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Development of a preliminary vegetation-based indicator of ecosystem health for coastal wetlands of the Laurentian Great Lakes

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ABSTRACT

Wetland plants, due to their sedentary nature, hold great potential for use as indicators of ecosystem condition in the Great Lakes. However, natural variations in lake levels have historically confounded efforts to create such indicators. Our goal was to use zone-level vegetation data collected over a seven-year period of low to high water levels to overcome these difficulties and identify metrics capable of accurately reflecting disturbance despite lake-level variation. Through a combination of multivariate statistical analyses and a review of the literature, we identified and tested a series of plant-based metrics for wet meadow, emergent, and submergent zones of lacustrine coastal wetlands of Western Lake Huron. These were combined into zone-specific indicators of ecosystem health, which were then applied to wetlands of the remaining Great Lakes to assess basin-wide viability. The resulting indicators were found to reflect disturbance without bias towards high or low water levels. While they must be assessed for use in riverine and barrier-beach coastal wetlands before full-scale implementation can occur, we suggest their use on a preliminary basis in monitoring and management efforts.

1. Introduction

Over the past two decades, there has been great interest in developing methods for monitoring the condition and function of Laurentian Great Lakes coastal wetlands. Coastal wetlands are incredibly diverse ecosystems and facilitate a number of ecosystem services vital to the Great Lakes region, from providing habitat to recreationally and economically important species to water filtration. However, over half of all coastal wetlands have been lost since European settlement, and those that are left are subject to an abundance of different anthropogenic stressors, such as agricultural runoff and increased urbanization (Albert and Minc, 2004; Danz et al., 2007; Kovalenko et al., 2014; Uzarski et al., 2017; Harrison et al., 2019; Horton et al., 2019; Host et al., 2019). As such, effective assessment methods must be able to reflect how coastal wetlands are being impacted by and responding to these disturbances. Indices of biotic integrity (IBIs), metric-based assessment methods focused on measuring certain attributes of biotic communities within wetlands, are commonly used to achieve this goal. As opposed to measuring various physical and chemical aspects of these systems, which often only provide a brief snapshot of stress present at a given time, biotic communities integrate disturbance over time, and are, therefore, more reflective of long-term stress (Karr, 1987; Grabas et al., 2012). Sets of biotic metrics for use in Great Lakes coastal wetlands have been developed using macroinvertebrates, fish, birds, and anurans (Uzarski et al., 2017).

There is a history of using the plant community within wetlands as indicators of disturbance (Albert and Minc, 2004; Rothrock and Simon, 2006; Mack, 2007; Grabas et al., 2012; Gara and Stapanian, 2015). Rooted plants are incapable of moving in response to stress, unlike other commonly monitored organisms such as fish and birds. Because of their sedentary nature, plants are often more responsive to and reflective of *in situ* stressors than other more mobile communities (Brazner et al., 2007; Johnston et al., 2008). Specific wetland plant genera and species have been correlated with a variety of different stressors, such as water-level regulation, nutrient enrichment, sedimentation, physical degradation, and land use/land cover (Lougheed et al., 2001; Albert and Minc, 2004; Boers et al., 2007; Brazner et al., 2007; Johnston and Brown, 2013). In addition, vegetation surveys are

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typically less expensive and time-consuming than other surveying methods. As such, a plant-based indicator would contribute significantly to the needs of the conservation and management community.

Development of such an indicator has proven difficult due to the variation in plant community composition created by the natural fluctuation of water levels, as well as differences in sediments, wave energy, and other physical constraints on wetland plant establishment and survival. This environmental variation is responsible for the unique plant zonation as well as high biodiversity seen in coastal wetlands (Wilcox et al., 2008; Keddy, 2010). However, changes in water levels can also cause significant shifts in community composition independent of changes in anthropogenic disturbance (Wilcox et al., 2002; Uzarski et al., 2017). Wilcox et al. (2002) concluded that the overriding influence of lake-level variation was so strong that biotic metrics for Great Lakes coastal wetlands could only be developed if they were made for different water-level histories. Despite this, robust indices have been developed using both macroinvertebrates (Burton et al., 1999; Uzarski et al., 2004) and fish (Uzarski et al., 2005; Cooper et al., 2018) by focusing on plant zone-specific metrics, as opposed to the wetland as a whole. Taking a similar approach to developing robust vegetation-based indicators within distinct plant zones proved to be more effective than entire-wetland indicators in a comparison of nineteen riverine wetlands along Lake Michigan (Albert et al., 2007), and we are testing similar zone-specific plant metrics in this study.

Data collection for the Coastal Wetland Monitoring Program (CWMP) began in the summer of 2011 and has been conducted every summer since, therefore providing an optimal opportunity to identify vegetation-based metrics throughout a sequence of low to high water level years. In 2011 and 2012, the Great Lakes were experiencing a prolonged period of historically low water levels, particularly in lakes Huron-Michigan and Superior (Gronewold et al., 2013). By 2014, the lakes had transitioned to a period of higher water levels, 10–20 cm above long-term water levels for lakes Huron-Michigan and Superior, continuing at least through 2019. Analyzing relations between plant community composition and disturbance along this gradient of inundation allowed us to create metrics that reflect ecosystem condition.

Through combining the zone-based methodology used in the development of macroinvertebrate and fish IBIs with zone-specific vegetation data collected along this series of low to high water levels, we hoped to accomplish what was previously not possible: the development of Great Lakes basin-wide vegetation-based indicators of ecosystem health capable of adequately describing disturbance across a series of variable water levels. By focusing our efforts on each broad vegetation zone and comparing community composition traits within these zones along a gradient of both disturbance and water levels, we identified metrics capable of accurately distinguishing levels of human impact. We compiled these metrics into indicators of ecosystem health and then assessed their viability for basin-wide use.

2. Methods

2.1. Study area

This study focuses on lacustrine coastal wetlands of the entire Great Lakes region sampled over the first seven years of the CWMP. Lacustrine coastal wetlands are broadly classified as those wetlands directly on the shores of the lake, and therefore directly controlled by hydrologic processes such as lake-level fluctuation, seiches, ice scour, etc. (Albert et al., 2005). There are two other broad hydrogeomorphic classes for Great Lakes coastal wetlands; riverine and barrier-beach (Albert et al., 2005). While these two wetland classes have been surveyed by CWMP, they were not evaluated during this study.

Broadly speaking, Great Lakes coastal wetlands can be split into three vegetation zones along an elevation and inundation gradient: wet meadow, emergent, and submergent zones. Wet meadows are characterized by a combination of graminoids such as sedges and grasses, a wide array of forbs such as mints and asters, and often small shrubs and juvenile trees; being the farthest upland, they are inundated for the shortest period over the course of a year, but can be completely inundated during high-water years. Emergent zones are characterized by bulrushes, spikerushes, bur-reeds, cattails, and support submergent and floating-leaved species; they are inundated much longer than wet meadows, often for years at a time. Submergent zones are characterized by various submerged and floating-leaved plants and are inundated for the longest period of time, typically for years at a time, as they border the open water of the lake (Lemein et al., 2017). In general, species richness is highest within the wet meadow zone, lowest in the submergent zone, and intermediate within the emergent zone. We analyzed community composition within each of these zones individually at each site, as opposed to the site as a whole.

2.2. Vegetation sampling

Vegetation sampling followed the procedures described in both Lemein et al. (2017) and Uzarski et al. (2017). Surveys were conducted between the beginning of June and end of August during the maximum growth of the community. Prior to accessing a site, three transects perpendicular to the shoreline were selected using satellite imagery. These transects intersected the three major vegetation zones with the goal of obtaining a dataset that was as representative of the vegetation community at each site as possible. Each transect was comprised of five sampling points per vegetation zone, evenly spaced within each respective zone. Totals of 15–45 sampling points were evaluated per wetland, depending on the number of zones present. Zones were ideally at least 11 m long, as this was the minimum width required to place five sampling points 1 m apart, and from the edges of the zone. When zones were present but less than 11 m long, a perpendicular transect was established at the center of the zone, and points were sampled at 5-m intervals along it. Percent cover for plant species present at each sampling point was determined using 1-m^2 quadrats, placed 2 m off the transect to reduce the effect of trampling. Any plant that could not be identified to species in the field was collected and identified in lab using a taxonomic key.

2.3. Establishing gradients of disturbance

Two different disturbance gradients were used in metric development and verification: RankSum (Uzarski et al., 2017) and AgDev (Johnson et al., 2015). RankSum has previously been used in the development of Great Lakes coastal wetland IBIs as it incorporates both water quality and land-use/land-cover data, and therefore provides a more comprehensive understanding of disturbance than other such measures (Uzarski et al., 2005; Cooper et al., 2018). Due to the shallow nature of wet meadow zones, lack of available water sometimes precludes collection of water chemistry data; therefore, RankSum is likely to be less representative of stress within these zones. In addition, wet meadows may be more responsive to non-water quality disturbances, as a previous study conducted in riverine wetlands of the Great Lakes demonstrated that wet meadows responded more strongly to localized land use than either emergent or submergent zones (Albert et al., 2007). AgDev is another disturbance gradient commonly used in analyses of disturbance in Great Lakes Coastal Wetlands (Hollenhorst et al., 2007; Johnston and Brown, 2013; Host et al., 2019). Unlike RankSum, it relies entirely on land-use/land-cover data and does not require any water quality data to be calculated. As such, AgDev was used to develop metrics in the wet meadow zone, while RankSum was used to develop metrics in the emergent and submergent zones.

RankSum was calculated using a mixture of *in situ* water quality variables, water chemistry, and land-use/land-cover. Data collection and processing followed the procedures described in Uzarski et al. (2017). In brief, once per sampling season, chemical and physical variables were measured in triplicate within each mono-dominant vegetation zone as determined by the field crews sampling fish and macroinvertebrates at each site. A multi-sonde water quality probe was used to collect *in situ* data, such as water temperature, dissolved oxygen percent saturation and concentration, redox potential, pH, chlorophyll *a*, turbidity, and temperature. Replicate water samples were then taken and stored for further analysis in the laboratory. These samples were analyzed for total nitrogen, total phosphorous, soluble reactive phosphorus, nitrate-nitrite-N and chloride concentrations. Lastly, percent cover for four land-use/land-cover variables (% developed, % agriculture, % wetland, and % natural areas) was calculated for each site at both a local (1 km) and watershed (20 km) level. These attributes were compiled for each zone at each site for a given year and then ranked, with the lowest score for a variable given to the zone indicating the most stress and *vice versa* for the highest score. These ranks were summed, averaged to the site level, and then scaled between 0 and 100 to achieve a final RankSum score. Since water quality can change from year to year, sites were only used for analysis if a RankSum score was associated with it for a year in which vegetation was also sampled.

AgDev is determined by calculating four land-use/land-cover variables within a 20-km buffer of each coastal wetland: percent agricultural land use, percent developed land use, road density (km/km^2), and population density (people/km^2). Percent agricultural and developed land use were calculated using satellite imagery data. Road density was calculated by determining the length of road present within each buffer from road maps available at the state/province and county level. Population density was estimated from the most recent census data available for the United States (2010) and Ontario (2016). Each variable was then scaled between 0 and 1. “Ag” was simply the scaled value of agricultural land cover, while “Dev” was the highest of the three development variables (% development, road density, population density). Sites were then plotted against each other, with Ag being the x-axis and Dev being the y-axis. “AgDev” was determined by calculating the Euclidean distance between the origin (0,0) and each site (Ag, Dev). The origin was representative of the lowest possible impact within a dataset, and as such, inferred disturbance increases with AgDev. Given the availability of both geospatial and census data, AgDev was calculated across the entire study period, as opposed to year-by-year.

2.4. Metric identification

A total of 42 coastal wetlands sampled along the western and northwestern shores of Lake Huron in 2011–2012 and 2014–2015 were used to identify and evaluate potential metrics; this represents every lacustrine coastal wetland sampled in this region over those time periods for which vegetation data was available. Wetlands were sampled once each over this time (Fig. 1). Lake Huron has been the subject of previous analyses of relationships between the composition of various communities and anthropogenic disturbance due to its latitudinal range and strong variation in stress from south to north, and is therefore an optimal region for trying to identify vegetation-based metrics responding to disturbance (Uzarski et al., 2004; Niemi et al., 2009). Data were limited to 2011–2012 and 2014–2015 to create a clear gradient from low to high water levels, while 2013 was considered a transitionary period between the two phases and was therefore omitted from metric identification.

Percent covers for all observed plant species were averaged to the zone level for each site. To identify potential relationships between plant community composition in each zone and their respective stressor gradients, the zone-averaged vegetation data for 2011–2012 and 2014–2015 were analyzed using correspondence analysis (CA). Correspondence analysis was previously used during the development and testing of both macroinvertebrate and fish-based IBIs in Great Lakes coastal wetlands, as it allows one to compare broad trends in community composition to predetermined gradients of anthropogenic disturbance (i.e. RankSum and AgDev; Uzarski et al., 2005). By doing so, we hoped to identify relationships between vegetation community composition and disturbance which could be used in metric development. As such, the resulting CA dimensions were compared to the relevant disturbance gradients, and the composition of plant species along these dimensions were analyzed, to identify potential metrics. In addition to relationships identified by this analysis, several potential indicators for each zone previously identified in the literature were evaluated. Relative covers for certain plant groups were determined by adding all the zone-averaged covers for each species together to achieve a zone-level average vegetation cover value and dividing the total average cover of a given group by this value. Likewise, relative frequencies were calculated by determining the species richness for a given zone and dividing the species richness of a specific group by that value.

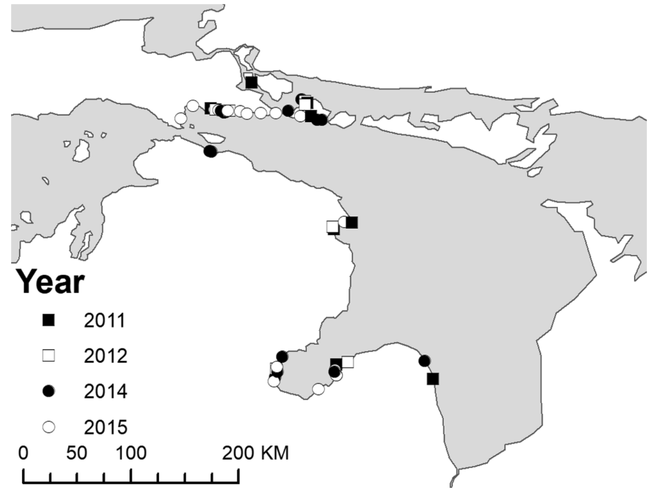

Fig. 1. Location of all lacustrine coastal wetlands sampled along the shores of western Lake Huron in Michigan, USA in 2011–2012 and 2014–2015. Vegetation data from these sites were used to identify and test potential metrics.

Metrics related to the coefficient of conservatism (hereby referred to as “C”) were evaluated for each vegetation zone. C is related to both a species’ ecological tolerance of disturbance, and its fidelity to natural remnant (i.e. pre-European settlement) areas (Gara and Stapanian, 2015). For the purposes of the CWMP, C values for the state of Michigan, assigned by Voss and Reznicek (2012), were used for the entire Great Lakes region. Native species are assigned a score between 1 and 10, with lower scoring species generally being tolerant of human disturbance, and higher scoring species being found mostly in least impacted habitats. Invasive and introduced species are assigned scores of 0. Mean C, a common metric, is calculated by averaging the C of every species found within a zone. We evaluated two separate categories for Mean C that were proposed by Bourdaghs et al. (2006). Native Species Mean C was calculated using only the native species found within a zone, while Total Species Mean C included the invasive and introduced species. Another commonly used metric is the Floristic Quality Index, or FQI (Bourdaghs et al., 2006). It is calculated by multiplying the square root of species richness by Mean C. We chose to focus on Mean C specifically for two reasons. First, given that FQI is derived from Mean C, including both in analysis would be redundant. Second, unlike FQI, Mean C has a defined range of possible values (0–10), which we believed to be better for designing and implementing metrics. Lastly, after identifying which vegetation zone CA dimensions were significantly correlated with their respective disturbance gradients, we analyzed the distribution of C along those dimensions. For example, if a dimension were positively correlated with RankSum, we would find the average C of those plant species ordinating in the direction of the less impacted wetlands (i.e. those with positive CA scores).

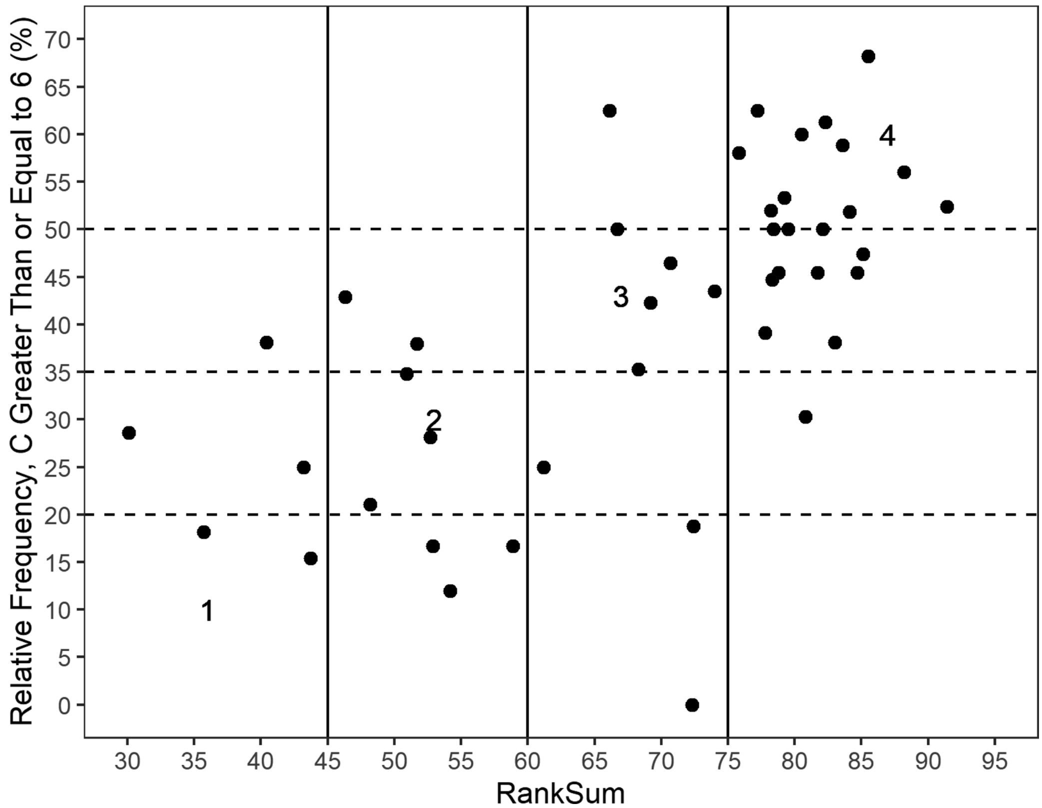

Fig. 2. Example of indicator creation. Solid lines represent quartile groupings along the stressor gradient, while dashed lines represent the bounds of the scoring ranges for the indicator.

2.5. Metric development and indicator verification

We calculated Pearson correlation coefficients to identify which potential metrics were significantly correlated ($p \leq 0.05$) with the stressor gradients and converted them into actual metrics by splitting their distributions into quartiles along their stressor gradient (x-axis, Fig. 2). Scoring ranges were determined by "binning" points within each quartile in such a manner that most points within that quartile would be represented (y-axis, Fig. 2). Ranges were then assigned scores between 1 and 4, with 1 indicating the most disturbed conditions and 4 indicating the least disturbed. To test the accuracy of the preliminary indicators within western Lake Huron, additional data from 30 coastal wetlands sampled in 2013 and 2016–2017 were used (Fig. 3). Species composition was averaged to the zone level as before, and the indicators were used to calculate scores for each zone; for example, if an indicator had four metrics scoring 2, 3, 1, and 1 respectively, the total indicator score for that zone would be 7. These scores were compared to the stressor gradients by calculating Pearson's correlation coefficients between the gradients and the indicator scores. This process was repeated with vegetation data from an additional 68 lacustrine coastal wetlands sampled throughout the rest of the Great Lakes basin from 2011 to 2017 to determine basin-wide viability (Fig. 3). Lastly, we used

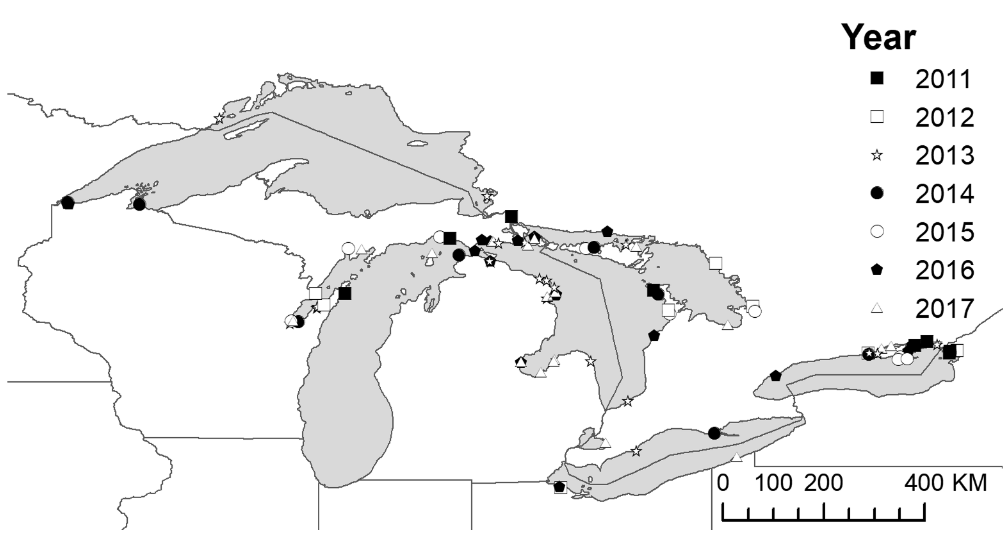

Fig. 3. Location of lacustrine coastal wetlands sampled throughout the Great Lakes Basin which were used to assess the accuracy of the preliminary indicators. All sites were sampled over the course of the Coastal Wetland Monitoring Project (2011–2017).

Table 1
Pearson correlation coefficients relating individual site CA dimensions for 2011–2012 and 2014–2015 western Lake Huron wetlands with their respective stressor gradient, with significant values (α = 0.05) bolded.

	Dim1	Dim2	Dim3	Dim4	Dim5
Wet Meadow	**−0.36**	**0.57**	0.30	−0.08	−0.16
Emergent	**0.69**	0.17	−0.30	0.03	0.27
Submergent	−0.19	**0.55**	−0.14	0.23	−0.03

a one-way analysis of variance (ANOVA) to examine any bias inherent in the final indicators due to water level, with year being used as a proxy for water level. All statistical analyses were done using R x64 3.4.3 (R Core Team 2017).

3. Results

3.1. Metric development and identification

CA and the subsequent analysis of relationships between site CA scores and the disturbance gradients determined that both Wet Meadow Dimensions 1 and 2 were correlated with AgDev; the relationship with Dimension 2 was stronger than Dimension 1 (r = 0.57 vs −0.36; Table 1), and was therefore used for analysis. The average C of those plant species ordinating in the direction of the least disturbed sites (i.e. those with negative CA scores) was 5.39. We rounded down to 5 and created two potential Wet Meadow metrics: relative percent cover and relative frequency of species with a C greater than or equal to 5. For the Emergent zone, Dimension 1 was determined to be positively correlated with RankSum (r = 0.69; Table 1). Species ordinating in the direction of less impacted sites had an average C of 5.92; we rounded up and evaluated both the relative cover and frequency of species with a C of 6 or greater. Lastly, Submergent Dimension 2 was determined to be positively correlated with RankSum (r = 0.55; Table 1). As with the other two zones, species ordinating in the direction of less impacted sites had an average C of 6.65; we rounded up and evaluated the relative cover and frequencies of species with a C of 7 or greater.

A summary of the correlation between potential metrics and their respective disturbance gradients can be found in Table 2. Those found not to be statistically significant were dropped from consideration as indicators. The correlation values for the relative cover and frequency of nutrient enrichment and sedimentation/turbidity-tolerant species within submergent zones were nearly identical. Since the species comprising these categories were nearly always the same, and the correlations were nearly identical, we combined the four metrics into two: the relative cover and frequency of nutrient/sedimentation-turbidity tolerant species. A summary of the resulting preliminary indicators and their individual metrics can be found in Table 3, and categorical rankings based on the scores of those indicators can be found in Table 4.

3.2. Indicator verification

The preliminary indicators were used to calculate scores for each of the vegetation zones at sites sampled along the western shore of Lake Huron in 2013 and 2016–2017. The Wet Meadow (r = −0.62), Emergent (r = 0.56), and Submergent (r = 0.59) indicator scores were all significantly correlated with their respective disturbance gradients (Fig. 4). The indicators were then used to calculate scores for lacustrine coastal wetlands sampled throughout the rest of the Great Lakes basin from 2011 to 2017. As before, the Wet Meadow (r = −0.53), Emergent (r = 0.64), and Submergent (r = 0.59) indicator scores were found to be significantly correlated with their respective disturbance gradients (Fig. 5). ANOVA determined no inherent bias in indicator scores according to lake level (Table 5).

4. Discussion

4.1. Final metrics

Most of the final metrics included in the indicators were also included in other wetland assessment programs or have at least been suggested for use in one form or another. The most obvious example of this is the inclusion of the relative cover of invasive and introduced species as a metric among the wet meadow and emergent indicators. Invasive species often take advantage of several different anthropogenic stressors both to establish and sustain populations. For example, nutrient enrichment is common along the shorelines of the Great Lakes, in large part due to sewage effluent and agricultural runoff from the watersheds draining into them. Many invasive plants common to coastal wetlands such as *Typha angustifolia* and *Typha × glauca* can rapidly respond to pulses in nutrients, allowing them to outcompete native species for light and space, eventually leading to the establishment of large mono-dominant stands of those species (Albert and Minc, 2004; Zedler and Kercher, 2004). Physical habitat disturbances, such as diking and dredging, disturb sediments. These areas then become prone to invasion by such species as *Phragmites australis* ssp. *australis* and *Lythrum salicaria*, which establish and then spread rapidly by rhizome or stolon growth (Albert and Minc, 2004; Voss and Reznicek, 2012). Even physical disturbances within the watersheds themselves can impact the presence of invasive species. For example, road density is often cited as a driver promoting the spread of invasive species due to the drainage ditches associated with roads acting as highly disturbed linear corridors of wetland habitat (Zedler and Kercher, 2004; Brisson et al., 2010). These relationships between the presence of invasive species and various stressors are so strong that Trebitz and Taylor (2007) suggested using the presence of particular invasive species as a rapid stand-alone metric for disturbance.

Overall cover by *Carex* species has also been suggested for use as an indicator and has been included in wetland indicators previously, albeit not specifically for lacustrine coastal wetlands (Mack, 2007; Rothrock and Simon, 2006). Regarding Great Lakes coastal wetlands specifically, Johnston et al. (2008) found that, while the species may differ by lake and geographic location, the presence of *Carex* was an important indicator of ecosystem health. Given this, and the prevalence of *Carex* species in the wet meadows of Great Lakes coastal wetlands, its inclusion as an indicator makes sense (Lemein et al., 2017). The same can be said of the various species within the family Cyperaceae as it pertains to emergent zones. For example, Croft and Chow-Fraser (2007) found that the three most common species of bulrush (*Schoenoplectus acutus*, *S. pungens*, and *S. tabernaemontani*) were all indicators of good-to-excellent condition, while Albert and Minc (2004) concluded that the absence of *S. acutus* and *S. pungens* within emergent zones were indicative of highly turbid (i.e. high sedimentation) conditions.

Increased sedimentation in coastal wetlands is in large part due to agricultural activities within watersheds and can have negative impacts on species presence and diversity in coastal wetlands (Albert and Minc, 2004). Sediment deposition can reduce the microtopographic variation within a wetland, which is often critical for maintaining diverse plant communities. In a study of the effects of sedimentation within sedge meadows of Wisconsin, Werner and Zedler 2002 determined that, with every 10 cm of sediment deposition, 1.2 species were lost. Sedimentation within wet meadows also favors colonization by aggressive invasive plant species, such as *Phragmites australis and Lythrum salicaria*. Lastly, sedimentation may inhibit the establishment of many graminoid species, such as those in Cyperaceae or grasses such as *Calamagrostis canadensis*. Boers et al. (2007) found that individuals of *Carex* spp. and *Calamagrostis canadensis* in early growth were incapable of standing erect in standing water, which they attributed to the effects of sedimentation; even though the leaves of these individuals were long enough to emerge from the water, the weight of deposited sediments on these leaves prevented such from occurring, inhibiting overall growth.

Table 2
List of all metrics evaluated for inclusion in preliminary indicators by zone. Pearson correlation (r) and statistical significance of relationship between potential metrics and corresponding disturbance gradients listed.

	Potential Metric	r	p
Wet Meadow	Relative Frequency, *Carex* spp. (%)	−0.49	0.0009
	Relative Cover, *Carex* spp. (%)	−0.52	0.0004
	Relative Frequency, Introduced/Invasive Species (%)	0.41	0.0057
	Relative Cover, Introduced/Invasive Species (%)	0.61	< 0.0001
	Relative Frequency, Coefficient of Conservatism ≥ 5 (%)	−0.42	0.0048
	Relative Cover, Coefficient of Conservatism ≥ 5 (%)	−0.23	0.1461
	Relative Cover, Turbidity/Sedimentation Intolerant Species (%)	−0.50	0.0006
	Total Species Mean Coefficient of Conservatism	−0.42	0.005
	Native Species Mean Coefficient of Conservatism	−0.37	0.0157
Emergent	Relative Cover, Invasive/Introduced Species (%)	−0.74	< 0.0001
	Relative Frequency, Coefficient of Conservatism ≥ 6 (%)	0.62	< 0.0001
	Relative Cover, Coefficient of Conservatism ≥ 6 (%)	0.65	< 0.0001
	Relative Frequency, Cyperaceae (%)	0.42	0.005
	Relative Cover, Cyperaceae (%)	0.54	0.0001
	Total Species Mean Coefficient of Conservatism	0.68	< 0.0001
	Native Species Mean Coefficient of Conservatism	0.53	0.0002
	Relative Frequency, Nutrient Enrichment Tolerant Species (%)	−0.39	0.0182
	Relative Cover, Nutrient Enrichment Tolerant Species (%)	−0.41	0.0132
Submergent	Relative Frequency, Turbidity/Sedimentation Tolerant Species (%)	−0.38	0.0229
	Relative Cover, Turbidity/Sedimentation Tolerant Species (%)	−0.41	0.0136
	Relative Frequency, Turbidity/Sedimentation Intolerant Species (%)	−0.07	0.6693
	Relative Cover, Turbidity/Sedimentation Intolerant Species (%)	−0.01	0.9626
	Relative Frequency, Coefficient of Conservatism ≥ 7(%)	0.30	0.0795
	Relative Cover, Coefficient of Conservatism ≥ 7(%)	0.45	0.0060
	Total Species Richness	0.32	0.0601
	Total Species Mean Coefficient of Conservatism	0.44	0.0072
	Native Species Mean Coefficient of Conservatism	0.35	0.0356

These impacts aid in understanding the relation between disturbance and the relative cover of turbidity/sedimentation-intolerant species within wet meadows. This category of turbidity/sedimentation-intolerant species is composed of three specific species with a ubiquitous distribution throughout the Great Lakes, which have all been determined to be indicators of higher quality systems: *Calamagrostis canadensis, Carex aquatilis*, and *C. stricta* (Albert and Minc, 2004; Johnston et al., 2008; Wilcox et al., 2008). These species are prominent components of wet meadows; Lemein et al. (2017) identified *C. canadensis- C. stricta* and *C. stricta* as two common wet meadow communities found throughout the Great Lakes.

Both the dominance of nutrient-responsive and turbidity-tolerant species in submergent zones were suggested as potential metrics by Albert and Minc (2004). Common submerged aquatic species, such as *Myriophyllum spicatum*, *Ceratophyllum demersum*, and *Elodea canadensis* have been shown to respond positively to nutrient enrichment; not only

Table 4
Ecosystem condition ratings for Great Lakes coastal wetland vegetation zones based on indicator scores.

Zone	Poor	Fair	Good	Very Good
Wet Meadow	5–8	9–12	13–16	17–20
Emergent	5–8	9–12	13–16	17–20
Submergent	4–7	8–10	11–13	14–16

Table 3
Preliminary indicators for each vegetation zone with scoring ranges. Minimum and maximum scores for each zone listed.

Metrics	1	2	3	4
Wet Meadow (minimum = 5, maximum = 20)				
Relative Cover, *Carex* spp. (%)	x < 3	3 ≤ x < 8	8 ≤ x < 15	x ≥ 15
Relative Cover, Invasive/Introduced Species (%)	x ≥ 20	10 ≤ x < 20	4 ≤ x < 10	x < 4
Relative Cover, Turbidity/Sedimentation Intolerant Species[a] (%)	x < 5	5 ≤ x < 20	20 ≤ x < 35	x ≥ 35
Relative Frequency, Coefficient of Conservatism ≥ 5 (%)	x < 30	30 ≤ x < 37	37 ≤ x < 45	x ≥ 45
Total Species Mean C	x < 3.7	3.7 ≤ x < 4.3	4.3 ≤ x < 5	x ≥ 5
Emergent (minimum score = 5, maximum score = 20)				
Relative Cover, Cyperaceae (%)	x ≤ 25	25 < x ≤ 35	35 < x ≤ 50	x > 50
Relative Cover, Invasive/Introduced Species (%)	x ≥ 40	15 ≤ x < 40	1 ≤ x < 15	x < 1
Relative Cover, Coefficient of Conservatism ≥ 6 (%)	x < 4	4 ≤ x < 20	20 ≤ x < 40	x ≥ 40
Relative Frequency, Coefficient of Conservatism ≥ 6 (%)	x < 20	20 ≤ x < 35	35 ≤ x < 50	x ≥ 50
Total Species Mean C	x < 3.5	3.5 ≤ x < 4.6	4.6 ≤ x < 5.5	x ≥ 5.5
Submergent (minimum score = 4, maximum score = 16)				
Relative Frequency, Nutrient and Turbidity Tolerant Species[b] (%)	x ≥ 30	15 ≤ x < 30	5 ≤ x < 15	x < 5
Relative Cover, Nutrient and Turbidity Tolerant Species[b] (%)	x ≥ 30	10 ≤ x < 30	4 ≤ x < 10	x < 4
Relative Cover, Coefficient of Conservatism ≥ 7 (%)	x < 0.5	0.5 ≤ x < 25	25 ≤ x < 40	x ≥ 40
Total Species Mean C	x ≤ 3	3 < x ≤ 4	4 < x ≤ 5	x > 5

a: *Calamagrostis canadensis, Carex aquatilis, C. stricta*
b: *Butomus umbellatus, Ceratophyllum demersum, Elodea canadensis, Heteranthera dubia, Lemna minor, Myriophyllum spicatum, Potamogeton crisups, P. foliosus, P. pusillus, Ranunculus longirostris, Stuckenia pectinata*

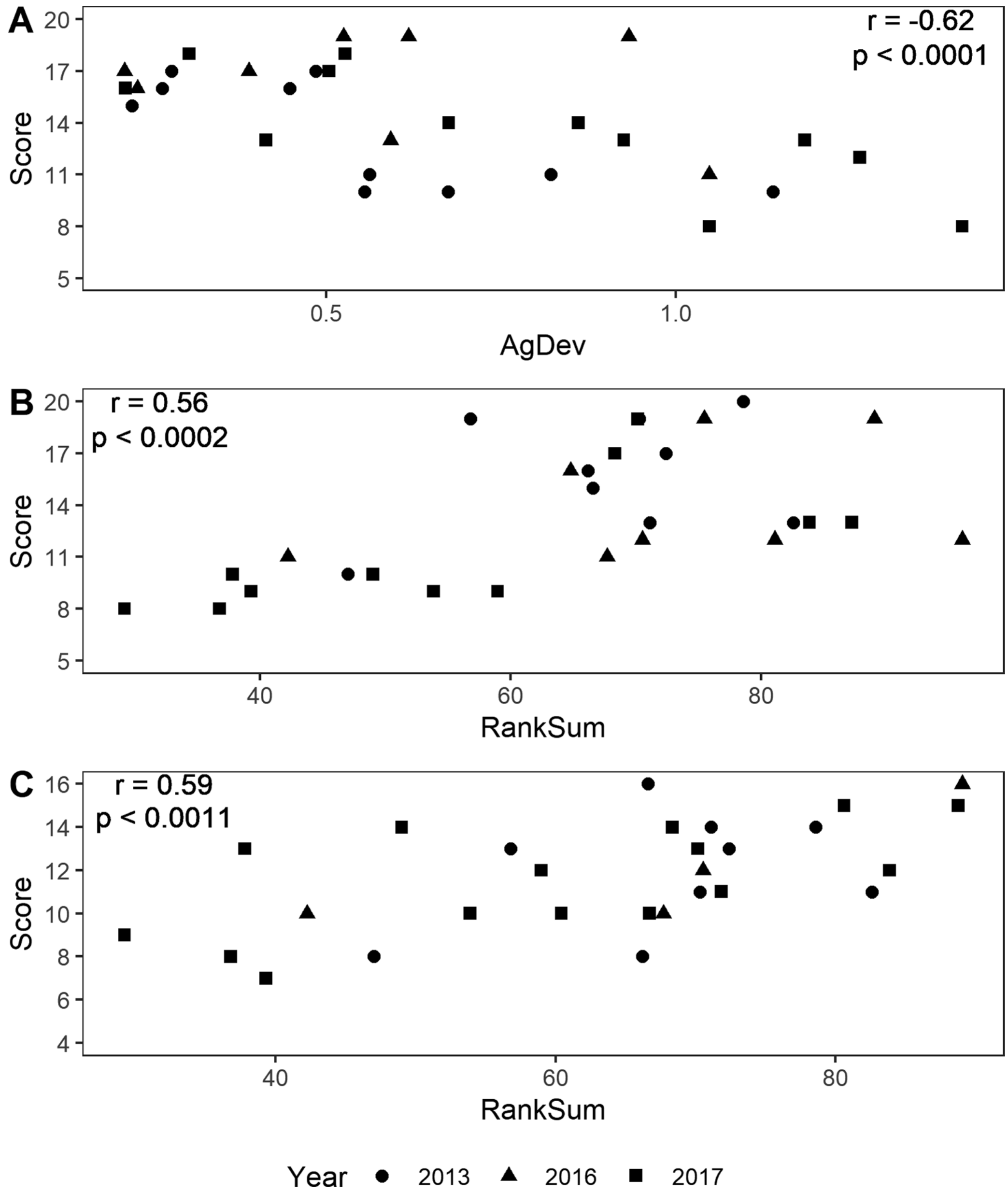

Fig. 4. Relationship between disturbance gradients and indicator scores for A). wet meadow, B). emergent, and C). submergent zones of western Lake Huron lacustrine coastal wetlands sampled in 2013 and 2016–2017. High AgDev and low RankSum scores are indicative of high anthropogenic disturbance.

are they tolerant of excessive nutrient inputs, their growth is enhanced by them. This same trend can be seen in certain floating-leaved species such as duck weed, *Lemna minor*. Many of these same submergent species are also tolerant of high turbidity, which prevents light from penetrating down into the water column. Without this light, most submerged aquatic vegetation cannot photosynthesize and are therefore excluded (Lougheed et al., 2001). As such, measuring the cover and abundance of these species should reveal information about these specific pressures.

Mean C, as a concept, has existed for many years and has been evaluated as a stand-alone metric for assessing ecosystem condition in Great Lakes coastal wetlands previously (Bourdaghs et al., 2006). Given that C is assigned based on a species' site fidelity and niche breadth, it follows that sites with higher Mean Cs would be less disturbed; data for all three vegetation zones reflected this relationship. We have also included metrics related to the abundance and cover of species above a certain C. The process we used to determine these groups was based on multi-variate statistical analysis, but the concept of evaluating the distribution of C within a site as a measure of disturbance has been used previously in the development of Ohio's Vegetation Index of Biotic Integrity (O-VIBI). The O-VIBI assumes that species with a C between 0 and 2 indicate disturbance, while those 6 and above indicate more pristine conditions (Gara and Stapanian, 2015). Our method of analysis produced results similar to the assumptions made by Gara and Stapanian (2015), albeit slightly differently in each vegetation zone.

4.2. Benefits of zone-specific metrics

There is evidence that treating each coastal wetland as a series of different vegetation zones and evaluating each zone individually with separate sets of metrics, as opposed to evaluating each wetland as a whole, provides benefits to evaluations that whole-site assessments do not. In their development of a preliminary macroinvertebrate-based IBI for Great Lakes coastal wetlands, Burton et al. (1999) elected to create metrics based on broad classes of vegetation likely to be present within a given wetland. The goal in taking this approach was to remove the

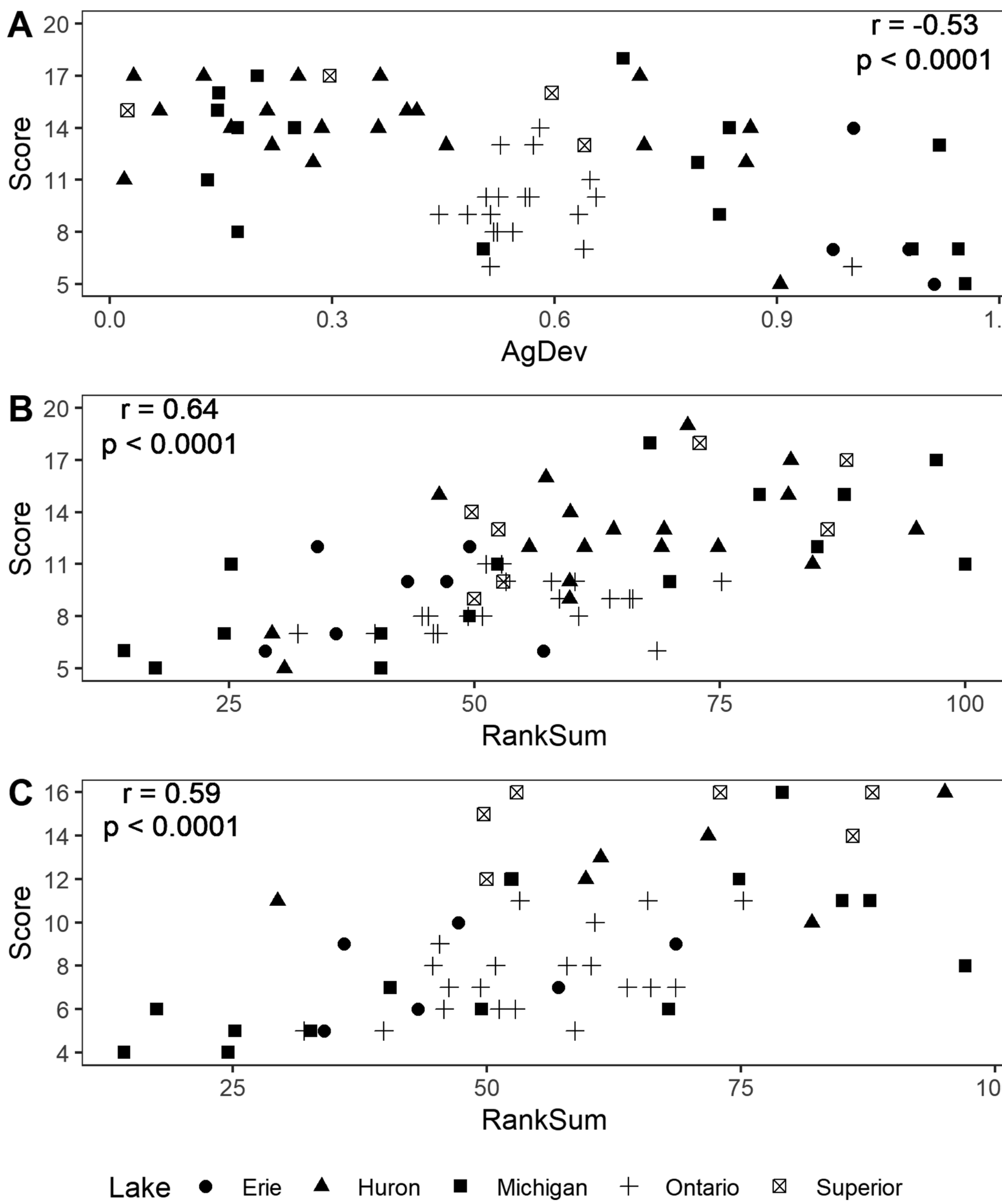

Fig. 5. Relationship between disturbance gradients and indicator scores for A). wet meadow, B). emergent, and C). submergent zones of Great Lakes lacustrine coastal wetlands sampled between 2011 and 2017. High AgDev and low RankSum scores are indicative of high anthropogenic disturbance.

Table 5
Results of a one-way ANOVA comparing indicator scores for each vegetation zone across year (2011–2017), which was used as a proxy for variable lake level. Verification data for western Lake Huron coastal wetland and the remaining Great Lakes coastal wetlands were combined for this analysis. No significant difference was detected across year for any of the indicators.

Vegetation Zone	n	Average	F value	p
Wet Meadow	93	12.5 ± 3.7	1.408	0.221
Emergent	94	11.5 ± 3.9	0.866	0.523
Submergent	82	10.1 ± 3.4	0.592	0.735

variation created by changes in lake level, as zones were likely to appear and disappear as a factor of lake level. While developed during a period of high-water levels, these same metrics were verified by Uzarski et al. (2004) during a period of low-water levels. This process was used again by Uzarski et al. (2005) and Cooper et al. (2018) to develop fish-based indicators, providing evidence that this approach could be used to develop biological indicators in wetlands that were robust in the face of variable lake level.

Our intent in assessing disturbance on the zone level was similar. While the broad vegetation zones described here are less likely to appear and disappear in the same way that the very specific vegetation zones described in Burton et al. (1999) do, the overall size and position of these zones will change as a factor of water level. All three of our zone-based indicators were reflective of their respective disturbance gradients (Figs. 4, 5). Equally important, though, like the indicators developed by Uzarski et al. (2005) and Cooper et al. (2018), the indicators described herein do not appear to be directly responding to changes in water level across time (Table 5). Given these results, it appears the assumptions made by Burton et al. (1999) about the robustness of zone-specific metrics also apply to vegetation-based indicators.

Another potential benefit to zone-specific metrics is that disturbance in wetlands may impact each zone differently. As an example, the wet meadow at a site may have been plowed and greatly altered during a

Table 6
Pearson correlation values between zone-level indicators and disturbance gradients with and without Lake Ontario, 2011–2017. All correlations had a significance at $p < 0.0001$.

Zone	With Lake Ontario	Without Lake Ontario
Wet Meadow	−0.53	−0.58
Emergent	0.64	0.67
Submergent	0.59	0.63

dry year, but the emergent and submergent zones may be intact and of high quality. In heavily farmed watersheds such as Saginaw Bay in Michigan, agricultural effluent is often introduced to Lake Huron by agricultural drains, bypassing the more upland portions of wetlands completely. In addition, a study of riverine wetlands along Lake Michigan found that the wet meadow zone was more impacted by localized land use than were the emergent and submergent zones (Albert et al., 2007), demonstrating that disturbance factors can impact the wet meadow, emergent, and submergent zones differently. The indicators proposed here avoid these problems by assessing impact on a zone-by-zone basis.

4.3. Issues

There are two issues with these indicators that need to be addressed. First, upon calculating and comparing indicator scores amongst the different lakes, we observed that all three indicators seemed not to perform well in Lake Ontario (Fig. 5). Indeed, while each indicator maintains statistical significance when Lake Ontario sites are included, removing them from correlation calculations improves correlation values (Table 6). This is most likely due to the overriding influence of historical lake-level management. Natural fluctuations in water levels are critical in maintaining the unique zonation and diversity of Great Lakes coastal marshes. High water levels cause dieback of vegetation incapable of surviving prolonged flooded conditions, while subsequent low water levels allow the regeneration of species from the seed bank more suited to less flooded conditions (Wilcox et al., 2008; Keddy, 2010). Water levels have been regulated on Lake Ontario since about 1960, compressing the expected range of water levels to roughly half of what it was pre-management (Wilcox et al., 2008). Under this modified hydrologic regime, Lake Ontario coastal wetlands have become dominated by invasive *Typha*, and lack the diversity typically seen of Great Lakes coastal wetlands. The absence of periodic high-water levels has allowed *Typha* to expand lakeward, as it is not excluded by prolonged flooding. Likewise, the absence of periodic low-water levels has allowed soils within the traditionally sedge/grass-dominated wet meadows to remain saturated, promoting landward invasion by Typha and preventing seed bank regeneration (Albert and Minc, 2004; Wilcox et al., 2008; Lemein et al., 2017). Upon expansion, stable water levels also create a positive feedback loop perpetuating the dominance of *Typha*; increased *Typha* coverage yields higher litter accumulation, which prevents the germination and growth of other emergent species, allowing further growth of *Typha* (Vaccaro et al., 2009). Our data reflects these trends; the dominant species present within Lake Ontario wet meadows and emergent zones in our study were *Typha angustifolia* and *T. × glauca*.

It is possible that our disturbance gradients do not adequately integrate hydrological disturbances. AgDev is entirely based on land-use/land-cover, while RankSum is driven primarily by water quality. While both pressures are certainly affecting Lake Ontario coastal wetlands, the pressure driving vegetation community composition is modified hydrology, which is not directly taken into account by either disturbance gradient, leading to indicator scores which do not seem to reflect either very well. As such, it may be necessary to develop separate sets of indicators for Lake Ontario, either by using AgDev/RankSum with only Lake Ontario coastal wetlands (i.e. without comparison to the rest of the Great Lakes), or by using another disturbance gradient entirely.

The second issue is that the wet meadow and emergent indicators appear to underestimate the quality of wetlands associated with low apparent disturbance (Figs. 4 and 5). None of the sites that fall within the upper quartile of either AgDev or RankSum achieve the highest possible scores from the indicators. There are a few potential explanations for this. Both RankSum and AgDev rank sites according to various aspects of disturbance but are ultimately “summaries” of those stressors; even those wetlands associated with high RankSum/low AgDev experience some level of disturbance, albeit less so than most. For example, while agriculture and urbanization represent major disturbance factors impacting coastal wetlands, non-point sources of pollution like atmospheric deposition can introduce pollutants to wetlands in more remote areas (Danz et al., 2007; Uzarski et al., 2017). As such, it is possible that pressures throughout the Great Lakes basin have become so great, and so many coastal wetlands have already been lost, that pristine (i.e. completely undisturbed, or “reference”) coastal wetlands are rare (Simon and Emery, 1995; Burton et al., 1999).

It is also possible that more localized pressures may be impacting these wetlands in ways that our disturbance gradients cannot quantify. For example, Ogontz Bay Area Wetland on Lake Michigan was sampled in 2016 and was assigned the highest possible RankSum score (100). Despite this, the emergent zone for this site scored a 15, according to our metrics. Notes taken by the crew who sampled this site indicated that it was on private land and was very clearly being mowed; this would explain the low score despite the apparent lack of disturbance from our gradients. The opposite relationship can also be seen with highly disturbed sites scoring well. Rondeau Provincial Park Wetland #1 is a Lake Erie wetland which was sampled in 2013 that, according to AgDev, was highly disturbed but still had a wet meadow score of 14. Again, notes taken by the crew indicated that this site was being actively managed to remove invasive *Phragmites*, an effort that had returned much of the native vegetation, possibly leading to the higher score. As with any monitoring efforts that use biotic indicators, scores must be assessed within the context of these kinds of factors, which may not be implicitly considered when determining disturbance.

4.4. Conclusion

The indicators of ecosystem health developed through this study appear to adequately reflect levels of disturbance at the zone-level for Great Lakes coastal wetlands. Their use as individual metrics, whose scores can be evaluated with respect to known disturbance on a site-by-site basis for management purposes, makes them justifiable. However, as these metrics were developed specifically using data from lacustrine coastal wetlands, they can only be said to be predictive in those ecosystems. As a result, the indicators do not apply to large areas of the Great Lakes coastline. For example, most of the coastal wetlands on the eastern shore of Lake Michigan are riverine, while the wetlands of Lake Superior’s southern shore are primarily a mixture of barrier-beach and riverine wetlands. Moving forward, these indicators should be tested in both riverine and barrier-beach systems. If they are found to be accurate, then these indicators could be implemented in monitoring efforts. If not, the developmental methodology used in this study should be applicable to these other systems, allowing for the creation of more appropriate indicators. In addition, focusing on or incorporating aspects of functional diversity, or the diversity of traits within a plant community, may also provide an avenue for future indicator development efforts. These traits, such as those related to nutrient use efficiency, may be able to discern specific stressors in coastal wetlands, particularly water quality-based stressors.

CRediT authorship contribution statement

Jacob M. Dybiec: Writing - original draft, Formal analysis, Conceptualization. **Dennis A. Albert:** Writing - review & editing, Conceptualization. **Nicholas P. Danz:** Writing - review & editing, Conceptualization. **Douglas A. Wilcox:** Writing - review & editing, Conceptualization. **Donald G. Uzarski:** Writing - review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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