovinces, with most agricultural activities occurring in the southern portion of the basin, while the northern portion of the basin remains largely forested. Metropolitan areas are more common in the southern basin.

A substantial body of literature exists on the effects of human activities on biota of the basin. Primary human pressures on coastal ecosystems in the basin result from land use and landscape change (Brazner 1997; Detenbeck and others 1999; Richards and others 1996), climate change (Hartmann 1990; Mortsch and Quinn 1996; Magnuson and others 1997; Kunkel and others 1998; Mortsch 1998), exotic species (Brazner and others 1998; Brazner and Jensen 1999), point and nonpoint source pollution (The Nature Conservancy, 1994), atmospheric deposition (Vitousek and others 1997; Nichols and others 1999), and various hydrological modifications (e.g., dredging, breakwaters, docks, harbors) (Environment Canada and U.S. EPA 2003).

Stress Measures

We developed a geographic information system (GIS) database with 86 spatially delineated variables (Appendix I) previously used to distribute sampling effort across a range of environmental conditions in the Great Lakes basin (Danz and others 2005). We used a preliminary multivariate analysis and our professional judgment to classify the variables into five categories of anthropogenic stress that are prominent in the Great Lakes basin:

1. Agriculture—21 variables characteristic of the major types of stresses associated with agricultural activities, including nutrient runoff, fertilizers, pesticide application, and erosion. Agricultural land cover *per se* was included in the land cover category described below.
2. Atmospheric deposition —11 variables summarizing precipitation chemistry from the National Atmospheric Deposition Program (NADP). Sulfate, nitrate, ammonium, chloride, base cations, and pH are among the variables included.
3. Human population—5 variables representing human population density, road density, developed land, and distance to nearest U.S. EPA Area of Concern (AOC).
4. Land cover—23 land use/land cover variables derived primarily from the National Land Cover Dataset (NLCD) (Vogelmann and others 2001) and also from the Natural Resources Inventory. Accuracy rates for the predominant NLCD classes in the basin (forest, cropland, urban) were above 0.80 in the Great Lakes region (Stehman and others 2003).
5. Point source pollution—26 variables representing point sources of pollution, including mines, power plant emissions, and facilities with permitted wastewater discharges from the National Pollutant Elimination Discharge System (NPDES).

Although all data characterized anthropogenic stress in some fashion, there was considerable variation in the types of variables used. Some variables represented the extent of non-natural land cover (e.g., percentage of land devoted to high-intensity residential uses, or to row crops), whereas others represented specific human activities (e.g., point locations of mines), specific stressors (e.g., estimated quantity of nitrogen runoff), or potential for pollution (e.g., areal density of wastewater discharge facilities). Our premise was that we could create useful measures of stress by combining these kinds of data (Locantore and others 2004). Throughout the article, we equate increasing levels of human activity to increasing amounts of stress.

Although we considered the wide variety of stress variables a strength of our project, this also provided a considerable challenge: the original GIS-based measurements were quantified by a variety of data types (e.g., points, polygons, pixels) aggregated over a broad range of spatial and classification resolutions. The challenge was to summarize the data from these differing *source* units to one consistent set of *target* units. In the geographical literature, the general problem of differing source and target units is called the *change of support problem* (COSP) (Gotway and Young 2002), which calls for spatial data transformation to convert the source data to a common unit (Arbia 1989). Our target units were 762 coastal watersheds, hereafter called segment-sheds, that encompassed the entire U.S. Great Lakes basin (Danz and others 2005). Each segment-shed consisted of the land area delineated by two features: 1) a segment of the U.S. Great Lakes shoreline extending in both directions from the mouth of a second-order or higher stream to one-half the distance to the adjacent streams, and 2) the associated drainage area. The distribution of segment-shed areas ranged widely from 30 ha to 1.7 million ha and was positively skewed, with many small and few large segment-sheds (25th percentile: 1900 ha, median: 4600 ha, 75th percentile: 14,000 ha, mean: 38,000 ha).

We used a variety of spatial transformation methods, depending upon the source units. Where possible, we accounted for segment-shed area by expressing variables on a per-unit area basis. For example, point locations of wastewater discharge facilities (NPDES) were summarized by calculating the density of facilities per segment-shed area; human population density per segment-shed was interpolated using areal weighting (Markoff and Shapiro 1973; Goodchild and Lam 1980). Land cover variables from the National Land Cover Dataset, originally 30-m pixel resolution, were transformed by computing the proportion of total segment-shed area in each land cover category. Appendix I contains a complete list of target and source units, and the method of spatial data transformation for all variables.

We used principal components analysis (PCA) to integrate the information within each of the five categories of stress variables into a small number of stress measures. PCA is a multivariate statistical technique that creates a set of novel orthogonal variables (principal components, PCs) that are linear combinations of the original variables (Rencher 1995). Because the first few PCs often summarize the majority of the variation in the input data, the remaining PCs can be excluded from further analyses, thereby reducing dimensionality and removing redundancy without losing much information. For all PCAs, we used the correlation matrix of the input data rather than the covariance matrix because the data were measured in various scales and units (Rencher 1995). We interpreted the PCs by evaluating the eigenvectors and correlations between the input variables and the PCs (James and McCulloch 1990). Individual PCs were normalized to range between zero (lowest stress) and 1 (highest stress).

A cumulative index of stress was created by summing the normalized first principal component from each of the five categories for each segment-shed; thus, the cumulative stress index had a theoretical minimum of 0 and maximum of 5. We used the first PCs to comprise this index because they were interpreted as the best indicators of overall stress in their respective categories. Because the PCs were summed, each category of stress contributed to the index with equal weight. We also explored more complex methods for developing a cumulative index, including weighting stresses differently and accounting for covariation among the stress measures; however, these methods resulted in indices that were nearly perfectly correlated with the index from the summation method. Thus, we chose the summation method for simplicity. To evaluate the spatial distribution of stresses across the basin, we created maps and tabulated frequencies for the first principal components and the cumulative stress index.

Relationships Between Stresses and Ecological Variables

We used univariate and multivariate associative analyses to evaluate relationships between the stress measures and characteristics of water chemistry, fish communities, and bird communities in the coastal region. Our goal was to provide an illustrative set of analyses showing the usefulness of the stress measures for investigating stress-response relationships, not to exhaustively analyze the entire set of water chemistry, fish, and bird variables. A stratified random design was used to select sampling units that spanned the primary stress gradients in the basin (Danz and others 2005), with different taxa having different sample sizes. Generally, there was one sampling unit per segment-shed. Although the sampling units were in the coastal region (birds <1 km from shore, fish and water chemistry from the coastal zone), the stress measures were summarized for segment-sheds that contained the sampling units. Sampling units were assigned stress scores according to the segment-shed where they occurred.

Water chemistry data were collected using a waterboat or canoe in 136 coastal wetlands, embayments, and high-energy shoreline units in the summers of 2002 and 2003 by groups using standardized methods (Reavie and others (2006), J.A. Morrice, U.S. EPA Mid-continent Ecology Division, personal communication). Full analytical details are provided by Reavie and others (in press). Briefly, multiple measurements were taken in the submergent zone (0.5-m depth) at each site. Measurements of specific conductance were made using a field meter calibrated according to accepted standards. Water was collected in a 10-L polypropylene carboy and later used to measure turbidity, particulate chlorophyll fluorescence (Axler and Owen 1994), and complete water chemistry (total nitrogen, total phosphorus, total suspended solids, chloride, dissolved organic carbon, and chlorophyll *a*) (Ameel and others 1998). Geometric means of each water chemistry variable were computed per site. We used canonical correlation analysis (CCorA) to evaluate how the set of water chemistry variables was related to the set of stress measures comprised of the first PC from each category (Table 1). CCorA is a statistical technique used to evaluate the relationship between two sets of variables by maximizing the correlation between a linear combination of the variables in the first set with a linear combination of variables in the second set (Rencher 1995). Additionally, we developed predictive models of three commonly used indicators of water quality (total nitrogen, total suspended solids, and chloride) using simple linear regression with the cumulative stress index as the predictor.

Fish were sampled in the summers of 2002 and 2003 in coastal wetlands, embayments, and high-energy shorelines, for a total of 138 sites (Bhagat 2005). At each site, four pairs of fyke-nets were set parallel to depth contours in a lead-to-lead fashion as described by Brazner and others (1998). One pair of larger (12-mm mesh, 0.9 × 1.2-m front opening) and one pair of smaller nets (4-mm mesh, 0.45 m × 0.9-m front-end opening) were set overnight in each of the two dominant habitat types for one to two nights at each site. Nets were located near the 1-m (large nets) and 0.5-m (small nets)-depth contours. Fish were identified primarily using taxonomic descriptions in Becker (1983), counted, and released. Turbidity tolerance estimates for each species were taken primarily from Trebitz and others (in review) and Hughes and others (1998). Becker (1983) and Hocutt and Wiley (1986) were used to classify non-native fishes. All data were expressed as presence/absence per site. Species present at fewer than 14 of 138 sites were excluded to minimize the undue effects of uncommon species; 41 species remained. We carried out partial Canonical Correspondence Analysis (pCCA) using CANOCO® version 4 software (ter Braak and Šmilauer 1998) to evaluate the influence of anthropogenic stress on fish community composition independent of potential effects of geography (species ranges) and ecosystem type (habitat). In partial CCA, the goal is to find the amount of species variance that is unique and shared between a set of explanatory variables and a set of covariables (Borcard and others 1992). Our explanatory variables consisted

Table 1 Pearson correlations (*r*) between input variables and principal components[a]

	PC1		PC2	
Stress category	Variable	*r*	Variable	*r*
Agriculture	Phosphorus fertilizer export into streams	0.98	Area with animal facility nutrient treatment application	0.70
	Nitrogen fertilizer export into streams	0.97	Amount of sediment delivered to streams	–0.42
	Phosphorus fertilizer applications	0.97	Estimated pesticide runoff	–0.36
	Potash applications	0.97	Excess manure leaching potential	0.36
	Phosphorus export from livestock waste	0.96	Treated with agricultural herbicides	0.34
Atmospheric deposition	Inorganic nitrogen (N)	0.97	Calcium	0.79
	Chloride (Cl^-)	0.96	Magnesium	0.58
	Nitrate (NO_3)	0.95	Hydrogen ion	-0.38
	Sulfate (SO_4)	0.95	Nitrogen deposition into streams	–0.33
	Sodium (Na^+)	0.95	Ammonium (NH_4)	0.31
Human population	Human population density	0.92	Trail density	0.88
	Total road density	0.85	Distance to nearest Area of Concern	–0.37
	Developed land	0.83	Human population density	0.05
	Distance to nearest Area of Concern	–0.65	Total road density	0.05
	Trail density	–0.40	Developed land	0.04
Land cover	Cultivated cropland	0.78	High intensity residential	0.82
	Row crops	0.74	Commercial/industrial/transportation	0.81
	Coniferous forest	–0.74	Urban/recreational grasses	0.77
	Hay	0.71	Low intensity residential	0.73
	Mixed forest	–0.65	Amount of grazing land	–0.45
Point source pollution	Facilities discharging solvents	0.88	Powerplant SO_2 emissions	0.73
	Facilities discharging heavy metals	0.88	Powerplant CO_2 emissions	0.72
	Facilities discharging hydrocarbons	0.87	Powerplant NO_x emissions	0.72
	Density of sewerage facilities	0.86	Density of mines	0.49
	Facilities discharging chlorinated compounds	0.86	Density of mine processing facilities	0.46

[a] For brevity, only the five variables with greatest absolute loadings are shown for each category of stress. See Appendix I for a complete listing.

of the first two PCs from each category of stress, excluding human population PC2 (9 PCs), and the covariables consisted of 12 dummy variables coding for lake (Superior, Michigan, Huron, Erie, Ontario), ecoprovince (LMF and EBF), and site geomorphic type (open lacustrine wetland, protected wetland, river-influenced wetland, high-energy shoreline, and embayment). We used a biplot to display the ordination and overlaid a vector for the projected effect of the cumulative stress index. Partial CCA was appropriate for these data because the fish community gradients were long (i.e. >4 standard deviations) and variance inflation factors for the stress measures were acceptably low (ter Braak and Šmilauer 1998).

Bird data were collected during late May to early July 2002 and 2003 in 171 segment-sheds randomly selected to span stress gradients in the U.S. portion of the basin (Danz and others 2005). In each segment-shed, a sampling route with 15 10-minute, 100-m radius point counts was located along roads within 1 km of the coastline. Points were randomly located at least 500 m apart along routes and included both wetland and upland habitats. At each point, trained observers counted all bird individuals seen or heard in early morning hours (Howe and others 1998). Bird species were grouped into four nesting and four habitat guilds based on similarity of life history traits from review of the literature (Hanowski and others 2003). Bird data were summarized by calculating the proportion of individuals per transect for each guild. Analyses of guilds are commonly used to study bird community responses to human disturbance and to develop bird indices of biotic integrity (O'Connell and others 1998). We carried out multiple linear regression with guilds as dependent variables using the first PC from agriculture, land cover, and human population categories as independent variables. We also regressed each guild against the cumulative stress index alone.

Results

Interpretation of Stress Measures and Summary of Spatial Distribution

Within each category of stress, more than half of the input variables had loadings (i.e., Pearson correlations) with magnitude greater than ±0.5 on the first PC

Table 2 Interpretations of first two principal components from each stress category[a]

Stress category	*n* variables	PC	% variance	Interpretation
Agriculture	21	1	0.73	Overall agriculture (+)
		2	0.07	Runoff and sedimentation (–) vs. manure application (+)
Atmospheric deposition	11	1	0.75	Overall amount of deposition (+)
		2	0.13	Acidic deposition (–) vs. basic deposition (+)
Human population	5	1	0.57	Overall human population density and development (+)
		2	0.18	Trail density (+)
Land cover	23	1	0.23	Forest classes (–) vs. agricultural classes (+)
		2	0.15	Grazed land (–) vs. residential and commercial (+)
Point source pollution	26	1	0.45	Overall discharge of point source pollutants (+)
		2	0.13	Powerplant emissions and mines (+)

[a] The sign in parentheses indicates the direction of the relationship, which is arbitrary in PCA. For example, watersheds with high proportions of forested cover received negative scores on Land Cover PC1, whereas watersheds with high proportions of agriculture received positive scores.

(Appendix I), and there was a substantial reduction in the proportion of the variance by PCs subsequent to PC1. Thus, we interpreted the PC1s as primary gradients in the overall amount of stress in each category (Table 1, Table 2).

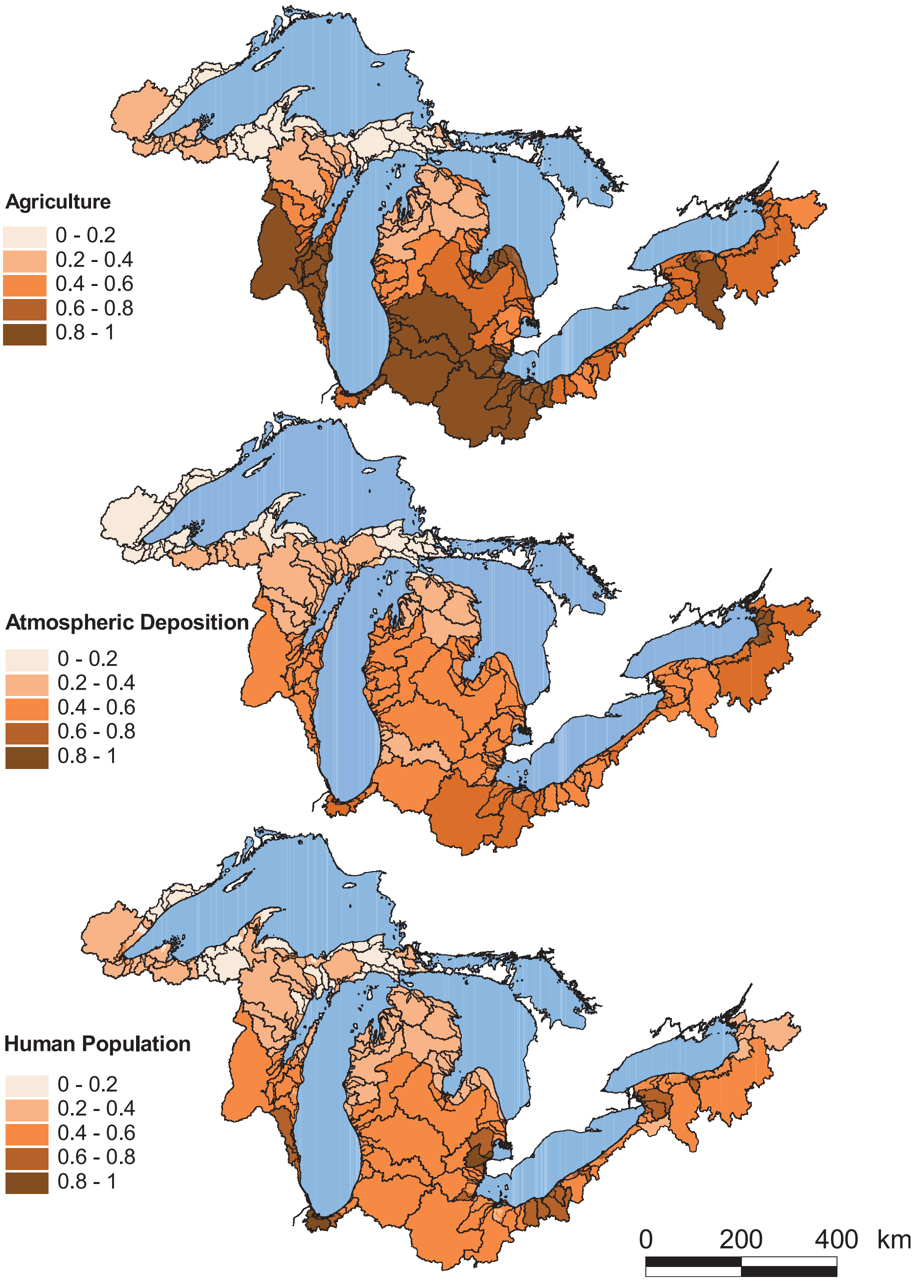
Agriculture. Variables related to nitrogen, phosphorus, and potash application or nitrogen and phosphorus runoff from fields and livestock feedlots tended to be most strongly related to PC1 ($r > 0.96$) (Table 1). Soil loss and total herbicide applications also had loadings (= correlations) > 0.90. Thus, the agriculture first PC combined information about disparate types of agricultural stress (nutrients from fertilizer and livestock manure, erosion, pesticides) into one overall summary index, accounting for 73% of the variation of the original suite of 21 variables. The stress scores of agricultural practices were generally low for the north and high for the south, especially so for segment-sheds of southern Lake Michigan, western Lake Erie, and southern Lake Huron (Fig. 2).

Atmospheric deposition. The first PC summarized a high amount of redundancy in the input variables (75% of the variance), and although it was strongly related to overall deposition (all 11 variables with loadings ≥0.59), this PC especially represented overlapping gradients in chloride, sulfate, nitrate, sodium, and inorganic nitrogen. The second PC represented a gradient from acidic to basic deposition, with calcium and magnesium having positive loadings and hydrogen ion deposition having the most negative loading. Atmospheric deposition displayed a strong west/east gradient across the basin, likely due in part to the prevailing wind direction and to greater industrial activity in the lower lakes, particularly around Lake Erie, southern Lake Michigan, and eastern Lake Ontario (Fig. 2). Greatest depositional stress was observed in segment-sheds in the northeast portion of Lake Ontario.

Human population. PC1 from the human population category integrated information about roads, population density, and developed areas. Strong positive correlations were observed between population density, total road density, the proportion of developed land, and the first PC (Table 1). PC1 accounted for 57% of the total variation in the original set of five variables. Trail density was the lone variable that loaded highly on PC2 ($r = 0.88$); this PC accounted for 18% of the variance. Population centers including Duluth, Green Bay, Milwaukee, Chicago, Detroit, Toledo, Cleveland, Buffalo, and Rochester received high scores on PC1, whereas sparsely populated areas, for example, along Minnesota's Lake Superior shoreline or in the eastern Upper Peninsula of Michigan, received low scores on PC1 (Fig. 2).

Land cover. Although the variance explained by the first land cover PC was low (23%), the interpretation was unambiguous: scores represented a gradient from forest to agriculture. Amount of forest cover and native grasslands were strongly negatively associated with PC1, whereas various classes of agricultural land cover were strongly positively correlated with this axis (especially cultivated crops, hay, grazing, uncultivated crops; Appendix I). Land used for residential and commercial purposes also correlated positively with this PC, but not as highly as with the second PC. Forest lands throughout the basin were generally cleared of timber in the 19th–20th centuries. Many segment-sheds of the Laurentian Mixed Forest province have returned to forest, whereas segment-sheds in the EBF

Fig. 2 Stress measures (first PCs) for agriculture, atmospheric deposition, and human population. Color categories are five equally spaced intervals on each stress measure, darker shading indicates greater stress. Boundaries were dissolved for 278 segment-sheds that were smaller than 3000 ha to improve clarity



portion of the basin have experienced much greater permanent conversion to agricultural lands and population centers (Fig. 3).

Point source pollution. PC1 from the pollution category reflected the overall discharge of a wide range of chemical pollutants from point sources of wastewater into streams in coastal segment-sheds. The first PC accounted for 45% of overall variation in the 26 pollution variables. PC2 accounted for an additional 13%, relating mainly to powerplant emissions and mine density (Table 2). Areas of Concern (International Joint Commission 2003) and larger population centers received high scores on PC1 for the pollution stress category (Fig. 3).

Although the PCAs were computed for five categories of stress individually, there were strong relationships among the PCs across categories. For example, PC1 from the agriculture variables had strong correlations with PC1 from atmospheric deposition, land cover, and human population categories (Table 3), which indicates that agriculture in coastal

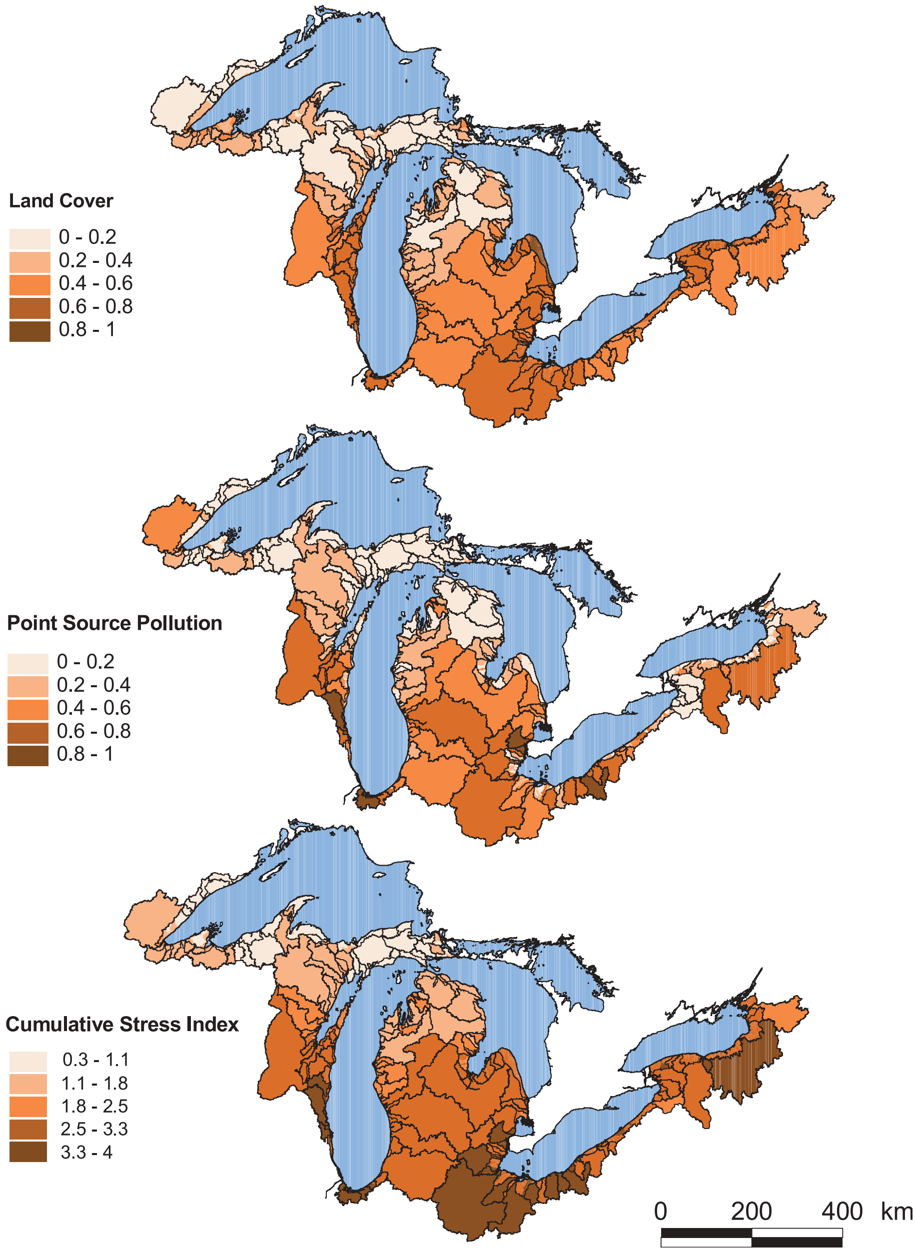


Fig. 3 Stress measures (first PCs) for land cover and point source pollution, and the cumulative stress index. Color categories are five equally spaced intervals on each stress measure, darker shading indicates greater stress. Boundaries were dissolved for 278 segments-sheds that were smaller than 3000 ha to improve clarity

segment-sheds co-occurs with other types of stress. The tendency for stresses to co-occur within segment-sheds was generally stronger for larger segment-sheds than smaller segment-sheds, although the scores along PC1 were not significantly related to segment-shed area for any stress category ($p > 0.05$). Despite the co-occurrence of stressors over the entire basin, relationships among stress types sometimes varied considerably for individual lakes. For example, agriculture PC1 and atmospheric deposition PC1 had a Pearson correlation of +0.83 for segment-sheds across the entire basin, but the correlation ranged from –0.89 (Lake Ontario) to +0.88 (Lake Huron) within lakes.

Cumulative Stress Index. The index ranged from 0.33 to 4.03 (mean = 2.08, median = 2.43, $n = 762$) and was positively correlated with each of the five component scores (Table 3), thereby representing a generalized stress gradient across the basin (Fig. 3). The correlation was strong ($r > 0.8$) for each of the stresses except the point source pollution measure ($r = 0.60$). The stress measures were individually more highly correlated with the cumulative stress index than with any other stress measure. Segment-sheds in the EBF ecoprovince had a mean stress index over two times greater than those in the LMF ecoprovince (2.9 ± 0.4 [SD] vs. 1.4 ± 0.8, respectively). On average, the

Table 3 Pearson correlation (r) matrix[a] for the principal components and cumulative stress index

		Agriculture		Atmospheric deposition		Human population		Land cover		Point source pollution		
Stress category	PC	1	2	1	2	1	2	1	2	1	2	Cumulative stress index
Agriculture	1	1										
	2	0	1									
Atmospheric deposition	1	0.83	0.16	1								
	2	0.12	0.02	0	1							
Human population	1	0.61	0.19	0.63	–0.02	1						
	2	–0.21	0.17	–0.17	–0.03	0	1					
Land cover	1	0.84	–0.15	0.69	–0.02	0.60	–0.32	1				
	2	0.07	0.10	0.15	0.12	0.26	0.26	0	1			
Point source pollution	1	0.34	0.12	0.34	0.07	0.29	0.60	0.65	0.15	1		
	2	0.02	0.04	0.00	0.02	-0.06	0.06	0.03	0.11	0	1	
Cumulative stress index		0.92	0.06	0.87	0.05	0.86	0.30	0.82	–0.16	0.60	0.00	1

[a] Statistical significance for correlations (n = 762 segment-sheds):
$r < 0.07$: $p > 0.05$
$0.07 \le r < 0.10$: $0.05 \ge p > 0.01$
$0.10 \le r < 0.15$: $0.01 \ge p > 0.0001$
$r > 0.15$: $p \le 0.0001$

index ranged from ~1.0 for Lake Superior to ~3.1 for Lake Erie. Lake Michigan and Lake Huron tended to have intermediate index scores, around 2.3, whereas Lake Ontario was most similar to Lake Erie. Within the Lake Superior basin, where little agriculture is generally practiced, the highest scoring segment-sheds were those with high population density (Superior, WI [2.7], Duluth, MN [2.4], and Ashland, WI [2.4]). For Lake Michigan and Lake Huron, the stress index clearly increased from north to south, reflecting a gradient from forest to agricultural and urban land use. All segment-sheds in Lake Erie and Lake Ontario had scores above the median. Segment sheds with the greatest amount of stress occurred on the western shore of Lake Michigan, southwest Lake Erie, and southeastern Lake Ontario (Fig. 3).

Relationships Between Stresses and Ecological Variables

Water chemistry characteristics in coastal ecosystems were strongly associated with stress measures in coastal segment-sheds, with the first canonical variables having a correlation coefficient of 0.81 (Fig. 4). Canonical variable 1 from the water chemistry data was related to overall pollution, with six variables representing increased nutrients, sediments, and ions having loadings >0.65. Canonical variable 1 of the stress data was related to increasing amounts of all five types of stress ($r > 0.60$). In particular, the agriculture stress measure was nearly perfectly correlated with stress canonical variable 1 (r = 0.97), reflecting the strong link between agriculture and coastal water chemistry across the basin. Measured total nitrogen, total suspended solids, and chloride, three widely accepted indicators of water quality, were clearly higher in Great Lakes coastal ecosystems having higher cumulative stress index scores (Fig. 5).

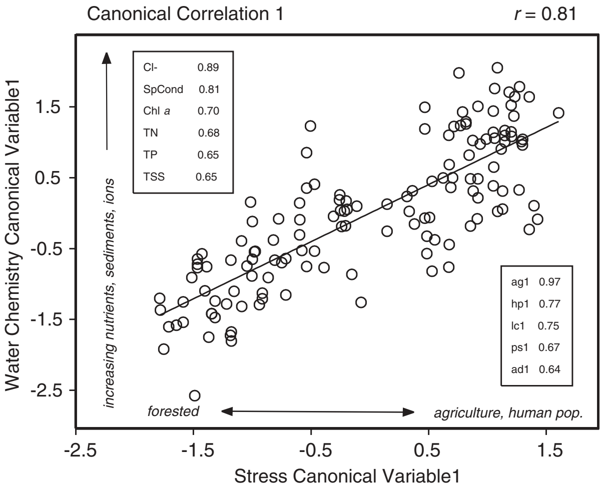


Fig. 4 First canonical correlation between nine water chemistry variables and five stress measures. Inset: loadings for individual variables on their canonical axis (Cl- = chloride, SpCond = specific conductivity, Chl *a* = chlorophyll *a*, TN = total nitrogen, TP = total phosphorus, TSS = total suspended solids; ag = agriculture, hp = human population, lc = land cover, ps = point source, ad = atmospheric deposition)

Total variance in fish community composition explained by stress, geographical location, and site geomorphology was 30%. Seven percent of the variation was unique to the stress variables and 14% was unique to geographic location and geomorphology. Five non-native fish species were commonly caught in the

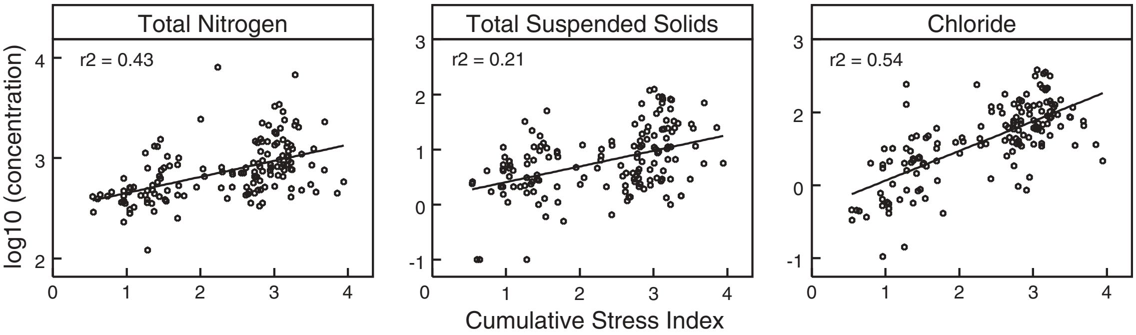


Fig. 5 Scatter plots showing the relationship between the cumulative stress index and sample concentrations of total nitrogen (μg/L), total suspended solids (mg/L), and chloride (μg/L). Note the logarithmic scale on the *y*-axis

fyke nets (round goby, common carp, alewife, goldfish, and white perch). These species were positioned along the left part of axis 1 (Fig. 6), in the direction of increasing stress for all five first PCs. Species tolerant of turbidity were also positioned in the direction of increasing stress, whereas three intolerant species (mudminnow, blacknose shiner, and slimy sculpin) were positioned in the direction of more natural land cover and decreasing stress. The lower right portion of the ordination plot is dominated by species sensitive to environmental degradation (e.g., blacknose shiner, slimy sculpin) as well as several important forage species that are sensitive to predation throughout the Great Lakes (e.g., bluntnose minnow, trout-perch, and common shiner). The upper left quadrant of the ordination comprised mainly species that are non-native or tolerant of highly disturbed and eutrophic environments (e.g., carp, alewife, gizzard shad). The vector for the cumulative stress index was positioned in the middle of the individual stress vectors, indicating that the projected influence of cumulative stress was related to the combined influence of the individual stresses.

The proportion of bird individuals in habitat and nesting guilds was significantly related to the stress measures for all guilds (Table 4). Human population PC1 was a significant predictor for all guilds except field/

Fig. 6 Partial canonical correspondence analysis diagram using presence/absence data for 41 fish species present on at least 14 of 138 sites. Non-native species are indicated with *, species intolerant or moderately intolerant of turbidity are indicated with #, species tolerant of turbidity are indicated with ^. The CCA was constrained by nine stress measures (only the six strongest shown) and used dummy variables for lakes, ecoprovinces, and site geomorphology as covariables. The total variance explained was 30%, with 7% unique to stress variables, 14% unique to covariables, and 9% shared between the two sets of variables

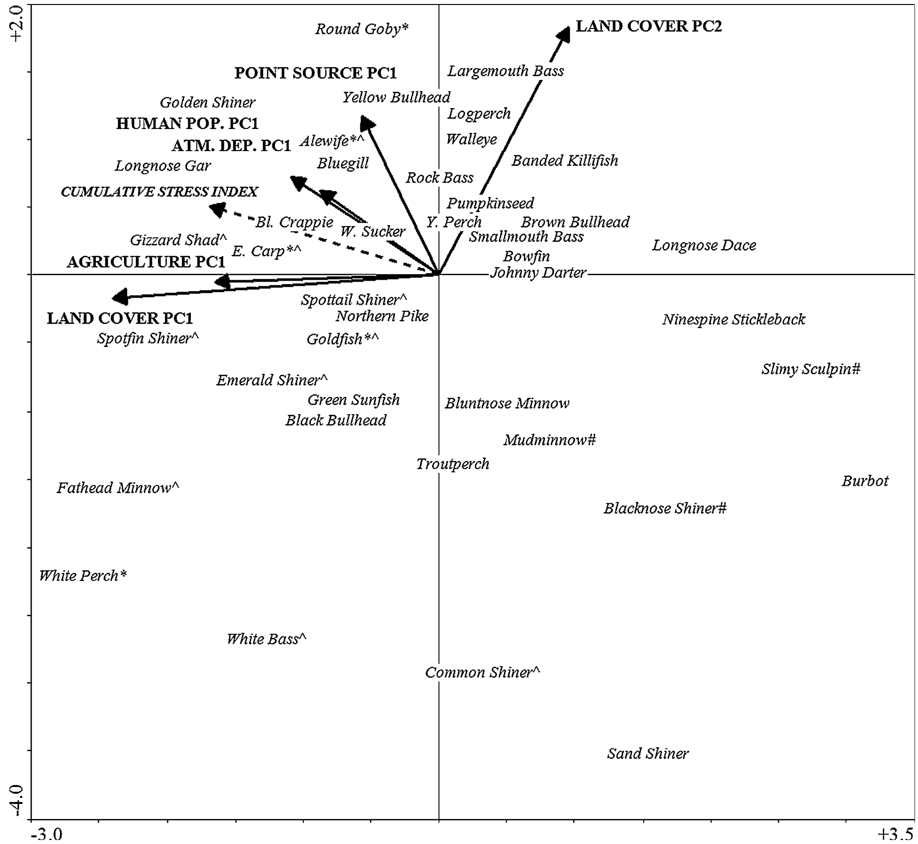


Table 4 Multiple linear regression models for bird guilds

		Parameter estimates			Overall model	
Guild	Category	Agriculture PC1	Land cover PC1	Human population PC1	R^2_{adj}	p
Nesting	Canopy	0.04	–0.16***	–0.14***	0.30	< 0.0001
	Shrub/subcancopy	0.03	0.09	–0.18**	0.04	0.02
	Forest ground	–0.13***	–0.02	–0.17***	0.66	< 0.0001
	Open ground	0.03	0.10	–0.06	0.03	0.03
Habitat	Forest interior	–0.15***	–0.08*	–0.26***	0.60	< 0.0001
	Forest generalist/edge	0.00	0.28**	0.28**	0.35	< 0.0001
	Fields and Meadows	0.04	0.20**	–0.08	0.21	< 0.0001
	Urban	0.04	0.08	0.60***	0.53	< 0.0001

*$0.10 \geq p > 0.01$

**$0.01 \geq p > 0.001$

***$p \leq 0.001$

meadow species and open-ground nesting species. Stress from agriculture, land cover, and human population corresponded to lower relative abundance of species requiring forest habitats, such as canopy nesting, forest-ground nesting, and forest interior species. Conversely, increasing stress was related to increasing proportion of forest generalist/edge, urban, and field/meadow species. Open-ground nesting and shrub/subcanopy nesting species, two guilds comprising species from a wide range of natural and disturbed habitats (e.g., forest, fencerows, fields, and towns) were poorly predicted by the stress variables despite having $p < 0.05$. The cumulative stress index was a significant predictor for all guilds except shrub/subcanopy nesting birds. Models using the cumulative stress index as the only predictor explained a slightly lower proportion of variance compared to models with three stress measures (Fig. 7), although the differences were minor (difference in adjusted R^2 ranged from 0 to 0.07 across the eight guilds).

Discussion

Objectives of biological monitoring and assessment range from finely resolved regulatory questions addressing the influence of a particular stressor on biological condition to broader integrated assessments of environmental quality over large geographic regions. As a result, there is probably no single universal method that best quantifies anthropogenic stress. Using readily available spatially referenced data, we developed integrated gradients of five types of stress and a cumulative stress index that reflect the major sources of ecological impairment in the Great Lakes basin. The stress measures were evaluated against ecological variables known to respond predictably to stress from other studies in the Great Lakes region (e.g., water chemistry: Crosbie and Chow-Fraser 1999, fish: Brazner 1997, birds: Miller 2003). Increasing amounts of anthropogenic stress were strongly related to increasing concentrations of water pollutants, to shifts in fish community composition towards non-native, turbidity-tolerant species, and to increasing proportions of urban and generalist bird species and decreasing proportions of bird species requiring forest habitats. These relationships help corroborate that the integrated measures indeed reflect stress and that they are ecologically meaningful. Hence, these measures may be appropriate for multiple objectives including interpreting the spatial pattern of stress across a large geographic region, prioritizing areas for management actions, and understanding relationships between human activities and coastal ecosystem condition.

Although it is usually not possible to acquire sufficient data to fully characterize the multiple pathways of impairment even for single watersheds, major mechanisms of impairment over a region can be identified by integrating broad-scale variables representing stress (Bryce and others 1999, Locantore and others 2004). We purposely summarized a large number of variables representing the major stresses of management concern in the basin (Environment Canada and U.S. EPA 2003). Although the first PCs summarize the greatest amount of redundancy among the input variables, they do not necessarily represent ecologically important gradients; the PCs must first be interpreted. Within each stress category, the high loadings of more than half of the variables on the first PC and the amount of variance explained made it clear that the PC1s represented composite gradients of stress.

Keeping stress categories separate allows interpretation of the major influential stresses for particular ecological variables. For example, decreased water quality in our field data was more strongly related to agriculture than other types of stress. Bird guilds comprising species that require forest habitat were

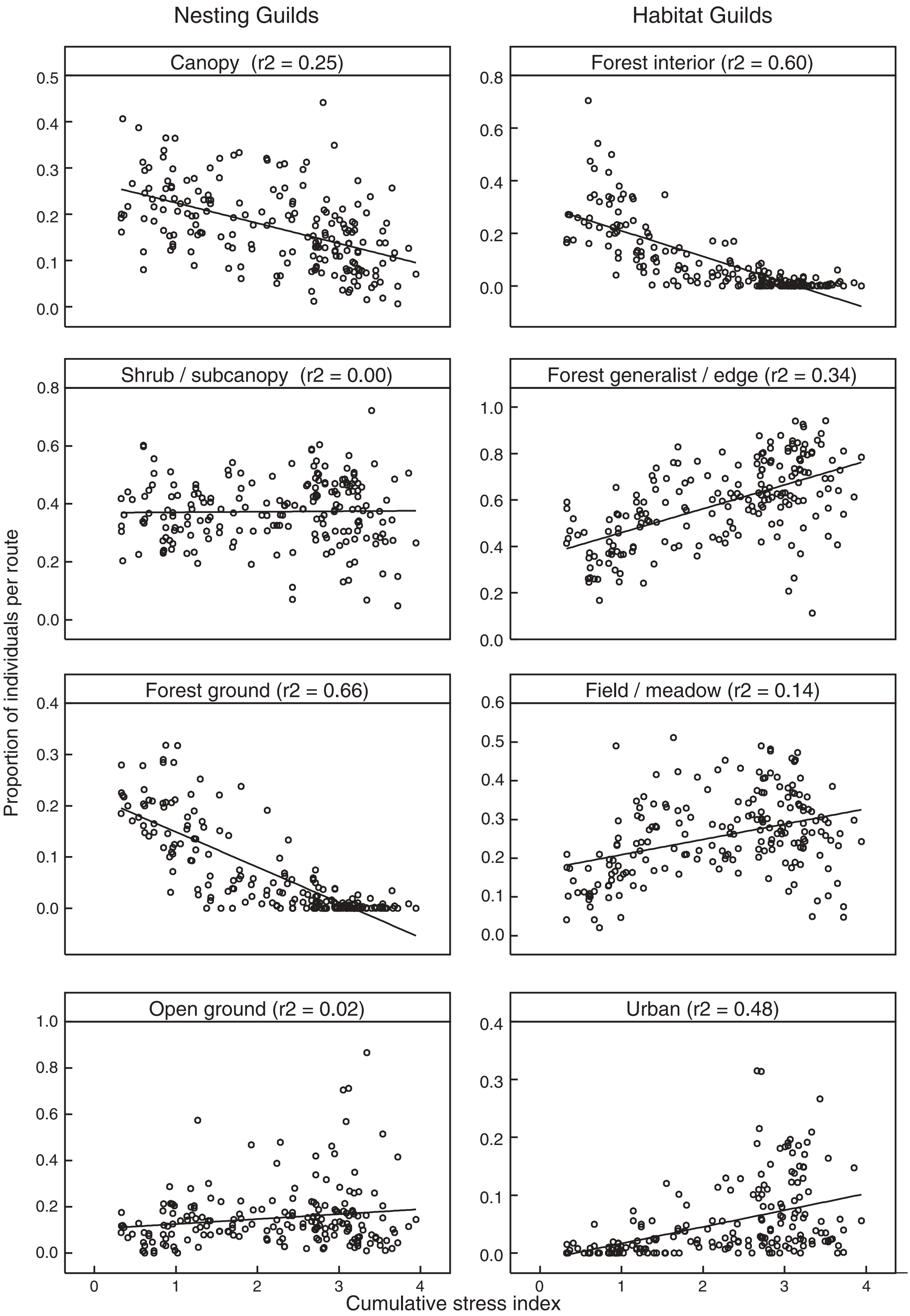


Fig. 7 Proportion of bird individuals per route in four nesting and four habitat guilds against the cumulative stress index

significantly negatively related to stress from both agriculture and human population. Although keeping the categories separate is useful for comparison among stress types, combining the stresses into an index will better represent their cumulative overlapping nature (Shoemaker 1994). In our fish community ordination, the vector representing the cumulative stress index pointed in the direction of fish communities comprising non-native and turbidity-tolerant species, and was centrally located between all the individual stress measures. Additionally, the cumulative stress index was nearly or equally as good a predictor as the individual stress measures combined for the eight bird guilds and was also a significant predictor of the three water quality indicators. Taken together, these strong links with our field data indicate that the cumulative stress index is useful for summarizing multiple stresses across the basin.

A major benefit of using spatial data in a GIS was that stresses could be summarized for the entire U.S. portion of the basin. Because many current environmental problems occur over large geographic regions (Hunsaker and others 1990), the ability to create wall-to-wall descriptions is of great importance for summarizing stresses that overlap in space or time (Wickham and others 1999). The large amount of readily available data from monitoring and reporting programs throughout the United States creates opportunities to transfer our technique to any region. Obtaining such data will generally involve minimal cost, but substantial effort may be required to process and summarize the data for the units of the study region (Strayer and others 2003).

In addition to the stresses we report on, there are other major regional threats to Great Lakes ecosystems that will be more difficult to quantify using our methodology. For example, stress from invasive species, one of the greatest risks to the health and productivity of Great Lakes coastal ecosystems (Holeck and others 2004), is difficult to quantify from a geospatial perspective due to a lack of available data and to the complex relationships between exotic and native species (Ricciardi 2001). Additionally, segment-sheds are possibly not appropriate summary units for stress from invasives because stress from terrestrial taxa is not likely transferred down the drainage network as other stresses such as agricultural nutrients and pesticides. Moreover, the distribution of invasive aquatic species is unlikely to be regulated by terrestrial topography, except if there are hydrological connections. Incorporation of information on why areas are susceptible to invasive species may allow the identification of areas under risk of serious damage from these species. Global climate change is another source of anthropogenic stress to Great Lakes coastal ecosystems (Kling and others 2003) that operates on broader spatial and temporal scales than the stresses we have reported on. Future analyses that include water level fluctuations in the coastal region over time could be used to incorporate human impacts from climate change into regional measures of stress.

There are strong spatial patterns of stress across the U.S. Great Lakes basin. In general, segment-sheds in the basins of Lake Erie, Lake Ontario, and the lower portions of Lake Michigan and Lake Huron had the greatest amounts of stress, whereas segment-sheds in northern Lake Michigan, northern Lake Huron, and Lake Superior had the lowest amounts. The spatial resolution of the gradients was fine enough to map local differences in stress. For example, the human population measure clearly identified the largest urban centers within the least populated lake: Duluth, MN; Superior, WI, and Ashland, WI had the highest scores on this gradient in Lake Superior (Fig. 5). The basin-wide patterns of stress are the product of interactions between human activities and physical characteristics of the environment. For example, climatic and geologic differences provide more favorable conditions for agriculture in the lower lakes. Additionally, the strong west/east gradient in atmospheric deposition is related to both greater industrial activity in the lower lakes and the westerly winds that prevail in the region (Environment Canada and US EPA 2003).

We believe the stress measures described herein represent the major threats to coastal ecosystems in the U.S. Great Lakes. In this study, fish, bird, and water chemistry characteristics were clearly correlated to terrestrial human activity in the Great Lakes coastal region. Although connections between human activities and ecological condition have been well established for streams, there are relatively few such results for freshwater coastal ecosystems. Studies from both Canadian and U.S. portions of the Great Lakes basin have demonstrated the influence of land use changes on water quality and biotic community structure in coastal wetlands (Crosbie and Chow-Fraser 1999, Lougheed and others 2001, Timmermans and Craigie 2003, Albert and Minc 2004, Grabas and others 2004, Uzarski and others 2004, Uzarski and others 2005). Soon-to-be-published studies from the Great Lakes Environmental Indicators (GLEI) project (Danz and others 2005) for amphibians, birds, contaminants, macroinvertebrates, water chemistry, and wetland vegetation will include more detailed approaches for describing responses to stress, investigating mechanisms of degradation, evaluating the spatial extents at which stresses are influential, and identifying thresholds below which minimally degraded coastal ecosystems remain.

There are several ongoing efforts in the Great Lakes to develop methods for assessing the condition of coastal habitats and to protect and restore their biological, chemical, and physical integrity (United States and Canada 1978), including the SOLEC process (Environment Canada and U.S. EPA 2003), the Great Lakes Coastal Wetland Consortium (http://www.glc.org/wetlands/) and Lakewide Management Plans (LaMPs; http://www.great-lakes.net/lakes/ref/lamps.html). Such regional-scale efforts are critical for understanding relationships between human disturbance and ecosystem response, and for prioritizing environmental decision-making at both regional and local scales. This will presumably lead to better protection of coastal areas, which are increasingly at risk from multiple human pressures (Niemi and others 2004). The analyses presented here provide an initial framework upon which multiple stressors can be quantified spatially and over extensive regions in a standardized fashion. Periodic updates of these data will provide a means of measuring the magnitude of improvement or continued degradation within specific regions or over the entire region.

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Appendix I Variables used to summarize anthropogenic stresses

Category	Variable	r_{PCI}	r_{PC2}	Resolution	Units	Agency	Web address	Program
	Area with animal facility nutrient treatment application	0.35	0.70	8-digit HUC	proportion	USDA-NRCS	http://ias.sc.egov.usda.gov/parmsreport/nutrient.asp	FY 2001 Performance Results Measurement System (PRMS)
Agriculture	Estimated soil loss from segment shed	0.95	–0.01	8-digit HUC	tons/ha/yr	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/pubs/wqpost2.html	Natural Resources Conservation Service
	Excess manure leaching potential	0.84	0.36	8-digit HUC	index	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/pubs/wqpost2.html	Natural Resources Conservation Service
	Excess manure runoff potential	0.87	0.33	8-digit HUC	index	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/pubs/wqpost2.html	Natural Resources Conservation Service
	Total nitrogen export by water from segment	0.82	–0.01	8-digit HUC	$kg/km^2/yr$ tons/sq	USGS	http://water.usgs.gov/nawqa/sparrow/wrr97/results.html	NAWQA SPARROW (surface water quality modeling of nutrients)
	Average amount of all nitrogen fertilizers applied	0.96	–0.15	County	mile	USGS	http://pubs.usgs.gov/wri/wri944176/	Water-Resources Investigations Report 94–4176
	Nitrogen fertilizer export into streams	0.97	0.04	8-digit HUC	$kg/km^2/yr$	USGS	http://water.usgs.gov/nawqa/sparrow/wrr97/results.html	NAWQA SPARROW (surface, water quality modeling of nutrients)
	Excess nitrogen fertilizer leaching potential	0.85	0.21	8-digit HUC	index	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/pubs/wqpost2.html	Natural Resources Conservation Service (NRCS)
	Excess nitrogen fertilizer runoff potential	0.90	0.11	8-digit HUC	index	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/pubs/wqpost2.html	Natural Resources Conservation Service (NRCS)
	Nitrogen export from livestock waste into streams	0.92	0.22	8-digit HUC	$kg/km^2/yr$	USGS	http://water.usgs.gov/nawqa/sparrow/wrr97/results.html	NAWQA SPARROW (surface water quality modeling of nutrients)
	Estimated pesticide leaching from segment shed	0.59	–0.33	8-digit HUC	lbs/ha/yr	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/pubs/wqpost2.html	Natural Resources Conservation Service (NRCS)
	Estimated pesticide runoff from segment shed	0.82	–0.36	8-digit HUC	lbs/ha/yr	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/pubs/wqpost2.html	Natural Resources Conservation Service (NRCS)
	Phosphorus fertilizer export into streams	0.98	0.01	8-digit HUC	$kg/km^2/yr$	USGS	http://water.usgs.gov/nawqa/sparrow/wrr97/results.html	NAWQA SPARROW (surface water quality modeling of nutrients)
	Phosphorus fertilizer application (average)	0.97	–0.16	County	$tons/mile^2$	USGS	http://pubs.usgs.gov/wri/wri944176/	Water-Resources Investigations Report 94–4176
	Phosphorus export from livestock waste into streams	0.96	0.13	8-digit HUC	kg/km2/yr	USGS	http://water.usgs.gov/nawqa/sparrow/wrr97/results.html	NAWQA SPARROW (surface water quality modeling of nutrients)
	Potash applications (average)	0.97	–0.13	County	$tons/mile^2$	USGS	http://pubs.usgs.gov/wri/wri944176/	Water-Resources Investigations Report 94-4176

Appendix I. Continued

Category	Variable	r_{PC1}	r_{PC2}	Resolution	Units	Agency	Web address	Program
	Total phosphorus export by water from segment	0.81	–0.03	8-digit HUC	$kg/km^2/yr$	USGS	http://water.usgs.gov/nawqa/sparrow/wrr97/results.html	NAWQA SPARROW (surface water quality modeling of nutrients)
	Segment rank for pesticide and nitrogen leaching	0.64	0.32	8-digit HUC	rank	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/pubs/wqpost2.html	Natural Resources Conservation Service (NRCS)
	Segment rank for erosion, pesticide and nitrogen runoff	0.85	–0.14	8-digit HUC	rank	USDA-NRCS	http://www.nrcs.usda.gov/teclinical/land/pubs/wqpost2.html	Natural Resources Conservation Service (NRCS)
	Amount of sediment delivered to streams	0.75	–0.42	8-digit HUC	tons/ha/yr	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/erosion.html	National Resources Inventory (NRI)
	Treated with agricultural herbicides	0.90	–0.34	County	proportion	USGS	http://pubs.usgs.gov/wri/wri944176/	U.S.G.S. summary of 1987 Census of Agriculture
Atmospheric deposition	Calcium deposition from atmosphere	0.59	0.79	point	kg/ha/yr	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)
	Chloride deposition from atmosphere	0.97	–0.20	point	ka/ha/yr	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)
	Hydrogen ion deposition (lab measurement)	0.90	–0.38	point	kg/ha/yr	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)
	inorganic nitrogen deposition	0.98	–0.05	point	kg/ha/yr	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)
	Potassium deposition from atmosphere	0.79	–0.01	point	kg/ha/yr	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)
	Magnesium deposition from atmosphere	0.77	0.58	point	kg/ha/yr	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)
	Sodium deposition from atmosphere	0.97	–0.04	point	kg/ha/yr	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)
	Ammonium deposition from atmosphere	0.90	0.31	point	kg/ha/yr	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)
	N export from atmosphere into streams	0.59	–0.33	point	kg/ha/yr	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)
	Nitrate deposition from atmosphere	0.96	–0.17	point	kg/ha/yr	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)

Appendix I. Continued

Category	Variable	r_{PC1}	r_{PC2}	Resolution	Units	Agency	Web address	Program
	Sulfate deposition from atmosphere	0.95	–0.22	point	$kg/km^2/yr$	multi-agency	http://nadp.sws.uiuc.edu/	National Atmospheric Deposition Program (NADP)
Human population	Developed land	0.83	0.04	8-digit HUC	proportion	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/urban.html	National Resources Inventory (NRI)
	Distance to nearest Area of Concern	–0.65	–0.37	point	km	USEPA	http://www.epa.gov/glnpo/aoc/index.html	U.S. EPA Region 5, Chicago, IL
	Human population density	0.92	0.05	Census block	$\#/km^2$	US Census Bureau	http://www.census.gov/geo/www/census2k.html	U.S. Census 2000
	Total road density	0.85	0.05	1:100,000	$\#/km^2$	US Census Bureau	http://www.census.gov/geo/www/tiger/index.html	Topologically Integrated Geographic Encoding and Referencing (TIGER)
	Trail density (4wd roads & walking trails)	–0.40	0.88	1:100,000	$\#/km^2$	US Census Bureau	http://www.census.gov/geo/www/tiger/index.html	Topologically Integrated Geographic Encoding and Referencing (TIGER)
	Amount of cultivated cropland	0.78	–0.26	8-digit HUC	proportion	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/cropland.html	National Resources Inventory (NRI)
Land cover	Amount of grazing land	0.55	–0.45	8-digit HUC	proportion	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/cropland.html	National Resources Inventory (NRI)
	Amount of non-cultivated cropland	0.55	–0.45	8-digit HUC	proportion	USDA-NRCS	http://www.nrcs.usda.gov/technical/land/cropland.html	National Resources Inventory (NRI)
	Bare Rock/Sand/Clay	–0.15	0.12	30 m* 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Evergreen Forest	–0.74	–0.18	30 m* 30m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Commercial/Industrial/Transportation	0.24	0.81	30 m* 30m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Deciduous Forest	–0.55	–0.12	30 m* 30m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Emergent Herbaceous Wetlands	–0.45	0.18	30 m* 30m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Great Lakes	0.03	0.11	30 m* 30m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Urban/Recreational Grasses	0.31	0.77	30 m* 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Grasslands/Herbaceous	–0.45	0.21	30 m* 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Pasture/Hay	0.71	–0.21	30 m* 30m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	High Intensity Residential	0.32	0.82	30 m* 30m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Low Intensity Residential	0.47	0.73	30 m * 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)

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Category	Variable	r_{PC1}	r_{PC2}	Resolution	Units	Agency	Web address	Program
	Mixed Forest	–0.65	–0.22	30 m * 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Quarries/Strip Mines/Gravel Pits	–0.11	0.24	30 m * 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Orchards/Vrneyards/Other	0.00	0.11	30 m * 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Row Crops	0.74	–0.16	30 m * 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Shrubland	–0.02	0.24	30 m * 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Transitional land	–0.53	0.03	30 m * 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Open Water	–0.50	0.33	30 m * 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Woody Wetlands	–0.57	0.03	30 m * 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
	Small Grains	0.01	0.21	30 m * 30 m	proportion	USGS	http://landcover.usgs.gov/natllandcover.html	National Land Cover Database (NLCD)
Point source pollution	Mine density in segment	0.37	0.49	point	#/shoreline km	USGS	http://geo-nsdi.er.usgs.gov/metadata/provisional/amis/metadata.html	Mineral resources spatial data
	Mine processing plant density in segment	0.42	0.46	point	#/shoreline km	USGS	http://geo-nsdi.er.usgs.gov/metadata/provisional/amis/metadata.html	Mineral resources spatial data
	N export from nonagricultural sources into streams	0.02	0.04	8-digit HUC	$kg/km^2/yr$	USGS	http://water.usgs.gov/nawqa/sparrow/wrr97/results.html	NAWQA SPARROW (surface water quality modeling of nutrients)
	N export from point sources into streams	0.48	0.04	8-digit HUC	$kg/km^2/yr$	USGS	http://water.usgs.gov/nawqa/sparrow/wrr97/results.html	NAWQA SPARROW (surface water quality modeling of nutrients)
	P export from nonagricultural sources into streams	0.02	0.03	8-digit HUC	$kg/km^2/yr$	USGS	http://water.usgs.gov/nawqa/sparrow/wrr97/results.html	NAWQA SPARROW (surface water quality modeling of nutrients)
	P export from point sources into streams	0.51	0.02	8-digit HUC	$kg/km^2/yr$	USGS	http://water.usgs.gov/nawqa/sparrow/wrr97/results.html	NAWQA SPARROW (surface water quality modeling of nutrients)
	Facilities discharging chlorinated compounds	0.86	–0.37	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Facilities discharging hydrocarbons	0.87	–0.28	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Facilities discharging heavy metals	0.88	–0.31	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)

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Category	Variable	r_{PCI}	r_{PC2}	Resolution	Units	Agency	Web address	Program
	Facilities discharging nutrients	0.83	–0.35	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Facilities discharging PAHs	0.58	0.16	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Facilities discharging particulates	0.51	0.16	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Facilities discharging pathogens	0.85	–0.40	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Facilities discharging pharmaceutical compounds	0.84	–0.41	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Facilities that physically disturb the landscape	0.51	0.20	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Facilities discharging salts	0.19	0.00	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Sewerage system facilities	0.86	–0.39	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Facilities discharching solvents	0.88	–0.32	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/pcs.htm	National Pollutant Discharge Elimination System (NPDES)
	Powerplant CO_2 emissions	0.49	0.72	point	tons/year	USGS	http://dssl.er.usgs.gov/ftp/nationalc/power_plants.zip	
	Powerplant NO_x emissions	0.49	0.72	point	tons/year	USGS	http://dssl.er.usgs.gov/ftp/nationalc/power_plants.zip	
	Powerplant SO_2 emissions	0.47	0.73	point	tons/year	USGS	http://dssl.er.usgs.gov/ftp/nationalc/power_plants.zip	
	Density of facilities discharging into the air	0.82	0.16	point	#ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/tri.htm	Toxic Release Inventory (TRI)
	Density of facilities discharging onto the land	0.81	0.19	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/tri.htm	Toxic Release Inventory (TRI)
	Density of facilities discharging into public water treatment plants	0.82	0.16	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/tri.htm	Toxic Release Inventory (TRT)

Appendix I. Continued

Category	Variable	r_{PC1}	r_{PC2}	Resolution	Units	Agency	Web address	Program
	Density of facilities discharging into underground injection wells	0.83	0.17	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/tri.htm	Toxic Release Inventory (TRI)
	Density of facilities discharging into surface waters	0.82	0.17	point	#/ha	US EPA	http://www.epa.gov/waterscience/basins/metadata/tri.htm	Toxic Release Inventory (TRI)