Sub-Indicator: Coastal Wetland Amphibians

Overall Assessment

Status (based on 2023 data): Fair

10-Year Trend (2013–2023): Unchanging

Long-term Trend (1995–2023): Undetermined

Rationale: Status and trends are based on the Index of Biotic Condition (IBC), an anuran-based (i.e., frog and toad-based) index of wetland health. Annual median IBC in coastal wetlands in the Great Lakes overall ranged from 4.3 (2012) to 5.6 (2020) out of 10 from 2011 to 2023, and did not significantly improve or deteriorate over the past 10 years (2013–2023) with fairly similar annual values in between. Median IBC was 5.1 based on data from 2021 to 2023, which is within the defined range for Fair status: 3.0 ≤ median IBC ≤ 5.9.

Lake-by-Lake Assessment

Lake Superior

Status (based on 2023 data): Fair

10-Year Trend (2013–2023): No Trend

Long-term Trend (1995–2023): Undetermined

Rationale: Annual median IBC in coastal wetlands in Lake Superior ranged from 3.9 (2019) to 5.6 (2016) out of 10 from 2011 to 2023, and did not significantly improve or deteriorate over the past 10 years (2013–2023) despite some annual increases and decreases in between. Median IBC was 5.2 based on data from 2021 to 2023, which is within the defined range for Fair status: 3.0 ≤ median IBC ≤ 5.9.

Lake Michigan

Status (based on 2023 data): Fair

10-Year Trend (2013–2023): No Trend

Long-term Trend (1995–2023): Undetermined

Rationale: Annual median IBC in coastal wetlands in Lake Michigan ranged from 3.9 (2014) to 5.6 (2016) out of 10 from 2011 to 2023, and did not significantly improve or deteriorate over the past 10 years (2013–2023) despite some annual increases and decreases in between. Median IBC was 5.2 based on data from 2021 to 2023, which is within the defined range for Fair status: 3.0 ≤ median IBC ≤ 5.9.

Lake Huron (including St. Marys River)

Status (based on 2023 data): Fair

10-Year Trend (2013–2023): Deteriorating

Long-term Trend (1995–2023): Undetermined

Rationale: Annual median IBC in coastal wetlands in Lake Huron ranged from 4.4 (2012) to 6.4 (2013) out of 10 from 2011 to 2023, and significantly deteriorated by -2.1% per year (-3.5, -0.7) [lower, upper 95% confidence limits for % annual change] over the past 10 years (2013–2023). Median IBC was 5.2 based on data from 2021 to

2023, which is within the defined range for Fair status: 3.0 ≤ median IBC ≤ 5.9.

Lake Erie (including St. Clair-Detroit River Ecosystem)

Status (based on 2023 data): Fair

10-Year Trend (2013–2023): No Trend

Long-term Trend (1995–2023): No Trend

Rationale: Annual median IBC in coastal wetlands in Lake Erie ranged from 2.8 (2011) to 5.4 (2002) from 1995 to 2023, and did not significantly improve or deteriorate over the past 10 years (2013–2023), despite some annual increases and decreases in between, or over the long term (1995-2023). Median IBC was 3.6 based on data from 2021 to 2023, which is within the defined range for Fair status: 3.0 ≤ median IBC ≤ 5.9.

Lake Ontario (including Niagara River and International section of the St. Lawrence River)

Status (based on 2023 data): Fair

10-Year Trend (2013–2023): No Trend

Long-term Trend (1995–2023): Improving

Rationale: Annual median IBC in coastal wetlands in Lake Ontario ranged from 2.0 (2000) to 6.4 (2020) from 1995 to 2023, did not significantly improve or deteriorate over the past 10 years (2013–2023) despite some annual increases and decreases in between, and significantly improved by 2.6% per year (1.3, 4.0) [lower, upper 95% confidence limits for % annual change] over the long term (1995–2023). Median IBC was 5.6 based on data from 2021 to 2023, which is within the defined range for Fair status: 3.0 ≤ median IBC ≤ 5.9.

Status Assessment Definitions

Status and trends are based on the Index of Biotic Condition (IBC), an anuran-based index of wetland health (Howe et al., 2023). Note that Howe et al. (2023) demonstrated the IBC approach based on wetland bird data, but the IBC can be applied to data from any animal group, as we have done here with anurans (Order Anura). IBCs range between 0 (Poor condition or most degraded) and 10 (Good condition or least degraded). Status was determined by placing the median IBC of coastal wetlands based on data from recent years (for 2025 reporting, status is based on data from 2021 to 2023) into one of three categories: Poor, Fair, or Good. The cut-points between Poor and Fair and between Fair and Good were approximately based on the 25th and 75th percentiles of IBCs throughout the Great Lakes from 2011 to 2023. Defining the cut-points in this manner captures the current baseline and will therefore be useful for promoting and measuring important, but realistic, improvements in wetland condition over time. Note that the values defining Poor, Fair, and Good below have changed since the 2022 State of the Great Lakes report, as part of the revision of the index used to assess status and trends—see Howe et al. (2023) for details.

Good: median IBC ≥ 6.0, i.e., most wetlands are mildly impacted or in reference condition.

Fair: 3.0 ≤ median IBC ≤ 5.9, i.e., most wetlands are moderately degraded or moderately impacted.

Poor: median IBC ≤ 2.9, i.e., most wetlands are degraded.

Undetermined: Data are not available or are insufficient to assess wetland condition.

Trend Assessment Definitions

Both regional and local wetland-breeding anuran populations naturally fluctuate over time (Gnass Giese et al., 2018; Tozer et al., 2024). Therefore, several years of monitoring data with suitable geographic coverage are required to detect statistically significant trends. Interpretation of this sub-indicator may be improved if coupled with patterns observed in other wetland sub-indicators (Brazner et al., 2007b, 2007a; Kovalenko et al., 2014).

The terms Improving, Unchanging, and Deteriorating were applied based on geometric mean rates of change in IBCs (% change per year) using equation 4 in Smith et al. (2014):

$$\%\ change\ per\ year = 100 * \left[\left(\frac{IBC_{endYear}}{IBC_{startYear}}\right)^{\frac{1}{endYear-startYear}} - 1\right]$$

The statistical significance of trends was assessed via parametric bootstrapping in R (R Core Team, 2024) using package "boot" (Canty and Ripley, 2013) and 1,000 bootstrap replicates. Bootstrapping was necessary to account for the varying precision of the annual estimate in the start and end year used to calculate each trend. For 10-year trends, the start year was 2013, and the end year was 2023. The year 2013 was chosen as the start year for 10-year trends because there are 10 possible transitions between years during 2013 to 2023, which was taken to be most representative of the trend during the most recent decade (IUCN Standards and Petitions Committee, 2022). Trend estimates with 95% confidence intervals that did not overlap zero were considered statistically significant.

Improving: A statistically significant increase in IBC.

Unchanging: No statistically significant increase or decrease in IBC, with similar values across years as determined by visual inspection.

No Trend: No statistically significant increase or decrease in IBC, with fluctuations across years as determined by visual inspection; for example, similar start and end values, but increases and decreases in between.

Deteriorating: A statistically significant decrease in IBC.

Undetermined: Data are not available or are insufficient to assess the trend in wetland condition.

Endpoints and/or Targets

Endpoints for this sub-indicator were left undefined for the 2025 report due to uncertainty around the best way to calculate meaningful values. Ongoing work by the authors will strive to develop useful endpoints.

Sub-Indicator Purpose

To assess the status and trends of the ecosystem health of Great Lakes coastal wetlands by directly measuring the composition and occurrence of wetland-breeding anurans, and thereby inferring the condition of coastal wetland habitat for this ecologically and culturally important component of wetland communities.

Ecosystem Objective

Coastal wetlands provide critical habitat for wildlife such as anurans. Conservation of remaining coastal wetlands and restoration or enhancement of previously degraded or destroyed wetlands are vital components of restoring

the Great Lakes ecosystem. Anurans are effective ecological indicators and can be used to report progress toward such an objective.

This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement, which states that the Waters of the Great Lakes should "support healthy and productive wetlands and other habitats to sustain resilient populations of native species."

Methods

Background —Wetland-breeding anurans are influenced by the physical, chemical, and biological components of wetlands and their surrounding landscapes. For example, the occurrence and/or reproductive success of multiple species in the Great Lakes basin decline as (1) wetland size decreases; (2) wetland habitat and natural cover in the surrounding landscape decrease or degrade in quality; and (3) pollution from pesticide, herbicide, and sediment runoff increases (Bishop et al., 1999; Brazner et al., 2007b, 2007a; Crosbie and Chow-Fraser, 1999; Eigenbrod et al., 2008a, 2008b; Gagné and Fahrig, 2007; Hecnar, 1995; Hecnar and M'Closkey, 1998, 1996; Houlahan and Findlay, 2003; Kolozsvary and Swihart, 1999; Price et al., 2004). Thus, the occurrence or abundance of sensitive wetland-breeding anurans can be a valuable indicator of the health of wetlands and the surrounding landscape.

Data—Several initiatives monitor Great Lakes wetland-breeding anurans. One of the longest running is the Great Lakes Marsh Monitoring Program (GLMMP) delivered by Birds Canada, which started in 1995 and has operated every year since then at coastal and inland wetlands throughout much of the Great Lakes basin in the U.S. and Canada (Tozer, 2020, 2016). Some of the previous reports for this sub-indicator were based solely on data from this ongoing broad scale program (e.g., Tozer, 2014). More recently, the Great Lakes Coastal Wetland Monitoring Program (CWMP) started in 2011 and is currently scheduled to operate until at least 2025 throughout both the U.S. and Canadian Great Lakes coastal zones (Uzarski et al., 2017). The CWMP is a program of the United States Environmental Protection Agency (USEPA) delivered by Central Michigan University and dozens of partner organizations in the U.S. and Canada (greatlakeswetlands.org/Collaborators). These programs have somewhat different study designs but rely on standardized, fixed duration point counts that can be adjusted to maximize cross-project compatibility. To garner large numbers of skilled, trained, volunteer surveyors to achieve large sample sizes at relatively low cost, and to engage the public in the importance of wetlands and wetland conservation, the GLMMP allows participants to select sample wetlands and sample points within them—a justifiable approach if one assumes that the sample locations are representative of wetlands across a region of interest. By contrast, the CWMP selects sample wetlands via stratified random sampling and survey sample points within them via paid professional staff. Nonetheless, both programs target wetlands dominated by non-woody emergent plants, such as cattails (*Typha* spp.) and sedges (e.g., *Carex* spp.), with sample points located within wetlands. In this report, the GLMMP and CWMP datasets described above were brought together to generate a comprehensive analysis of the status and trend of Great Lakes coastal wetland-breeding anurans and associated wetland health. We note that only GLMMP data from coastal wetlands were used for assessments of status or trends in this report, whereas GLMMP data from inland wetlands were analyzed and illustrated only to provide context and for making comparison to results from coastal wetlands. Coastal wetlands were defined as wetlands under direct hydrologic influence from Great Lakes waters or their connecting river systems, whereas inland wetlands were not under direct hydrologic influence (McKee et al., 1992).

Surveys—Anurans were sampled to an unlimited distance from one point (hereafter "sample point"), or up to six points, located at the edge of or within a wetland (> 100 m from the edge) depending on its size. With few exceptions, only shoreline locations were sampled due to night-time, over-water safety issues, with sample points distributed as much as possible throughout the wetland in all major vegetation types. Sample points were > 500 m

apart to avoid multiple detections of the same individuals. Each sample point was surveyed for 3 minutes on three visits separated by at least 10 or 15 days during the main anuran breeding season, typically between late March and early July. During each point count, observers recorded all species heard. Surveys occurred at night starting at least 0.5 hr after local sunset to 4.5 hr after local sunset and only under weather conditions that were favourable for detecting all species present (no persistent or heavy precipitation; wind: Beaufort 0–3, 0–19 km/hr). The first survey in the season was conducted when night-time air temperature had reached > ~5°C, the second when > ~10°C had been reached, and the third when > ~17°C had been reached. The survey protocols of each of the programs were similar to the North American Amphibian Monitoring Program protocol (Weir et al., 2009, 2014). The survey protocols are summarized in Tozer et al. (2018) for the GLMMP and in Uzarski et al. (2017) for the CWMP.

Analysis

Background—Numerous methods are available for assessing the health of Great Lakes coastal wetlands based on anuran data. Some previous analyses for this report were based on the occurrence of 8 wetland-breeding anuran species (e.g., Tozer, 2014). Alternative approaches include various anuran-based indices of wetland health, which combine data from suites of species (Chin et al., 2015). The latter approach is likely more objective and more practical for the purposes of State of the Great Lakes reporting because it provides a single comprehensive metric that represents the collective responses of anuran species to wetland condition. Multi-species metrics, like the widely used Index of Biotic Integrity for fishes (Karr and Chu, 1999) and mean coefficient of conservatism for plants (Taft et al., 1997), are robust when they are tested against known stressor gradients and include enough species to allow for calculations even if some species are absent due to extraneous factors. For example, a wide-ranging resident species might go undetected because, by chance, all local individuals of that species happen to be absent or inactive within the survey plot during the sampling period. Similarly, a high-quality wetland might be missing a species because of factors unrelated to habitat, such as a regional epidemic that affects individuals regardless of wetland condition. Since 2017, analyses for this report have been based on multi-species indices first developed by Howe et al. (2007a, 2007b) and refined in Tozer et al. (2017, 2019, 2022). In this report, we assess coastal wetland-breeding anuran status and trends based on the multi-species metric described by Howe et al. (2023), referred to as the Index of Biotic Condition (IBC), which builds on the strengths of the previous multi-species metrics used in this report (see Howe et al., 2023 for details).

Species—We focused our analysis on species or groups of species that are widely encountered in the Great Lakes (Table 1). Uncommon or rare species are important for conservation and ecological restoration, so we created an additional group of species, referred to as “Other,” to account for seldom-encountered or geographically-limited species. In general, the nine species or groups of species selected for our analysis can potentially occur anywhere in the Great Lakes coastal zone where their ecological needs are met (Table 1). Chorus frogs (*Pseudacris* spp.) were combined together (referred to in this report as “Chorus Frog”) and treefrogs (*Dryophytes* spp.) were combined together (referred to in this report as “Gray Treefrog”) due to challenges with identifying species within each of these groups by sound in the field.

Environmental reference gradient—The first step in calculating the IBC is to quantify the responses of the selected taxa to an explicit, independently-derived gradient of environmental condition (Howe et al., 2007b). The nature of this gradient is critical to the estimation of species- or taxon-specific responses to the gradient. Our purpose was to identify species or species groups that are sensitive to environmental stress and to characterize the nature of these responses over a reference gradient of increasing environmental quality (or inverse environmental stress). Because the IBC is used for assessing conservation priorities and for monitoring the outcome of conservation actions, we attempted to represent a wide range of environmental stressors that can be mitigated by conservation actions. Coastal wetlands can be degraded by a host of factors, including direct habitat destruction or

fragmentation, cultural eutrophication, invasive species, industrial or agricultural toxins, hydrological disturbances, and changes in physical conditions (e.g., water levels, precipitation amounts, air and water temperature) (Allan et al., 2013; Danz et al., 2007). To capture the diversity of these many different factors, we refer to the environmental reference gradient as the "human footprint" (Gnass Giese et al., 2015; Venter et al., 2016).

We used a combination of landscape and local variables to quantify potential environmental stress among 580 coastal wetlands for which relevant land cover data were available. Elliott (2019) developed multi-scale occupancy models for selected cryptic marsh birds using more than 50 habitat, landscape, hydrologic, and atmospheric variables associated with wetlands in the Great Lakes region. We selected six of these variables for estimating potential environmental stress: 1) percent cover of developed land (industrial buildings, residential sites, golf courses, etc.) within 2 km of the sample point; 2) percent cover of agricultural cropland within 2 km of the sample point; 3) total meters of primary and secondary roads within 2 km of the sample point; 4) percent cover of non-woody emergent wetland within 500 m of the sample point, 5) percent cover of cropland in the entire watershed associated with the wetland, and 6) percent cover of developed land within the watershed. The latter two variables were calculated by Brazner et al. (2007b) and Danz et al. (2007b). These six environmental variables were selected because they are minimally correlated ($-0.30 \leq r \leq 0.31$) and represent three scales of reference: local (< 500 m), landscape (< 2 km), and watershed. Notably, the two agricultural land cover variables ($r = -0.01$) and the two land development variables ($r = 0.02$) were largely independent. While this environmental gradient was originally developed for marsh birds, we applied it to breeding anurans since these stressors negatively impact both taxa.

We relativized each of the six variables to a uniform scale (0–10), with percent cover of non-woody emergent wetland reversed, so that in all cases 0 = worst condition and 10 = best condition. We did this for each variable by designating the highest value as 10, and then standardized all other values to the observed range as follows:

$$Relativezed\ score = \left[\frac{V_x}{(V_{max} - V_{min})}\right] * 10$$

Where V_x = the measured value for wetland x.

The average score among the six adjusted variables therefore yielded an overall environmental condition index (Cenv) also ranging from 0 to 10. The collection of all Cenv scores among wetland sampling points defined a reference gradient for analysis of each anuran species' sensitivity (or biotic response) to the "human footprint."

Biotic response (BR) functions—Howe et al. (2007b) used an asymptotic function to calculate taxon-specific responses to the environmental reference gradient. More recent applications (e.g., Gnass Giese et al., 2015) have applied a general normal probability distribution function, yielding some part of the familiar bell-shaped curve. Both of these functions aim to accurately quantify how species or groups of species respond to changes in environmental condition. By specifying the range of relevant values (0–10), but allowing the function's mean to lie within or outside this range, we can generate best-fit "curves" that are monotonically increasing (the upward part of the normal curve), monotonically decreasing (the downward part of the normal curve), or unimodal with complete or truncated tail(s). We have written an algorithm that selects the best-fit parameters of the normal bell-shaped curve, following the familiar normal probability density function, using R function *dnorm* (R Core Team, 2024). Three parameters define the curves: μ = mean; σ = standard deviation; and h = scale factor. The best-fit parameters are estimated by an R script with the *nlminb* function developed by Bates and Sarkar (Gray, 1990). We used the sum of squared deviations of data points from the predicted normal distribution as the goodness-of-fit criterion.

The land use variables used by Elliott (2019) were derived from the 2010 North American Land Cover 30-m dataset from the North American Land Change Monitoring System. Great Lakes water levels reached record-lows

during the late-1990s to early-2010s and then increased to unprecedented highs by 2017 to 2020 depending on the lake, which caused significant changes in the coastal zone (Gronewold and Rood, 2019). To minimize the mismatches between land cover variables and coastal wetland-breeding anuran occurrences, we only used anuran point samples from 2011 to 2015 (*n* = 1,418) for generating BR functions. The parameters from this analysis can be applied to wetland assessments in any year; our purpose in generating the BR functions was simply to quantify the relative sensitivity of different species or species groups to an empirical gradient of wetland disturbance.

Groups of 10 anuran sampling points with the most similar environmental condition scores (Cenv) were combined into "bins" for calculating probabilities of occurrence across the reference gradient. For example, points with the 10 lowest Cenv scores were assigned to the first bin, points with the next 10 lowest scores were assigned to the second bin, and so on. The last bin contained only 8 points, since our 1,418 samples were not evenly divisible by 10. Sometimes bins included multiple points from the same wetland, but typically they included points from different lakes or distant parts of the same lake. A species' probability of occurrence (i.e., frequency) in each bin is defined as the proportion of the 10 points where the species was detected during at least one of the three point-specific counts during a sample year. The environmental condition score for each bin was the mean value of scores (mean of the six relativized environmental variables) for the 10 points.

BR functions for the nine taxa (Figure 1) provide information about the relative frequency/probability of occurrence of each species in Great Lakes coastal wetlands (the height of the curve) and the sensitivity of the species to differences in Cenv (i.e., the shape of the curve across the 0–10 environmental gradient). These curves best describe the reality of how frequent (or infrequent) a species is in this system and how these frequencies change across the gradient. Most of the species show strong sensitivity to the gradient (i.e., they are most frequent at sites with high Cenv), and are generally common, achieving a probability of occurrence of 0.3 or greater at the maximum. American Toad (*Anaxyrus americanus*) and Chorus Frog (*Pseudacris maculata*, *P. triseriata*), on the other hand, are most frequently found in wetlands impacted by human activities.

Index of Biotic Condition (IBC)—IBC values for individual points are calculated using parameters from BR functions for ecologically-relevant taxa (Table 1) encountered during standardized field surveys. Weights for each species or species group were calculated as the product of two parameters: 1) the mean of the BR function, $\bar{x}_i$ (the value of Cenv when the BR function is at its peak frequency or probability of occurrence), and 2) the difference between $p(\bar{x}_i)_i$ (the predicted probability of occurrence of the species/species group at the mean of the BR function) and $p(0)_i$ (the predicted value of the BR function when the environmental gradient (Cenv) = 0). The BR function mean, $\bar{x}_i$, reflects the sensitivity of the species to the reference gradient; in general, the more sensitive the species, the larger the mean. The shape of BR functions can represent normal distribution functions whose means extend beyond the limits (0–10) of the reference gradient (Gnass Giese et al., 2015), but we capped the maximum value of $\bar{x}_i$ for calculating weights at 15. The second parameter $[p(\bar{x}_i)_i - p(0)_i]$ reflects the difference between the peak frequency of occurrence/detection of the species and its frequency of occurrence/detection when the environmental condition is most degraded (Cenv = 0). If two species are equally infrequent at degraded sites, absence of the more common species will impose a larger penalty on the IBC score because the common species is more frequent at peak conditions. Absence of rare species generally carries a relatively small penalty because these species never reach a high frequency.

The value of IBC is the sum of weights for all species present at the wetland during the three seasonal point counts, scaled from 0 (when no species are present) to 10 (when all species are present):

$$IBC = \left[\sum_{i=1}^{present} \bar{x}_i \left[p(\bar{x}_i)_i - p(0)_i\right]\right]\left[10 / \sum_{j=1}^{all} w_j\right]$$

where:

$\bar{x}_i$ = mean of the BR function for species i,

$p(\bar{x}_i)_i$ = predicted probability of the species/species group occurring at the peak of the BR function; i.e., when Cenv = $\bar{x}_i$,

$p(0)_i$ = predicted probability of the species/species group occurring when Cenv = 0, and

$\sum_{j=1}^{all} w_j$ = sum of weights of all species used in the analysis, even those absent in the sample (in our case, the sum of the weights of 9 species or species groups, or 15.66; Table 1).

Because we have derived empirical species weights from BR functions of sampled Great Lakes anuran assemblages between 2011 and 2015 (Table 1), the IBC calculation for Great Lakes coastal wetland-breeding anurans can be simplified to:

$$IBC = \left[\sum_{i=1}^{present} w_i\right] 0.639$$

where:

w_i = predetermined weight for species i (Table 1).

In other words, the IBC is simply the sum of weights for all taxa present multiplied by the scaling factor 0.639, which adjusts the IBC values to range from 0 (worst condition) to 10 (best condition). Note that the scaling factor will be different for other systems or groups of species.

IBCs for each sample point during a given year were based on species detected during any one of the field visits. Next, the point-level IBCs were averaged across all sample points within each wetland or wetland complex in each year, which standardizes wetlands containing differing numbers of sample points. Box-and-whisker plots of these wetland-level mean IBCs for coastal wetlands in each basin and throughout the entire Great Lakes basin (hereafter "overall") are reported in each year. These wetland-level means form the basis for the status and trend assessments. IBC metrics were also calculated for inland wetlands for comparison to Great Lakes coastal wetlands but are not used for any assessments of status or trends. In addition, box-and-whisker plots of wetland-level mean IBCs for coastal wetlands in each basin and overall based on data in recent years (2021–2023) are reported to illustrate current status. Density plots of wetland-level mean IBCs for coastal and inland wetlands in each basin (but not inland for lakes Superior and Michigan due to insufficient sample size) based on the most recent 5 years of data (2019–2023) are reported to illustrate variation in distributions. These plots can be thought of as smoothed histograms, which are useful for continuous data that come from an underlying smooth distribution. To further illustrate distributions, these same data for coastal wetlands are mapped throughout each of the basins. In the calculations for status, density plots, and the map, wetland-level mean IBC values were averaged across years for wetlands that were sampled in multiple years. We used the most recent 3 years of data (2021–2023) for status calculations because these data were newly-available since the previous report, and we used the most recent 5 years of data (2019–2023) for density plots and the map to maximize the total number of wetlands depicted, given nearly all of the wetlands were surveyed in at least one of the past 5 years.

Discussion

Data coverage—The dataset consisted of 66,303 point counts conducted at 5,428 sample points in 1,907 wetlands over 29 years from 1995 to 2023 throughout coastal and inland areas of the Great Lakes basin (Figure 2). The number of years that each wetland was surveyed varied from 1 to 29, with a mean of 4.3 years ± 4.4 (SD),

due mostly to large differences in observer participation in the long-running, broad-scale GLMMP (Figure 2). The majority of the surveyed wetlands were coastal (*n* = 1,203; 63%) rather than inland (*n* = 705; 37%) because the CWMP focused entirely on coastal wetlands, whereas the GLMMP surveyed both coastal and inland wetlands (Figure 2).

The number of coastal and inland wetlands surveyed per year (283 ± 119 [mean ± SD]) ranged from 113 to 450, with substantially more wetlands surveyed from 2011 to 2023 due to the CWMP operating during those years (Figure 3). Annual coverage was higher in Lake Erie and Lake Ontario compared to the upper Great Lakes mostly because GLMMP coverage is more extensive in the lower lakes. Annual coverage was higher at coastal compared to inland wetlands (Figure 3). The number of wetlands available for surveys also varied depending on location, as some sections of the Great Lakes shoreline naturally have no, or almost no, wetlands. As a result of low sample sizes in certain years (Figure 3), we focus on data from coastal wetlands from 2011 to 2023 for lakes Superior, Michigan, and Huron, and in the Great Lakes overall, and data from 1995 to 2023 for lakes Erie and Ontario.

Overall—Annual median IBC in coastal wetlands in the Great Lakes overall ranged from 4.3 (2012) to 5.6 (2020) out of 10 from 2011 to 2023, and did not significantly improve or deteriorate over the past 10 years (2013–2023) with fairly similar annual values in between (Table 2, Figure 4). Median IBC was 5.1 based on data from 2021 to 2023 (Figure 5). For this report, we concluded that there was not enough information to perform reliable statistical significance testing for long-term trends due to low sample size in lakes Superior, Michigan, and Huron during 1995 to 2010 (Figure 3). Based on these patterns, the status of coastal wetland health based on anuran communities in the Great Lakes overall is Fair, and the 10-year trend is Unchanging. IBCs at inland wetlands in the Great Lakes watershed showed little change over the long term (1995–2023), although they significantly deteriorated by -1.1% per year (-2.3, 0.0) [lower, upper 95% confidence limits for % annual change] over the past 10 years (2013–2023), and were similar compared to coastal wetlands based on data from 2023 (median inland IBC based on data from 2021 to 2023 = 4.3; Table 2; Figures 4, 7). A mix of low (< 3) and high (> 6) IBCs occurred throughout each of the lakes (Figure 6). Notable clusters of low IBCs occurred at the western end of lakes Superior, Erie, and Ontario (Figure 6).

Since the 2022 State of the Great Lakes report, the 10-year trend for coastal wetlands in the Great Lakes overall has changed from Improving to Unchanging, and the long-term trend has changed from Improving to Undetermined. The difference in the 10-year trend may be due to improvements in assessment methodology since the last report (see Analysis for details), and/or changes in anuran communities due to factors that remain unclear. The difference in the long-term trend is due to the determination that sample sizes were too limiting in lakes Superior, Michigan, and Huron during 1995 to 2010 for an overall assessment (Figure 3).

Lake Superior—Annual median IBC in coastal wetlands in Lake Superior ranged from 3.9 (2019) to 5.6 (2016) out of 10 from 2011 to 2023, and did not significantly improve or deteriorate over the past 10 years (2013–2023) despite some annual increases and decreases in between (Table 2, Figure 4). Median IBC was 5.2 based on data from 2021 to 2023 (Figure 5). For this report, we concluded that there was not enough information to perform reliable statistical significance testing for long-term trends due to low sample size during 1995 to 2010. Based on these patterns, the status of coastal wetland health based on anuran communities in Lake Superior is Fair, and the trend assessment is No Trend. IBCs at inland wetlands in the Lake Superior watershed were too sparse for meaningful comparison with coastal wetlands (Figure 3, 4).

Since the 2022 State of the Great Lakes report, the 10-year trend for coastal wetlands in Lake Superior has changed from Undetermined to No Trend. The difference is due to substantially more coastal wetlands being surveyed from 2011 to 2023 by the CWMP, which provided suitable sample sizes during the past 10 years for statistical analysis.

Lake Michigan—Annual median IBC in coastal wetlands in Lake Michigan ranged from 3.9 (2014) to 5.6 (2016) out of 10 from 2011 to 2023, and did not significantly improve or deteriorate over the past 10 years (2013–2023) despite some annual increases and decreases in between (Table 2, Figure 4). Median IBC was 5.2 based on data from 2021 to 2023 (Figure 5). For this report, we concluded that there was not enough information to perform reliable statistical significance testing for long-term trends due to low sample size during 1995 to 2010. Based on these patterns, the status of coastal wetland health based on anuran communities in Lake Michigan is Fair, and the trend assessment is No Trend. IBCs at inland wetlands in the Lake Michigan watershed were too sparse for meaningful comparison with coastal wetlands (Figure 4).

Since the 2022 State of the Great Lakes report, the 10-year trend for coastal wetlands in Lake Michigan has changed from Undetermined to No Trend. The difference is due to substantially more coastal wetlands being surveyed from 2011 to 2023 by the CWMP, which provided suitable sample sizes during the past 10 years for statistical analysis.

Lake Huron (including St. Marys River)—Annual median IBC in coastal wetlands in Lake Huron ranged from 4.4 (2012) to 6.4 (2013) out of 10 from 2011 to 2023, and significantly deteriorated by -2.1% per year (-3.5, -0.7) [lower, upper 95% confidence limits for % annual change] over the past 10 years (2013–2023; Table 2, Figure 4). Median IBC was 5.2 based on data from 2021 to 2023 (Figure 5). For this report, we concluded that there was not enough information to perform reliable statistical significance testing for long-term trends in coastal wetlands due to low sample size during 1995 to 2010. Based on these patterns, the status of coastal wetland health based on anuran communities in Lake Huron is Fair, and the trend is Deteriorating. IBCs at inland wetlands showed little change across years, and were similar compared to coastal wetlands based on data from 2023 (median inland IBC in 2023 = 4.6; Table 2; Figures 4, 7).

Since the 2022 State of the Great Lakes report, the status of coastal wetlands in Lake Huron has changed from Good to Fair, and the 10-year trend has changed from Unchanging to Deteriorating. The difference may be due to improvements in assessment methodology since the last report (see Analysis for details), and/or changes in anuran communities due to factors that remain unclear.

Lake Erie (including St. Clair-Detroit River Ecosystem)—Annual median IBC in coastal wetlands in Lake Erie ranged from 2.8 (2011) to 5.4 (2002) from 1995 to 2023, and did not significantly improve or deteriorate over the long term (1995–2023) or over the past 10 years (2013–2023) despite some annual increases and decreases in between (Table 2, Figure 4). Median IBC was 3.6 based on data from 2021 to 2023 (Figure 5). Based on these patterns, the status of coastal wetland health based on anuran communities in Lake Erie is Fair, and the trend assessment is No Trend. IBCs at inland wetlands in the Lake Erie watershed significantly deteriorated by -1.2% per year (-2.1, -0.3) [lower, upper 95% confidence limits for % annual change] over the long term (1995–2023); plus, they significantly deteriorated by 2.8% per year (-4.9, -0.7) over the past 10 years (2013–2023), and were similar compared to coastal wetlands based on data from 2021 to 2023 (median inland IBC based on data from 2021 to 2023 = 3.8; Table 2; Figure 4).

Since the 2022 State of the Great Lakes report, the 10-year trend and the long-term trend for coastal wetlands in Lake Erie have changed from Unchanging to No Trend. The difference is due to the adoption of a new term “No Trend” to better describe the pattern of annual fluctuations within the time period of the trend (see Trend Assessments Definitions above for details).

Lake Ontario (including Niagara River)—Annual median IBC in coastal wetlands in Lake Ontario ranged from 2.0 (2000) to 6.4 (2020) from 1995 to 2023, did not significantly improve or deteriorate over the past 10 years (2013–2023) despite some annual increases and decreases in between, and significantly improved by 2.6% per year (1.3, 4.0) [lower, upper 95% confidence limits for % annual change] over the long term (1995–2023; Table 2, Figure 4).

Median IBC was 5.6 based on data from 2021 to 2023 (Figure 5). Based on these patterns, the status of coastal wetland health based on anuran communities in Lake Ontario is Fair, and the trend assessment is No Trend. IBCs at inland wetlands in the Lake Ontario watershed showed little change across years, and were slightly lower compared to coastal wetlands based on data from 2021 to 2023 (median inland IBC based on data from 2021 to 2023 = 4.7; Table 2; Figures 4, 7).

Since the 2022 State of the Great Lakes report, the 10-year trend for coastal wetlands in Lake Ontario has changed from Improving to No Trend. The difference may be due to improvements in assessment methodology since the last report (see Analysis for details), and/or changes in anuran communities due to factors that remain unclear.

Comments—The status of wetland-breeding anurans as a measure of coastal wetland health throughout the Great Lakes was Fair based on data from the most recent 3 years (2021–2023). The status based on data from the most recent 3 years (2021–2023) was also Fair in lakes Michigan, Huron, Erie, and Ontario (note that a separate determination of status and trend was made for the Overall Assessment based on data from all of the individual lake basins, rather than averaging across the lake-by-lake assessments). In addition, it was found that coastal IBCs located towards the Poor end of the ecological condition gradient were more common at the western end of lakes Superior, Erie, and Ontario (Figure 6). The low IBCs are probably due to greater anthropogenic stress from agriculture, development, and perhaps wetland loss in these areas compared to elsewhere (Allan et al., 2013; Bourgeau-Chavez et al., 2015; Danz et al., 2007; Niemi et al., 2011, 2009; Tozer et al., 2024).

Despite the Fair status throughout the Great Lakes, it is important to note that high-quality coastal wetlands (IBC ≥ 6) are present throughout each of the Great Lakes (Figures 4–7). By illustrating and documenting differences in wetland health based on wetland-breeding anuran communities, we provide a unique baseline that informs wetland restoration and conservation efforts at various scales across the Great Lakes basin. For instance, the presence of high-quality wetlands with healthy wetland-breeding anuran communities (IBC ≥ 6) in highly-stressed regions of the Great Lakes, such as Green Bay in Lake Michigan and Saginaw Bay in Lake Huron, among others (Figure 6), is highly encouraging and supports increased investment in wetland restoration and conservation efforts targeting wetland-breeding anurans and associated wetland health throughout the Great Lakes.

Coastal wetland health based on wetland-breeding anurans significantly increased in Lake Ontario over the long term (1995–2023), whereas it significantly deteriorated in Lake Huron over the past 10 years (2013–2023; Table 2, Figure 4). The cause of the recent 10-year decrease in IBCs in coastal wetlands in Lake Huron is unclear. By contrast, the improvement in coastal IBCs over the long term in Lake Ontario may be at least partially due to improvement in coastal wetland condition. An index of water quality significantly improved across 22 wetlands along the Canadian shore of Lake Ontario between 2003 and 2014 (Croft-White et al., 2017). The improvement in water quality is indicative of concurrent improvement in wetland-breeding anuran habitat (Bishop et al., 1999; Boyer and Grue, 1995; Macecek and Grabas, 2011). Increases in water quality and concurrent improvements in wetland-breeding anuran habitat associated with restoration efforts may at least partially explain increasing patterns in IBCs elsewhere within the Great Lakes basin.

In addition to assessing status and trend of the health of coastal wetlands, status and trend of inland wetlands were examined for comparison (Table 2; Figures 4, 7). Due to differences in sample sizes, the ability to compare coastal and inland wetlands was best for lakes Erie and Ontario, whereas it was more limited for the other lake basins. It is worth noting that patterns in IBCs differed in some cases between coastal and inland wetlands. In general, where and when IBCs in coastal wetlands increased or decreased, there were no corresponding changes in IBCs at inland wetlands (Table 2, Figure 4). Thus, wetland health as represented by wetland-breeding anurans may be responding to different intensities of stressors in coastal versus inland wetlands within certain watersheds.

This idea is supported by previous analyses using only the GLMMP dataset, which showed that occurrence of certain wetland-breeding anuran species was different at coastal wetlands compared to inland wetlands (Tozer, 2020). Thus, continued sampling of both coastal and inland wetlands by the GLMMP, CWMP, and others throughout the Great Lakes basin will be useful for generating a more complete understanding of the health of wetlands based on anurans throughout the entire Great Lakes watershed.

The overall Fair status and Unchanging trend reported for coastal wetlands throughout the Great Lakes overall contrasts with some previous reports for this sub-indicator (i.e., before 2019). The differences among the reports are at least partially due to differences in sampling. Some of the previous reports were based predominantly on data from the southern portion of the Great Lakes basin due to reliance on the mostly southern GLMMP dataset (Tozer, 2014). The current report provides a more balanced assessment throughout the entire Great Lakes basin by bringing GLMMP data together with data from the CWMP. Nevertheless, the patterns reported here are based on a comprehensive IBC metric, which represents the collective responses of many wetland-breeding anuran species to wetland condition. Multiple different species, however, experience long-term population trajectories in the Great Lakes that differ from trends in the IBC (Tozer, 2020; Tozer et al., 2024). These taxa are likely responding to environmental stressors in species-specific ways, warranting unique actions or presenting unique opportunities for restoration to improve wetland health.

Linkages

Coastal wetland-breeding anurans are influenced by numerous local and landscape-level characteristics, some of which are monitored by other State of the Great Lakes sub-indicators. For instance, some coastal wetland-breeding anurans are known to be influenced by water levels (Gnass Giese et al., 2018; Tozer et al., 2024). Thus, the Coastal Wetland Amphibians sub-indicator can be expected to co-vary with the Water Levels sub-indicator, and in turn, with atmospheric-related impacts that indirectly affect water levels, such as the Surface Water Temperatures, Ice Cover, and Precipitation Amounts sub-indicators. By contrast, we note that we saw little evidence within individual lake basins or overall across the entire Great Lakes basin for an effect of changing lake levels on IBCs for coastal wetlands based on anuran communities. For instance, coastal IBCs based on breeding anurans changed very little during the period of rapid lake level rise from record lows to record highs from the early-2010s to early-2020s (Figure 4; mean increase in lake level from 2013 to 2018: 0.16–0.97 m depending on the lake; Hohman et al. Hohman et al., 2021) (see Water Levels Sub-Indicator for further details including historical context back to 1918). We did, however, observe far fewer anurans at some wetlands where water levels were especially high. Thus, further exploration of the potential influence of lake levels on anuran communities is a worthwhile area for future research.

In addition, timing of breeding of wetland anurans can be influenced by altered temperatures (Klaus and Lougheed, 2013; Walpole et al., 2012). Whether this influence results in changes in anuran occurrence and abundance is unknown, so it may be possible that the Coastal Wetland Amphibians sub-indicator can be expected to directly co-vary with the Surface Water Temperatures sub-indicator. As well, coastal wetland breeding anurans are influenced by various water pollutants, particularly nitrates (e.g., Rouse et al., 1999). Thus, the Coastal Wetland Amphibians sub-indicator can be expected to co-vary with all of the Toxic Chemicals and Nutrients sub-indicators. The Coastal Wetland Amphibians sub-indicator can also be expected to co-vary with sub-indicators that track the extent and spatial arrangement of wetland-breeding anuran habitat (e.g., Coastal Wetlands: Extent and Composition, Aquatic Habitat Connectivity) and prey (Coastal Wetland Invertebrate; Coastal Wetland Fish). And finally, the occurrence of multiple species of anurans is known to be lower in developed and urban landscapes (Price et al., 2007, 2004), as reflected in the pattern of IBCs based on anuran communities presented here (Figure

6). Thus, the Coastal Wetland Amphibians sub-indicator can be expected to co-vary with the Human Population sub-indicator.

Citizen Science, Traditional Ecological Knowledge (TEK), and other Bodies of Knowledge

The tremendous power to report robust status and trends for this sub-indicator is made possible by a rigorous standardized anuran count protocol, large sample sizes, and extensive survey coverage accomplished by two anuran monitoring programs operating throughout the Great Lakes. The Great Lakes Marsh Monitoring Program (GLMMP) delivered by Birds Canada, which draws upon the dedication and skills of hundreds of volunteer surveyors annually, provided much of the data used here from 1995 to 2011, as well as numerous additional data from coastal wetlands from 2011 to 2023, and all of the inland data used for comparison to coastal wetlands (Tozer, 2020). The USEPA's Great Lakes Coastal Wetland Monitoring Program (CWMP) delivered by Central Michigan University and dozens of partners in the U.S. and Canada has provided much needed expansion of coverage in coastal wetlands particularly in the northern portion of the Great Lakes since 2011 (Uzarski et al., 2017). Ongoing support of both of these programs will ensure that these high-quality data continue to be available for understanding the condition of the health of the Great Lakes ecosystem.

Assessing Data Quality

Data Characteristics	Agree	Neutral or Unknown	Disagree	Not Applicable
Data are documented, validated, or quality-assured by a recognized agency or organization	X			
Data are from a known, reliable and respected generator of data and are traceable to original sources	X			
Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X			
Data obtained from sources within the U.S. are comparable to those from Canada	X			
Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X			

Data used in assessment are openly available and accessible	Yes	Data are available by request here: CWMP: https://www.greatlakeswetlands.org/Home.vbhtml GLMMP: https://naturecounts.ca/nc/default/main.jsp

Notes on Accessing Data

CWMP: Click on “complete and submit the request form” to create a new user account and request access to the data. You must be a registered user with an account to download data from the site.

GLMMP: scroll down to “Access Data,” and follow either the option to “Download Raw Data” or the “NatureCounts R package.” You must have a NatureCounts account to access data from the site or through the R package.

Data Limitations

This sub-indicator may be more powerful if evaluated as part of an overall analysis of biological communities of Great Lakes coastal wetlands and nearshore aquatic systems. This can be done by considering the coastal wetland sub-indicators in combination because they function and indicate anthropogenic disturbance at different spatial and temporal scales and have varying resolution of detection.

The three annual survey visits made to each sample point in this report were efficient and accurate for detecting all of the species or species groups present, given that up to nine annual survey visits failed to detect any additional species on average (Podoliak et al., 2022). Nonetheless, more rigorous methods to survey wetland-breeding anurans exist, such as dip-nets and/or minnow traps (e.g., Tawa et al., 2024). Such methods may detect more species (although this remains untested), and yield additional information on reproductive success and survival at different life stages (Crawford et al., 2023), but these methods are time-intensive and impractical to implement across the large number of sample points surveyed in this report. Applying the survey approach used here, as well as more rigorous methods at a small sub-sample of targeted wetlands might be useful in the future.

Great Lakes coastal wetlands are diverse. Some are protected from wind and wave action; some are open to the lake. Some are associated with river mouths, others are not. Additional variation is imposed by underlying geomorphology and meteorological differences across different regions and by human impacts. This variation in wetland types carries over to influence wetland-breeding anurans. Thus, the most powerful data for estimating anuran-based indices of ecosystem health at broad scales, such as across individual Great Lakes basins, are those collected via spatially-balanced randomized experimental designs, which account for and capture this variation. Most, but not all, of the existing wetland-breeding anuran datasets suitable for use with this sub-indicator address these sampling issues in their experimental designs, although there is room for improvement.

The status and trend assessment of coastal wetland health based on wetland-breeding anurans utilized BR functions developed using CWMP data only. The BR functions were also developed based on information from multiple stressor gradients related to development, agriculture, and road density. The ability of the IBC to capture the health of coastal wetlands based on anuran data might be improved by expanding the development of the BR functions to include all of the wetland-breeding anuran data that are available from the GLMMP and CWMP, which would include data from inland wetlands. The performance of the IBC might also be improved by

incorporating other known or suspected wetland-breeding anuran stressors in the development of BR functions. These ideas are fruitful areas for future expansion.

Two large wetland-breeding anuran datasets were brought together, specifically the GLMMP and CWMP datasets, to perform the analyses summarized in this report. This provided tremendous analytical power at many different scales compared to using only one of the datasets. However, it was evident that the combined dataset is deficient in information from healthy wetlands. Future collection of anuran data from wetlands located towards the pristine end of the degraded-pristine gradient might improve the performance of the IBC.

IBC values were calculated for individual sample points, and these values were averaged for wetlands where more than one point was sampled. Averaging point-level samples implicitly assumes that the character of wetlands is uniform, which likely is not the case, especially for large wetlands that cover multiple wetland zones (Dybiec et al., 2020). Howe et al. (2023) described an alternative method for IBC calculations that combines point-level results for all point counts within a wetland. This method invariably yields higher IBC values for larger wetlands because the multiple points usually cover different vegetation zones or localized populations within the wetland. In most cases, large wetlands also yield relatively high point-level IBC values, but this alternative site-level approach might complement the results presented here.

Additional Information

Over half of all Great Lakes coastal wetlands have been lost due to conversion to other land uses, and remaining coastal wetlands have been changed by human activities and suffer from anthropogenic stressors, such as nutrient and sediment loading, fragmentation, invasive species, shoreline alteration, and water-level control (Land Cover sub-indicator; Amani et al., 2022; Michaud et al., 2022). Such wetland loss and stress are especially apparent in certain developed portions of the Great Lakes basin (Figure 6; Allan et al., 2013; Bourgeau-Chavez et al., 2015).

One approach to improve the health of Great Lakes coastal wetlands is to identify factors that promote occupancy of wetland-breeding anuran species in coastal wetlands. Factors that are positively related to occupancy of wetland-breeding anurans then translate into actions and opportunities that ultimately help improve wetland health. This approach has been completed using components of the larger dataset analyzed in this report, i.e., data from 10,000s of GLMMP and/or CWMP point counts or other datasets have been used to determine important local, wetland, and landscape-scale factors influencing occupancy of eight widespread wetland-breeding anuran species in coastal and inland wetlands throughout different parts of the Great Lakes basin (Carr and Fahrig, 2001; Cosentino et al., 2014; Eigenbrod et al., 2009, 2008a; Gagné and Fahrig, 2007; Gnass Giese et al., 2018; Hecnar and M'Closkey, 1998; Houlahan and Findlay, 2003; Knutson et al., 2004, 1999; Lehtinen et al., 1999; Marsh et al., 2017; Pope et al., 2000; Price et al., 2004; Sawatzky et al., 2019; Tozer et al., 2024; Trenham et al., 2003). The results of these studies suggest that multiple wetland-breeding anuran species will benefit from the protection and restoration of large Great Lakes coastal wetlands or wetland complexes, which contain clean, unpolluted water and diverse communities of native marsh vegetation, and which are surrounded by low amounts of roads and urban land use and high amounts of forest cover in the surrounding watershed or landscape. These actions will likely increase occupancy or abundance, or promote establishment or reduce local extinction of wetland-breeding anurans within coastal wetlands. These actions will also ultimately help improve associated coastal wetland health across the southern portion of the Great Lakes basin.

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References

Allan, J.D., McIntyre, P.B., Smith, S.D.P., Halpern, B.S., Boyer, G.L., Buchsbaum, A., Burton, G.A., Campbell, L.M., Chadderton, W.L., Ciborowski, J.J.H., Doran, P.J., Eder, T., Infante, D.M., Johnson, L.B., Joseph, C.A., Marino, A.L., Prusevich, A., Read, J.G., Rose, J.B., Rutherford, E.S., Sowa, S.P., Steinman, A.D., 2013. Joint analysis of stressors and ecosystem services to enhance restoration effectiveness. Proc Natl Acad Sci 110, 372–377. https://doi.org/10.1073/pnas.1213841110

Amani, M., Kakooei, M., Ghorbanian, A., Warren, R., Mahdavi, S., Brisco, B., Moghimi, A., Bourgeau-Chavez, L., Toure, S., Paudel, A., Sulaiman, A., Post, R., 2022. Forty years of wetland status and trends analyses in the Great Lakes using landsat archive imagery and Google Earth engine. Remote Sensing 14, 3778. https://doi.org/10.3390/rs14153778

Bishop, C.A., Mahony, N.A., Struger, J., Ng, P., Pettit, K.E., 1999. Anuran development, density and diversity in relation to agricultural activity in the Holland River watershed, Ontario, Canada (1990–1992). Environ Monit Assess 57, 21–43. https://doi.org/10.1023/A:1005988611661

Bourgeau-Chavez, L., Endres, S., Battaglia, M., Miller, M.E., Banda, E., Laubach, Z., Higman, P., Chow-Fraser, P., Marcaccio, J., 2015. Development of a bi-national Great Lakes coastal wetland and land use map using three-season PALSAR and Landsat imagery. Remote Sens 7, 8655–8682. https://doi.org/10.3390/rs70708655

Boyer, R., Grue, C.E., 1995. The need for water quality criteria for frogs. Environ Health Perspect 103, 352–357. https://doi.org/10.2307/3432288

Brazner, J.C., Danz, N.P., Niemi, G.J., Regal, R.R., Trebitz, A.S., Howe, R.W., Hanowski, J.M., Johnson, L.B., Ciborowski, J.J.H., Johnston, C.A., Reavie, E.D., Brady, V.J., Sgro, G.V., 2007a. Evaluation of geographic, geomorphic and human influences on Great Lakes wetland indicators: A multi-assemblage approach. Ecol Indic 7, 610–635. https://doi.org/10.1016/j.ecolind.2006.07.001

Brazner, J.C., Danz, N.P., Trebitz, A.S., Niemi, G.J., Regal, R.R., Hollenhorst, T., Host, G.E., Reavie, E.D., Brown, T.N., Hanowski, J.M., Johnston, C.A., Johnson, L.B., Howe, R.W., Ciborowski, J.J.H., 2007b. Responsiveness of Great Lakes wetland indicators to human disturbances at multiple spatial scales: a multi-assemblage assessment. J Great Lakes Res, Coastal Indicators 33, 42–66. https://doi.org/10.3394/0380-1330(2007)33[42:ROGLWI]2.0.CO;2

Canty, A., Ripley, B., 2013. Package boot. https://cran.r-project.org/web/packages/boot/boot.pdf.

Carr, L.W., Fahrig, L., 2001. Effect of road traffic on two amphibian species of differing vagility. Conserv Biol 15, 1071–1078.

Chin, A.T.M., Tozer, D.C., Walton, N.G., Fraser, G.S., 2015. Comparing disturbance gradients and bird-based indices of biotic integrity for ranking the ecological integrity of Great Lakes coastal wetlands. Ecol Indic 57, 475–485. https://doi.org/10.1016/j.ecolind.2015.05.010

Cosentino, B.J., Marsh, D.M., Jones, K.S., Apodaca, J.J., Bates, C., Beach, J., Beard, K.H., Becklin, K., Bell, J.M., Crockett, C., Fawson, G., Fjelsted, J., Forys, E.A., Genet, K.S., Grover, M., Holmes, J., Indeck, K., Karraker, N.E., Kilpatrick, E.S., Langen, T.A., Mugel, S.G., Molina, A., Vonesh, J.R., Weaver, R.J., Willey, A., 2014. Citizen science reveals widespread negative effects of roads on amphibian distributions. Biol Conserv 180, 31–38. https://doi.org/10.1016/j.biocon.2014.09.027

Crawford, J.A., Peterman, W.E., Kuhns, A.R., Phillips, C.A., 2023. Effectiveness of rapid sampling assessments for wetland-breeding amphibians. Ecological Indicators 154, 110736. https://doi.org/10.1016/j.ecolind.2023.110736

Croft-White, M.V., Cvetkovic, M., Rokitnicki-Wojcik, D., Midwood, J.D., Grabas, G.P., 2017. A shoreline divided: Twelve-year water quality and land cover trends in Lake Ontario coastal wetlands. J Great Lakes Res 43, 1005–1015. https://doi.org/10.1016/j.jglr.2017.08.003

Crosbie, B., Chow-Fraser, P., 1999. Percentage land use in the watershed determines the water and sediment quality of 22 marshes in the Great Lakes basin. Can J Fish Aquat Sci 56, 1781–1791. https://doi.org/10.1139/f99-109

Danz, N.P., Niemi, G.J., Regal, R.R., Hollenhorst, T., Johnson, L.B., Hanowski, J.M., Axler, R.P., Ciborowski, J.J.H., Hrabik, T., Brady, V.J., Kelly, J.R., Morrice, J.A., Brazner, J.C., Howe, R.W., Johnston, C.A., Host, G.E., 2007. Integrated measures of anthropogenic stress in the U.S. Great Lakes Basin. Env Manag 39, 631–647. https://doi.org/10.1007/s00267-005-0293-0

Dybiec, J.M., Albert, D.A., Danz, N.P., Wilcox, D.A., Uzarski, D.G., 2020. Development of a preliminary vegetation-based indicator of ecosystem health for coastal wetlands of the Laurentian Great Lakes. Ecol Indic 119, 106768. https://doi.org/10.1016/j.ecolind.2020.106768

Eigenbrod, F., Hecnar, S.J., Fahrig, L., 2009. Quantifying the Road-Effect Zone: Threshold Effects of a Motorway on Anuran Populations in Ontario, Canada. Ecol Soc 14.

Eigenbrod, F., Hecnar, S.J., Fahrig, L., 2008a. The relative effects of road traffic and forest cover on anuran populations. Biol Conserv 141, 35–46. https://doi.org/10.1016/j.biocon.2007.08.025

Eigenbrod, F., Hecnar, S.J., Fahrig, L., 2008b. Accessible habitat: an improved measure of the effects of habitat loss and roads on wildlife populations. Landscape Ecol 23, 159–168. https://doi.org/10.1007/s10980-007-9174-7

Elliott, L., 2019. Habitat associations and conservation of wetland-obligate birds (PhD thesis). University of Minnesota, Duluth, Minnesota, USA.

Gagné, S.A., Fahrig, L., 2007. Effect of landscape context on anuran communities in breeding ponds in the National Capital Region, Canada. Landscape Ecol 22, 205–215. https://doi.org/10.1007/s10980-006-9012-3

Gnass Giese, E.E., Howe, R.W., Wolf, A.T., Miller, N.A., Walton, N.G., 2015. Sensitivity of breeding birds to the "human footprint" in western Great Lakes forest landscapes. Ecosphere 6, art90. https://doi.org/10.1890/ES14-00414.1

Gnass Giese, E.E., Howe, R.W., Wolf, A.T., Niemi, G.J., 2018. Breeding birds and anurans of dynamic coastal wetlands in Green Bay, Lake Michigan. J Great Lakes Res 44, 950–959. https://doi.org/10.1016/j.jglr.2018.06.003

Gray, D.M., 1990. Usage summary for selected optimization routines, Computing science technical report No. 153, 1-21. AT&T Bell Laboratories, Murray Hill, New Jersey, USA.

Gronewold, A.D., Rood, R.B., 2019. Recent water level changes across Earth's largest lake system and implications for future variability. Journal of Great Lakes Research 45, 1–3. https://doi.org/10.1016/j.jglr.2018.10.012

Hecnar, S.J., 1995. Acute and chronic toxicity of ammonium nitrate fertilizer to amphibians from southern ontario. Environ Toxicol Chem 14, 2131–2137. https://doi.org/10.1002/etc.5620141217

Hecnar, S.J., M'Closkey, R.T., 1998. Species richness patterns of amphibians in southwestern Ontario ponds. J Biogeogr 25, 763–772. https://doi.org/10.1046/j.1365-2699.1998.2540763.x

Hecnar, S.J., M'Closkey, R.T., 1996. Regional Dynamics and the Status of Amphibians. Ecol 77, 2091–2097. https://doi.org/10.2307/2265703

Hohman, T.R., Howe, R.W., Tozer, D.C., Gnass Giese, E.E., Wolf, A.T., Niemi, G.J., Gehring, T.M., Grabas, G.P., Norment, C.J., 2021. Influence of lake levels on water extent, interspersion, and marsh birds in Great Lakes coastal wetlands. J Great Lakes Res 47, 534–545. https://doi.org/10.1016/j.jglr.2021.01.006

Houlahan, J.E., Findlay, C.S., 2003. The effects of adjacent land use on wetland amphibian species richness and community composition. Can J Fish Aquat Sci 60, 1078–1094. https://doi.org/10.1139/f03-095

Howe, R.W., Niemi, G.J., Bracey, A.M., Brady, V., Elliott, L., Fiorino, G.E., Gaul, W., Gehring, T.M., Gnass Giese, E.E., Lawrence, G., Norment, C.J., Panci, H., Tozer, D.C., Uzarski, D., Walton, N.G., Wheelock, B., 2023. An Index of biotic condition (IBC) using birds as indicators of coastal wetland quality in North America's Laurentian Great Lakes. Ecol Appl 156, 111174. https://doi.org/10.1016/j.ecolind.2023.111174

Howe, R.W., Regal, R.R., Hanowski, J., Niemi, G.J., Danz, N.P., Smith, C.R., 2007a. An index of ecological condition based on bird assemblages in Great Lakes coastal wetlands. J Great Lakes Res, Coastal Indicators 33, 93–105. https://doi.org/10.3394/0380-1330(2007)33[93:AIOECB]2.0.CO;2

Howe, R.W., Regal, R.R., Niemi, G.J., Danz, N.P., Hanowski, J.M., 2007b. A probability-based indicator of ecological condition. Ecol Indic 7, 793–806. https://doi.org/10.1016/j.ecolind.2006.09.003

IUCN Standards and Petitions Committee, 2022. Guidelines for using the IUCN red list categories and criteria. Version 15.1. Prepared by the Standards and Petitions Committee. http://www.iucnredlist.org/documents/RedListGuidelines.pdf.

Karr, J.R., Chu, E.W., 1999. Restoring life in running waters: better biological monitoring. Island Press, Washington, DC.

Klaus, S.P., Lougheed, S.C., 2013. Changes in breeding phenology of eastern Ontario frogs over four decades. Ecol Evol 3, 835–845. https://doi.org/10.1002/ece3.501

Knutson, M.G., Richardson, W.B., Reineke, D.M., Gray, B.R., Parmelee, J.R., Weick, S.E., 2004. Agricultural ponds support amphibian populations. Ecol Appl 14, 669–684. https://doi.org/10.1890/02-5305

Knutson, M.G., Sauer, J.R., Olsen, D.A., Mossman, M.J., Hemesath, L.M., Lannoo, M.J., 1999. Effects of landscape composition and wetland fragmentation on frog and toad abundance and species richness in Iowa and Wisconsin, U.S.A. Conserv Biol 13, 1437–1446.

Kolozsvary, M.B., Swihart, R.K., 1999. Habitat fragmentation and the distribution of amphibians: patch and landscape correlates in farmland. Can J Zool 77, 1288–1299. https://doi.org/10.1139/z99-102

Kovalenko, K.E., Brady, V.J., Brown, T.N., Ciborowski, J.J.H., Danz, N.P., Gathman, J.P., Host, G.E., Howe, R.W., Johnson, L.B., Niemi, G.J., Reavie, E.D., 2014. Congruence of community thresholds in response to anthropogenic stress in Great Lakes coastal wetlands. Freshw Sci 33, 958–971. https://doi.org/10.1086/676913

Lehtinen, R.M., Galatowitsch, S.M., Tester, J.R., 1999. Consequences of habitat loss and fragmentation for wetland amphibian assemblages. Wetlands 19, 1–12. https://doi.org/10.1007/BF03161728

Macecek, D., Grabas, G.P., 2011. Applying a regional coastal wetland monitoring framework to refine and report on wildlife and habitat delisting criteria in the Bay of Quinte Area of Concern. Aquat Ecosyst Health Manag 14, 94–103. https://doi.org/10.1080/14634988.2011.549439

Marsh, D.M., Cosentino, B.J., Jones, K.S., Apodaca, J.J., Beard, K.H., Bell, J.M., Bozarth, C., Carper, D., Charbonnier, J.F., Dantas, A., Forys, E.A., Foster, M., General, J., Genet, K.S., Hanneken, M., Hess, K.R., Hill, S.A., Iqbal, F., Karraker, N.E., Kilpatrick, E.S., Langen, T.A., Langford, J., Lauer, K., McCarthy, A.J., Neale, Z., Patel, S., Patton, A., Southwick, C., Stearrett, N., Steijn, N., Tasleem, M., Taylor, J.M., Vonesh, J.R., 2017. Effects of roads and land use on frog distributions across spatial scales and regions in the Eastern and Central United States. Divers Distrib 23, 158–170. https://doi.org/10.1111/ddi.12516

McKee, P.M., Batterson, T.R., Dahl, T.E., Glooschenko, V., Jaworski, E., Pearce, J.B., Raphael, C.N., Whillans, T.H., LaRoe, E.T., 1992. Great Lakes aquatic habitat classification based on wetland classification systems, in: Busch, W.-D.N., Sly, P.G. (Eds.), The Development of an Aquatic Habitat Classification System for Lakes. CRC Press, Boca Raton, Florida, USA.

Michaud, W.J., Telech, J., Green, M., Daneshfar, B., Pawlowski, M., 2022. Sub-indicator: land cover, in: State of the Great Lakes 2022 Technical Report. Published by Environment and Climate Change Canada and U.S. Environmental Protection Agency.

Niemi, G.J., Brady, V.J., Brown, T.N., Ciborowski, J.J.H., Danz, N.P., Ghioca, D.M., Hanowski, J.M., Hollenhorst, T.P., Howe, R.W., Johnson, L.B., Johnston, C.A., Reavie, E.D., 2009. Development of ecological indicators for the U.S. Great Lakes coastal region – A summary of applications in Lake Huron. Aquat Ecosyst Health Manag 12, 77–89. https://doi.org/10.1080/14634980802711943

Niemi, G.J., Reavie, E.D., Peterson, G.S., Kelly, J.R., Johnston, C.A., Johnson, L.B., Howe, R.W., Host, G.E., Hollenhorst, T.P., Danz, N.P., Ciborowski, J.J.H., Brown, T.N., Brady, V.J., Axler, R.P., 2011. An integrated approach to assessing multiple stressors for coastal Lake Superior. Aquat Ecosyst Health Manag 14, 356–375. https://doi.org/10.1080/14634988.2011.628254

Podoliak, J., Norment, C.J., Amatangelo, K.L., 2022. Increasing number of point counts influences estimates of bird and anuran species richness at the wetland scale. Wetlands Ecol Manage 30, 99–110. https://doi.org/10.1007/s11273-021-09837-1

Pope, S.E., Fahrig, L., Merriam, H.G., 2000. Landscape Complementation and Metapopulation Effects on Leopard Frog Populations. Ecol 81, 2498–2508. https://doi.org/10.2307/177470

Price, S.J., Howe, R.W., Hanowski, J.M., Regal, R.R., Niemi, G.J., Smith, C.R., 2007. Are anurans of Great Lakes coastal wetlands reliable indicators of ecological condition? J Great Lakes Res, Coastal Indicators 33, 211–223. https://doi.org/10.3394/0380-1330(2007)33[211:AAOGLC]2.0.CO;2

Price, S.J., Marks, D.R., Howe, R.W., Hanowski, J.M., Niemi, G.J., 2004. The importance of spatial scale for conservation and assessment of anuran populations in coastal wetlands of the western Great Lakes, USA. Landscape Ecol 20, 441–454. https://doi.org/10.1007/s10980-004-3167-6

R Core Team, 2024. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org.

Rouse, J.D., Bishop, C.A., Struger, J., 1999. Nitrogen pollution: an assessment of its threat to amphibian survival. Environ Health Perspect 107, 799–803. https://doi.org/10.1289/ehp.99107799

Sawatzky, M.E., Martin, A.E., Fahrig, L., 2019. Landscape context is more important than wetland buffers for farmland amphibians. Agric Ecosyst Environ 269, 97–106. https://doi.org/10.1016/j.agee.2018.09.021

Smith, A.C., Hudson, M.-A.R., Downes, C., Francis, C.M., 2014. Estimating breeding bird survey trends and annual indices for Canada: how do the new hierarchical Bayesian estimates differ from previous estimates? Can Field-Nat 128, 119–134. https://doi.org/10.22621/cfn.v128i2.1565

Taft, J.B., Wilhelm, G.S., Ladd, D.M., Masters, L.A., 1997. Floristic quality assessment for vegetation in Illinois, a method for assessing vegetation integrity. Illinois Native Plant Society, Westville, Illinois, USA.

Tawa, V., Tozer, D.C., Green, D.M., 2024. Natural disturbance allows multiple anuran taxa to persist in a dynamic wetland complex. J Wildl Manage 88, e22617. https://doi.org/10.1002/jwmg.22617

Tozer, D.C., 2020. Great Lakes Marsh Monitoring Program: 25 years of conserving birds and frogs. Birds Canada, Port Rowan, Ontario, Canada. www.birdscanada.org/glmmp25.

Tozer, D.C., 2016. Marsh bird occupancy dynamics, trends, and conservation in the southern Great Lakes basin: 1996 to 2013. J Great Lakes Res 42, 136–145. https://doi.org/10.1016/j.jglr.2015.10.015

Tozer, D.C., 2014. Coastal wetland birds, in: State of the Great Lakes 2011. Cat No. En161-3/1-2011E-PDF. EPA 950-R-13-002. Published by Environment Canada and U.S. Environmental Protection Agency.

Tozer, D.C., Bracey, A.M., Brady, V., Chislock, M., Ciborowski, J., Cooper, M., Fiorino, G.E., Gehring, T.M., Gnass Giese, E.E., Grabas, G.P., Harrison, A., Howe, R.W., Lamberti, G., Lawrence, G.J., Niemi, G.J., Uzarski, D., Wheelock, B.A., Ethier, D.M., 2024. Occurrence patterns and trends of frogs in coastal wetlands of the Great Lakes, 2011–2023, call for further habitat restoration. In preparation, unpublished manuscript.

Tozer, D.C., Howe, R.W., Niemi, G.J., Gnass Giese, E.E., Bracey, A.M., Fiorino, G.E., Gehring, T.M., Lawrence, G.L., Norment, C.J., 2022. Sub-indicator: coastal wetland birds, in: State of the Great Lakes 2022 Technical Report. Cat No. En161-3/1E-PDF. EPA 905-R-22-004. Published by Environment and Climate Change Canada and U.S. Environmental Protection Agency.

Tozer, D.C., Howe, R.W., Niemi, G.J., Gnass Giese, E.E., Walton, N.G., Bracey, A.M., Gaul, W., Grabas, G.P., Norment, C.J., Gehring, T.M., 2019. Sub-Indicator: coastal wetland birds, in: State of the Great Lakes 2019 Technical Report. Cat No. En161-3/1E-PDF. EPA 905-R-20-044. Published by Environment and Climate Change Canada and U.S. Environmental Protection Agency.

Tozer, D.C., Howe, R.W., Niemi, G.J., Gnass Giese, E.E., Walton, N.G., Bracey, A.M., Gaul, W., Norment, C.J., Gehring, T.M., 2017. Sub-Indicator: coastal wetland birds, in: State of the Great Lakes 2017 Technical Report. Cat No. En161-3/1E-PDF. EPA 905-R-17-001. Published by Environment and Climate Change Canada and U.S. Environmental Protection Agency.

Tozer, D.C., Steele, O., Gloutney, M., 2018. Multispecies benefits of wetland conservation for marsh birds, frogs, and species at risk. J Environ Manage 212, 160–168. https://doi.org/10.1016/j.jenvman.2018.01.055

Trenham, P.C., Koenig, W.D., Mossman, M.J., Stark, S.L., Jagger, L.A., 2003. Regional dynamics of wetland-breeding frogs and toads: turnover and synchrony. Ecol Appl 13, 1522–1532.

Uzarski, D.G., Brady, V.J., Cooper, M.J., Wilcox, D.A., Albert, D.A., Axler, R.P., Bostwick, P., Brown, T.N., Ciborowski, J.J.H., Danz, N.P., Gathman, J.P., Gehring, T.M., Grabas, G.P., Garwood, A., Howe, R.W., Johnson, L.B., Lamberti, G.A., Moerke, A.H., Murry, B.A., Niemi, G.J., Norment, C.J., Ruetz, C.R., Steinman, A.D., Tozer, D.C., Wheeler, R., O'Donnell, T.K., Schneider, J.P., 2017. Standardized measures of coastal wetland condition: implementation at a Laurentian Great Lakes basin-wide scale. Wetlands 37, 15–32. https://doi.org/10.1007/s13157-016-0835-7

Venter, O., Sanderson, E.W., Magrach, A., Allan, J.R., Beher, J., Jones, K.R., Possingham, H.P., Laurance, W.F., Wood, P., Fekete, B.M., Levy, M.A., Watson, J.E.M., 2016. Global terrestrial Human Footprint maps for 1993 and 2009. Sci Data 3, 160067. https://doi.org/10.1038/sdata.2016.67

Walpole, A.A., Bowman, J., Tozer, D.C., Badzinski, D.S., 2012. Community-level response to climate change: shifts in anuran calling phenology. Herpetol Conserv Biol 7, 249–257.

Weir, L., Fiske, I.J., Royle, J.A., 2009. Trends in anuran occupancy from northeastern states of the North American Amphibian Monitoring Program. Herpetol Conserv Biol.

Weir, L.A., Royle, J.A., Gazenski, K.D., Villena, O.C., 2014. Northeast regional and state trends in anuran occupancy from calling survey data (2001-2011) from the North American Amphibian Monitoring Program. Herpetol Conserv Biol 9, 223–245.

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Table 1. Anuran species and groups of species (*n* = 9) used to generate biotic response (BR) functions (Figure 1) and associated weights for calculating the Index of Biotic Condition (IBC) as a measure of the health of Great Lakes wetlands. See Index of Biotic Condition section above for how the weights were calculated.

Source: based on Howe et al. (2023).

Table 2. Long-term (1995–2023) and 10-year (2013–2023) trends of median Index of Biotic Condition (IBC) based on wetland-breeding anurans throughout coastal and inland wetlands of the entire Great Lakes (overall) and within each basin (e.g., Superior). Shown are geometric mean rates of change (Trend: % per year) based on differences between the first and last year in the trend, along with "lower" and "upper" 95% confidence limits. Instances where sample sizes were too low to calculate reliable trends are shown with dashes. Trends calculated using equation 4 in Smith et al. (2014) with 1,000 bootstrap replicates. Statistically significant trends are shown in bold, based on confidence intervals that do not overlap zero.

Source: Great Lakes Marsh Monitoring Program, Great Lakes Coastal Wetland Monitoring Program.

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Figure 1. Schematic representation of the steps required to calculate the Index of Biotic Condition (IBC) based on anuran data from coastal wetlands throughout the Great Lakes basin. For each of nine anuran species or groups of species (see Table 1 for details), a biotic response function (A) depicting the species' probability of occurrence as a function of a combined "human footprint" variable (environmental condition, Cenv) based on wetland, developed, and agricultural land cover (0 = Poor condition, 10 = Good condition) was used to calculate two parameters (B), which were multiplied together to derive a weight; then the weights for all of the species present were summed and scaled out of 10 to produce IBCs for particular wetlands. For example, a wetland where only Green Frog was present received an IBC of 1.3; a wetland where Green Frog and Spring Peeper were present received an IBC of 3.2; and a wetland where all nine species or species groups were present received an IBC of 10.

Source: Great Lakes Coastal Wetland Monitoring Program, based on Howe et al. (2023)

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Figure 5. Distribution of the Index of Biotic Condition (IBC) based on anuran community data from the past 3 years (2021–2023) throughout the entire Great Lakes basin (overall) and each individual lake basin. Shown are box-and-whisker plots of wetland-level means. Whiskers represent data within 1.5 times the interquartile range; dots are outliers. Vertical, dashed, grey lines show defining values for Poor, Fair, and Good status.

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Figure 6. Index of Biotic Condition (IBC) throughout coastal wetlands of the Great Lakes based on anuran community data from the past 5 years (2019–2023). Shown are wetland-level mean IBCs, averaged across years for wetlands that were sampled in multiple years. The most recent 5 years of data were used to boost sample sizes.

Source: Great Lakes Marsh Monitoring Program, Great Lakes Coastal Wetland Monitoring Program

Figure 7. Density plots of the Index of Biotic Condition (IBC) based on anuran community data from the past 5 years (2019–2023) throughout the entire Great Lakes basin (overall) and each individual lake basin for coastal and inland wetlands. Shown are probability density functions based on kernel density estimates, which can be thought of as smoothed histograms. Density plots are useful alternatives to histograms for continuous data that come from an underlying smooth distribution, as is the case here. Shown are plots based on wetland-level mean IBC values, averaged across years for wetlands that were sampled in multiple years. Inland data for lakes Superior and Michigan are not shown due to small sample sizes.

Source: Great Lakes Marsh Monitoring Program, Great Lakes Coastal Wetland Monitoring Program

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Source: based on Howe et al. (2023).

No.	Label	Species	Weight
1	American Bullfrog	American Bullfrog (*Lithobates catesbeianus*)	1.96
2	American Toad	American Toad (*Anaxyrus americanus*)	0.07
3	Chorus Frog	Boreal Chorus Frog (*Pseudacris maculata*), Western Chorus Frog (*P. triseriata*)	0.29
4	Gray Treefrog	Cope's Gray Treefrog (*Dryophytes chrysoscelis*), Eastern Gray Treefrog (*D. versicolor*)	2.99
5	Green Frog	Green Frog (*Lithobates clamitans*)	1.99
6	Northern Leopard Frog	Northern Leopard Frog (*Lithobates pipiens*)	3.65
7	Other	Fowler's Toad (*Anaxyrus fowleri*), Mink Frog (*Lithobates septentrionalis*), Pickerel Frog (*L. palustrisis*)	0.62
8	Spring Peeper	Spring Peeper (*Pseudacris crucifer*)	3.05
9	Wood Frog	Wood Frog (*Lithobates sylvaticus*)	1.04

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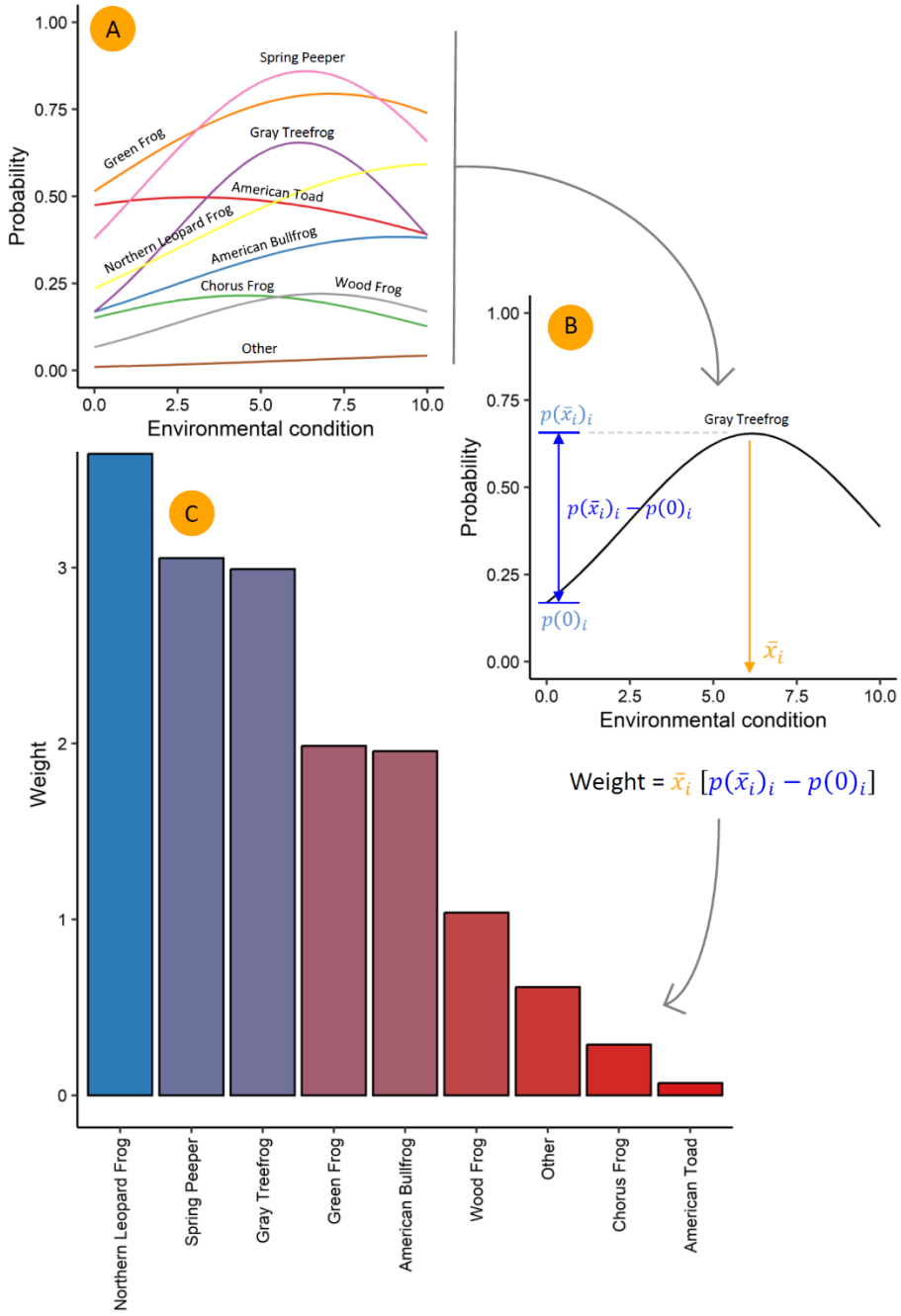
Source: Great Lakes Marsh Monitoring Program, Great Lakes Coastal Wetland Monitoring Program.

Wetland type	Basin	Start year	End year	Trend	Lower	Upper
Coastal	Overall	1995	2023	–	–	–
		2013	2023	0.1	-0.8	1.0
	Superior	1995	2023	–	–	–
		2013	2023	0.6	-1.8	3.1
	Michigan	1995	2023	–	–	–
		2013	2023	0.4	-2.1	2.8
	Huron	1995	2023	–	–	–
		2013	**2023**	**-2.1**	**-3.5**	**-0.7**
	Erie	1995	2023	-0.1	-1.2	0.9
		2013	2023	2.1	-0.7	4.8
	Ontario	**1995**	**2023**	**2.6**	**1.3**	**4.0**
		2013	2023	0.7	-0.6	2.0
Inland	Overall	1995	2023	–	–	–
		2013	**2023**	**-1.1**	**-2.2**	**0.0**
	Superior	1995	2023	–	–	–
		2013	2023	–	–	–
	Michigan	1995	2023	–	–	–
		2013	2023	–	–	–
	Huron	1995	2023	-0.8	-1.8	0.2
		2013	2023	-0.1	-3.4	3.1
	Erie	**1995**	**2023**	**-1.2**	**-2.1**	**-0.3**
		2013	**2023**	**-2.8**	**-4.9**	**-0.7**
	Ontario	1995	2023	-0.4	-1.3	0.5

		2013	2023	-0.8	-2.4	0.7



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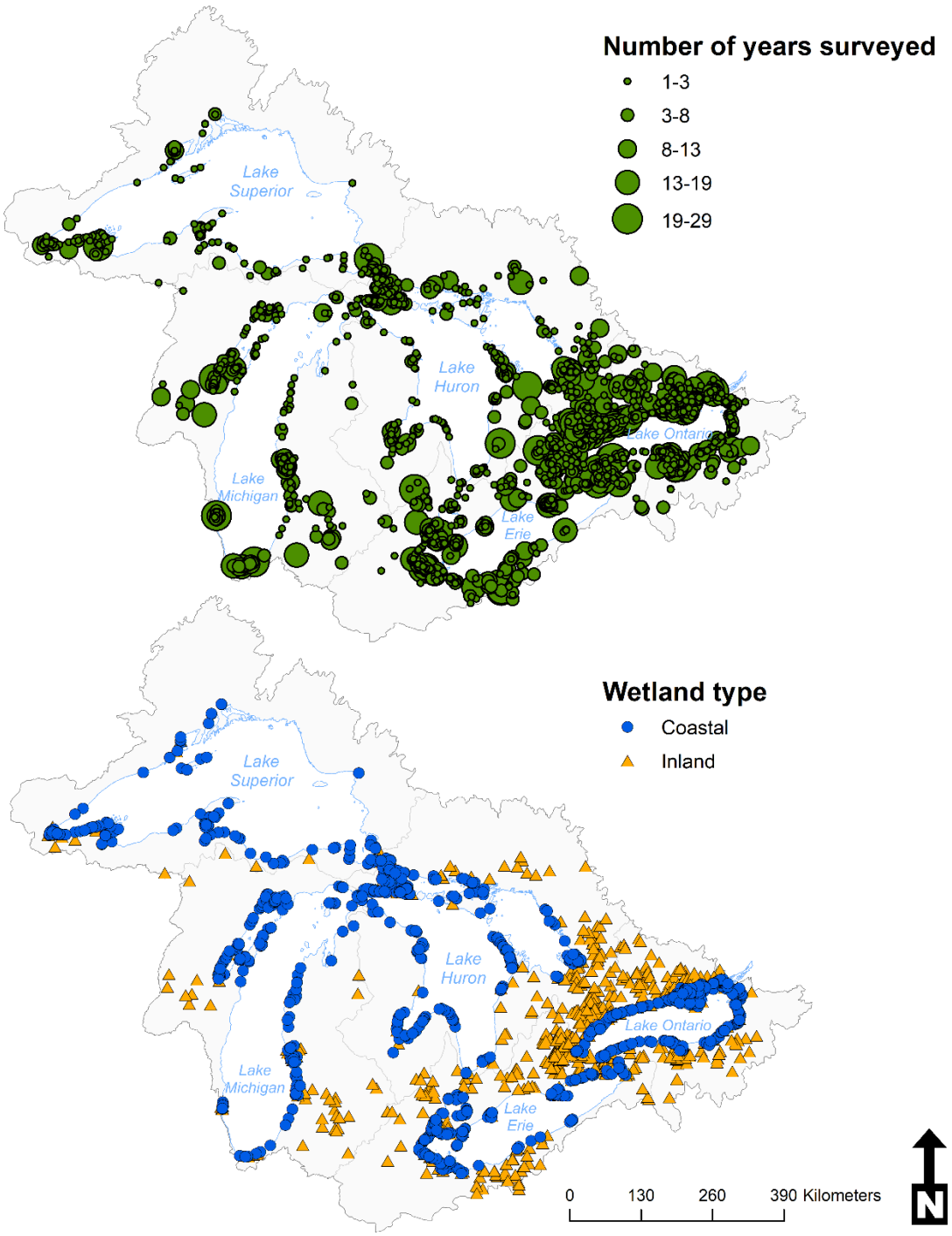

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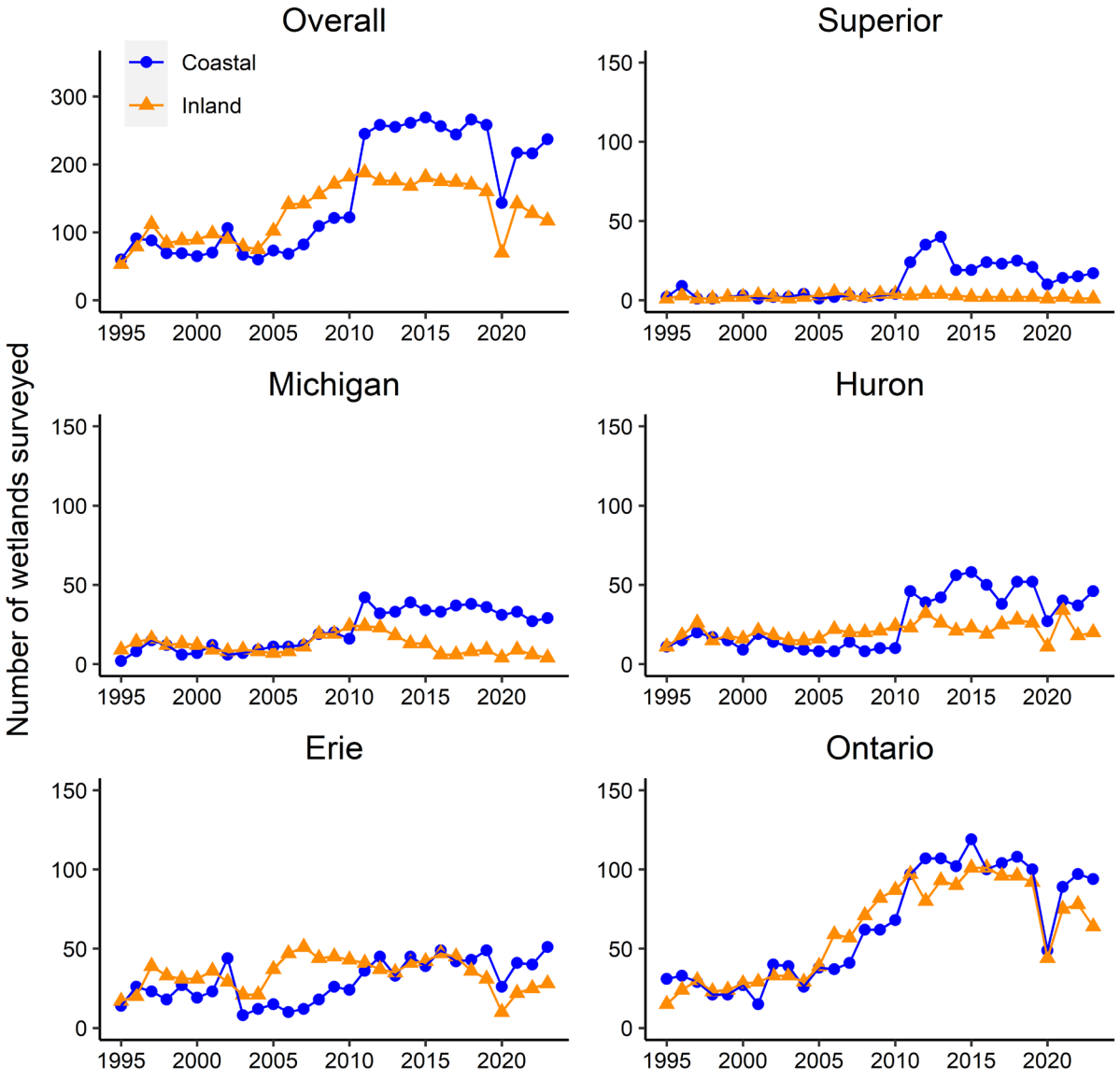

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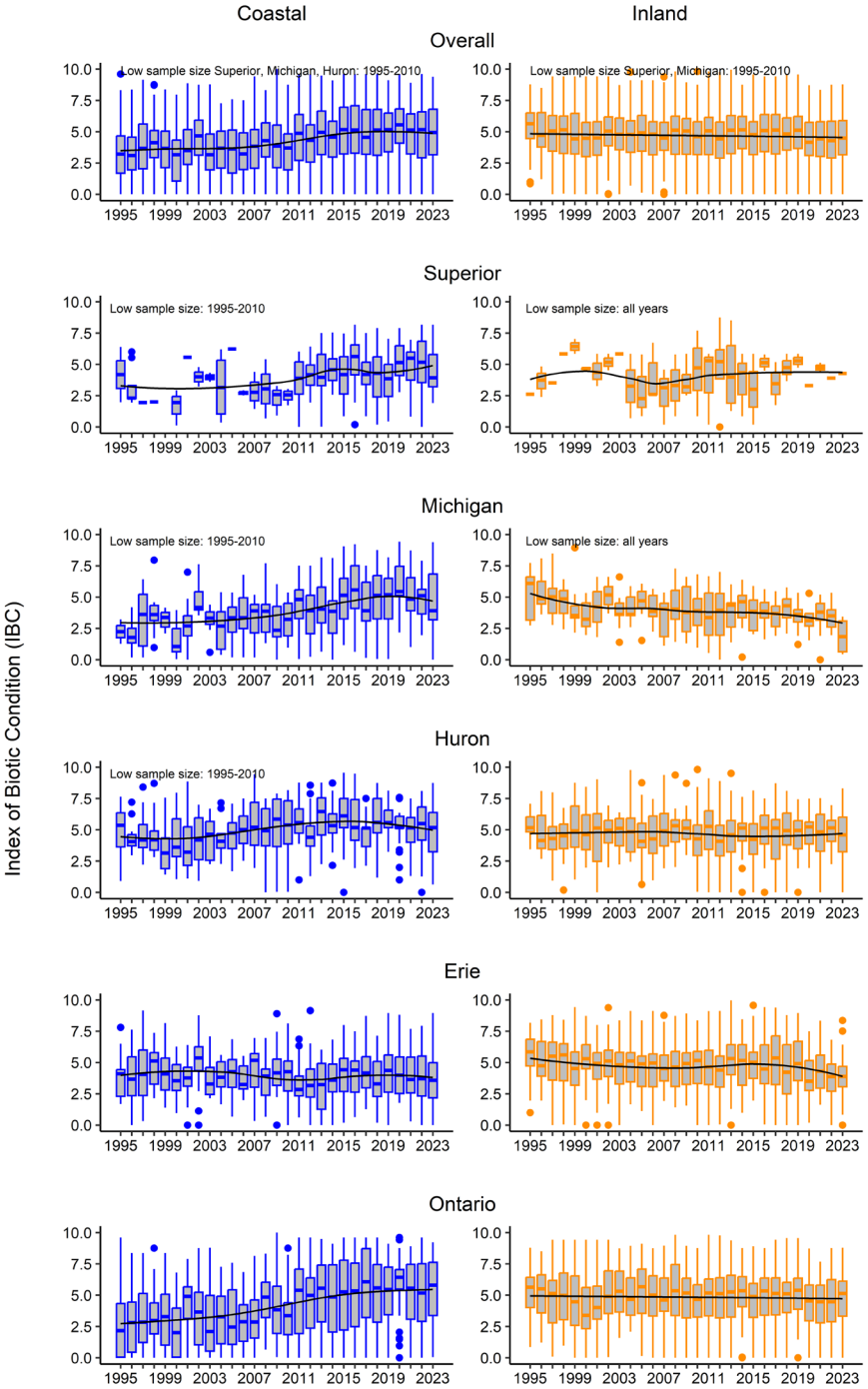

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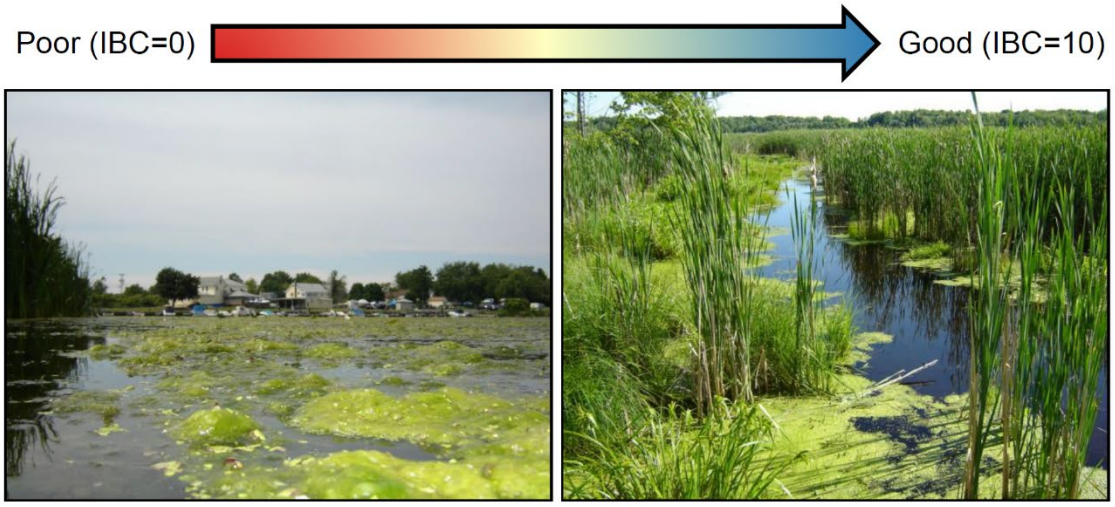

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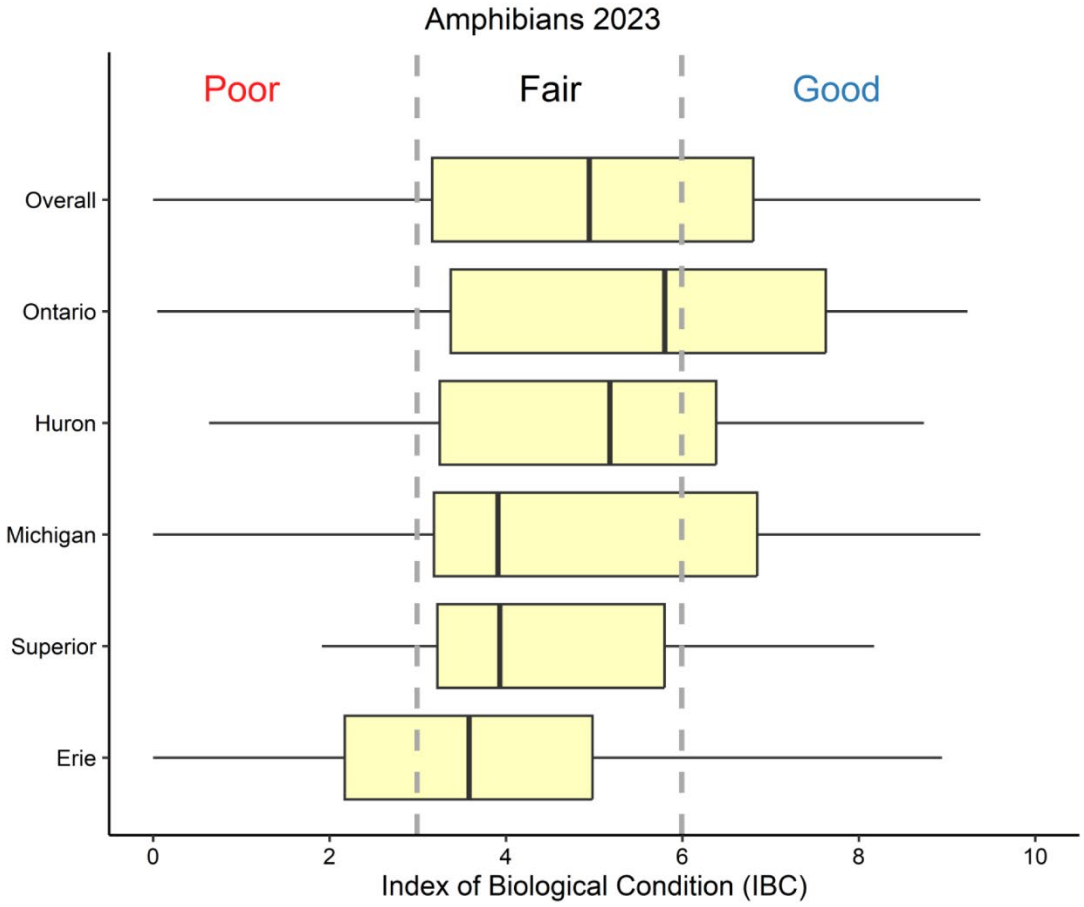

Figure 5. Distribution of the Index of Biotic Condition (IBC) based on anuran community data from the past 3 years (2021–2023) throughout the entire Great Lakes basin (overall) and each individual lake basin. Shown are box-and-whisker plots of wetland-level means. Whiskers represent data within 1.5 times the interquartile range; dots are

outliers. Vertical, dashed, grey lines show defining values for Poor, Fair, and Good status. Source: Great Lakes Marsh Monitoring Program, Great Lakes Coastal Wetland Monitoring Program.

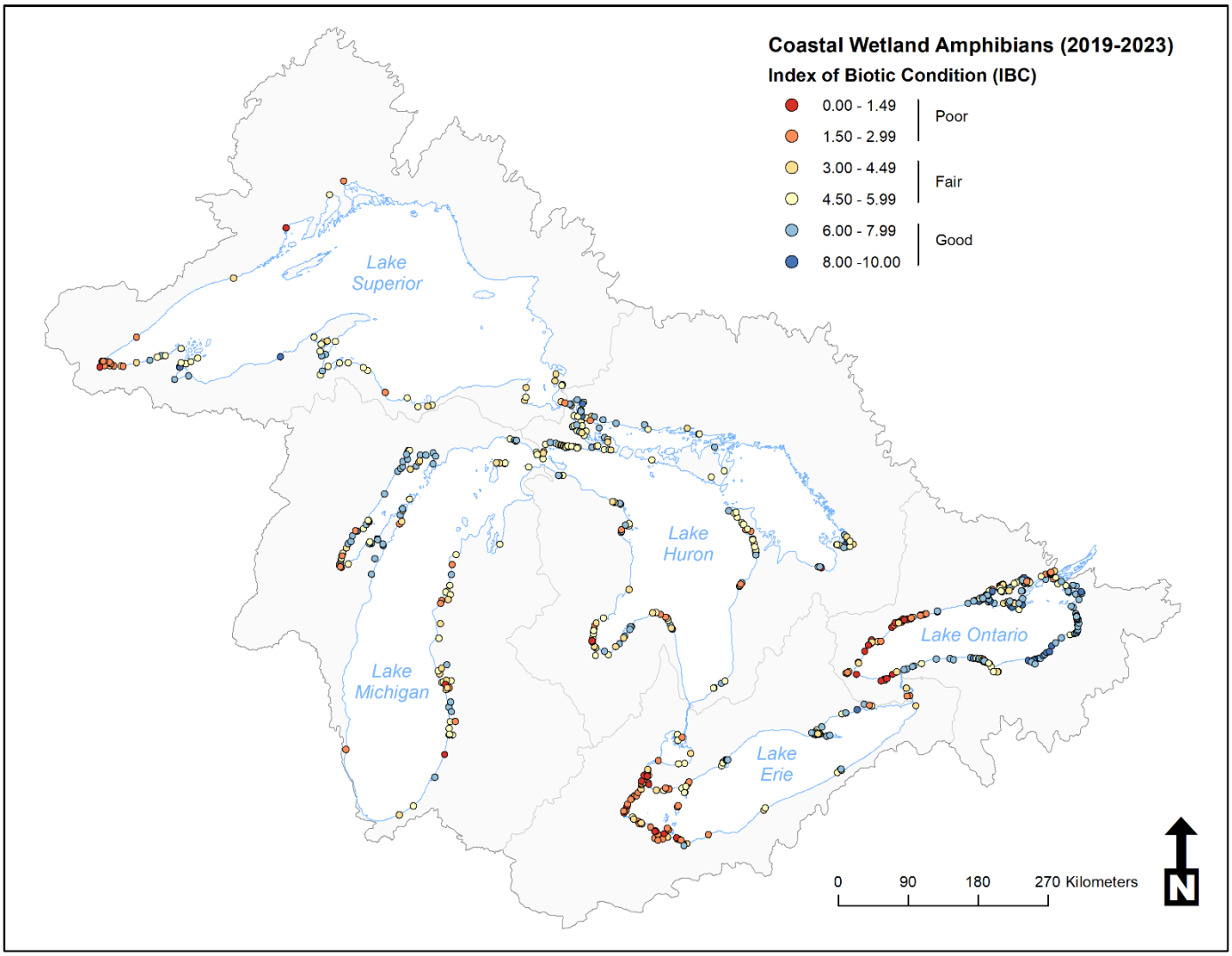

Figure 6. Index of Biotic Condition (IBC) throughout coastal wetlands of the Great Lakes based on anuran community data from the past 5 years (2019–2023). Shown are wetland-level mean IBCs, averaged across years for wetlands that were sampled in multiple years. The most recent 5 years of data were used to boost sample sizes. Source: Great Lakes Marsh Monitoring Program, Great Lakes Coastal Wetland Monitoring Program.

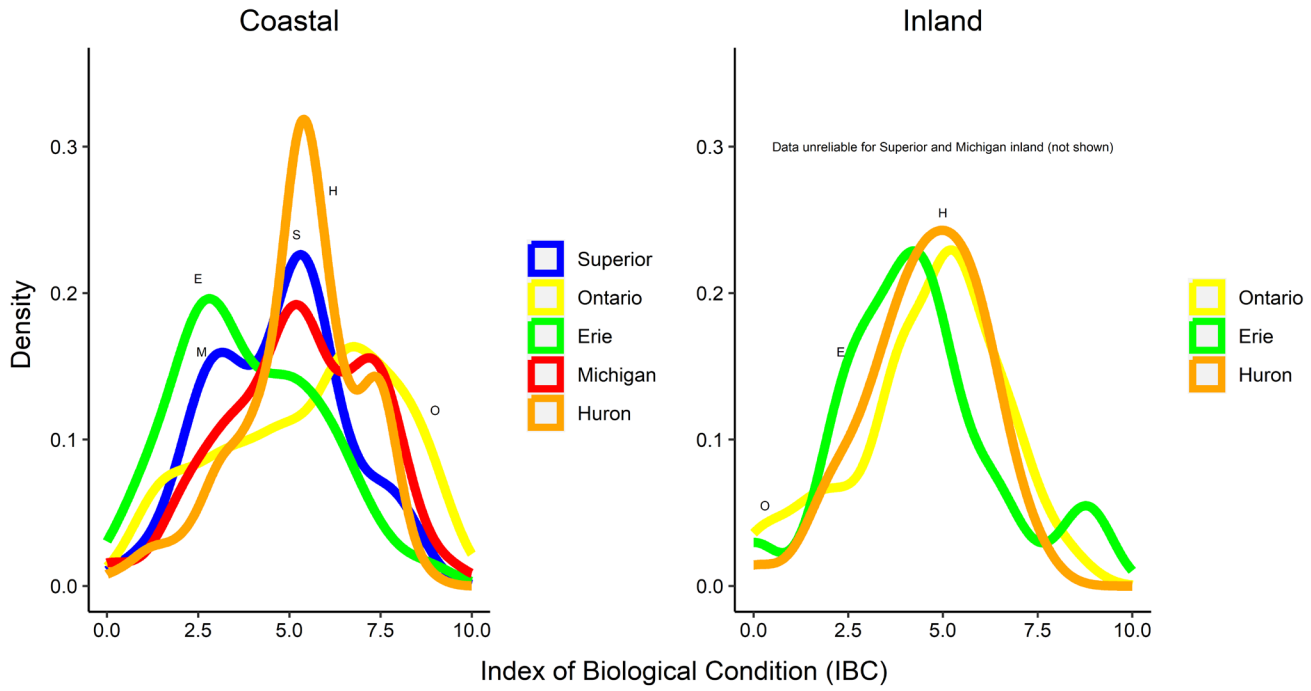

Figure 7. Density plots of the Index of Biotic Condition (IBC) based on anuran community data from the past 5 years (2019–2023) throughout the entire Great Lakes basin (overall) and each individual lake basin for coastal and inland wetlands. Shown are probability density functions based on kernel density estimates, which can be thought of as smoothed histograms. Density plots are useful alternatives to histograms for continuous data that come from an underlying smooth distribution, as is the case here. Shown are plots based on wetland-level mean IBC values, averaged across years for wetlands that were sampled in multiple years. Inland data for lakes Superior and Michigan are not shown due to small sample sizes.

Source: Great Lakes Marsh Monitoring Program, Great Lakes Coastal Wetland Monitoring Program.