Muskegon Lake Habitat Focus Area
Macrophyte and Invertebrate Assessment
Year 1 Report

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Introduction

The Muskegon Lake Habitat Focus Area (HFA) project was designed to assist the delisting process of Muskegon Lake as an Area of Concern (AOC) by supporting the removal of habitat-related Beneficial Use Impairments (BUI). In 2009, NOAA began providing support for habitat restoration in the Muskegon Lake AOC under a $10 million dollar American Reinvestment and Recovery Act (ARRA) investment. The ARRA-funded project implemented 50.2 acres (20.3 ha) of coastal habitat restoration, including 32.3 acres (13.1 ha) of emergent and open water wetland, along 13,073 feet (3,985 m) of shoreline. The project used "living shoreline" techniques such as coir lift systems, pre-vegetated coir pillows, coir log wave diffusers, tree trunks, root ball structures, large woody debris, live stakes, native trees, plugs, and seed mixes specific to moisture zones and un-mowed buffer strips. The current HFA project was designed to assess the effectiveness of the ARRA-funded restoration work and implement four designs to improve the resiliency of 24.2 acres of critical habitat along 10,575 feet of shoreline.

Historically, the lake has been heavily used by industry, starting with lumber mills in the mid-19th century, which were located around the shoreline. At the height of the lumber industry, there were 47 active sawmills on Muskegon Lake. After the demise of lumbering in the late 19th century, foundries and factories became prevalent, especially on the southern and eastern shorelines of the lake. These industrial activities left a legacy of pollutants, which resulted in Muskegon Lake being listed as a Great Lakes AOC. By the mid-20th century, nearly 800 acres of shallow water and wetland habitat in Muskegon Lake had been filled in with slab wood, saw dust, coal ash, broken concrete, asphalt, foundry slag, and scrap metal, reducing the lake from its original size. Approximately 65% of the shoreline was hardened leading to loss of habitat, restricted public access and recreational opportunities, and changes in the hydrodynamics of the lake (see Steinman et al. 2008). These changes resulted in significant degradation of benthic communities and local fish and wildlife populations, as well as their habitat.

A number of major restoration projects and activities have been initiated and completed in Muskegon Lake, in an attempt to address these BUIs (Table 1). Four of the nine BUIs in the Muskegon Lake AOC have been successfully removed. Remediation and restoration of coastal and aquatic habitat in Muskegon Lake and the Muskegon River have led to tangible benefits for the local economy (Isely et al. 2018).

The primary objective of the Muskegon Lake HFA project is to "develop collaborative research partnerships that will help the agency fill science information gaps to support ongoing and planned habitat restoration and management activities, in particular monitoring of the effectiveness of the restoration work and its impact on Muskegon Lake, the Muskegon River, and the Lake Michigan nearshore". The original proposal identified 5 specific task elements to address the needs of the Muskegon Lake HFA, although modifications over time resulted in changes to these elements. This report focuses on element #3, which involved the monitoring of macrophyte, macroinvertebrate, and fish abundance and community structure at 3 sites to assess success of prior restoration efforts. The fish report is provided in Appendix B.

Table 1. Selected restoration and monitoring activities associated with Muskegon Lake.

Name	**Year(s)**	**Description**
Redirect wastewater discharge into lake	1973-1974	Diversion of municipal and industrial wastewater away from the lake to waste water management system as part of Clean Water Act requirements
Groundwater and soil remediation activities	On-going	Various projects throughout the AOC dealing with chemical contamination
Listing of Muskegon Lake as an AOC	1985	Established Muskegon Lake Public Advisory Council (now Muskegon Lake Watershed Partnership) to identify targets and indicators for BUI removal; coordinate with local, state, and federal partners to develop and implement plans to achieve targets
Remediation of Ruddiman Creek	2006	Great Lakes Legacy Act (GLLA) funding to remove 204,000 lbs of Cr; 126,000 lbs of Pb; 2,800 lbs of Cd, 320 lbs of PCBs; and 260 lbs of benzo-(a)-pyrene
Remediation of Division Street Outfall	2012	GLLA funding to remove 41,000 yd^3 of sediment containing mercury and PAHs and restore habitat
Shoreline restoration	2009-2013	NOAA ARRA funding resulted in removal of 208,620 metric tons of unnatural fill, and restoration of 50.2 acres of habitat and 13,073 linear feet of shoreline.
Reconnection/restoration of Bear Lake muck fields	2013-2017	NOAA GLRI funding to reconnect a 39-acre, former celery fields to adjacent Bear Creek to restore habitat, fish passage, remove P-rich sediment and improve water quality
Reconnection of lower Muskegon River (Bosma)	2016-2018	NOAA GLRI funding to reconnect 53.5 acres of formerly farmed floodplain to adjacent Muskegon River to restore habitat
Muskegon Lake monitoring program	2003-present	AWRI-GVSU initiated program, funded through an endowment fund at the local Community Foundation, to assess long-term health of lake
Muskegon Lake Observatory	2011-present	GLRI-funded buoy that monitors near real-time water quality in Muskegon Lake

Methods

Site description

Muskegon Lake is a ~17 km^2 drowned river mouth lake that serves as the receiving water body for the Muskegon River watershed. Muskegon Lake connects directly to Lake Michigan through a navigation channel, which modulates the influence of the watershed in nearshore areas of Lake Michigan and vice versa.

Prior sampling occurred each August from 2009-2012 (Ogdahl and Steinman 2015). In 2018, transects at 3 of 7 historic, previously sampled sites around Muskegon Lake's shoreline were re-sampled for macrophyte (aquatic plant) biomass and abundance, and sediment organic matter (OM): the NW Reference transect on the north side of the lake and two restored transects at Heritage Landing and Grand Trunk on the south side of the lake (Table 2, Figure 1) (Ogdahl and Steinman 2015). In addition to the 2018 replication of the 2009-2012 analyses, data were collected for new project components, including sediment particle size distribution and macroinvertebrate community composition (detailed below).

Field protocols

Sampling in 2018 occurred July 16-17 & 19 for macrophytes and sediment, and July 23-24 for macroinvertebrates. We followed protocols previously used in 2009-2012 to maintain consistency to the greatest extent possible. Macrophytes were again surveyed along each transect, which extended perpendicular from shore until plants were no longer observed (Ogdahl and Steinman 2015). Sampling points (hereafter "points") along each transect were sampled every 5 m between 0-10 m from shore, every 10 m between 10-100 m from shore, every 25 m between 100-300 m from shore, and every 50 m from 300 m and beyond, when needed. Measurements were taken for depth, and latitude and longitude were recorded using a Trimble Geo7x centimeter edition handheld GPS unit. Transect ends were determined by either (1) two consecutive points with no growth, or (2) the absence of macrophytes at a point greater than 4.5 m deep, indicating the drop-off beyond which macrophytes can grow had been reached (see Figure 2). A 10 m transect width was used based on the field crew's ability to visually assess macrophyte communities within ~5 m of the boat in any direction.

Table 2. Location information for the origin of each sampling transect and restoration details.

Site	Latitude (N)	Longitude (W)	Scheduled Date of Restoration	Actual Date of Restoration	Restoration Type
NW Reference	43˚ 14' 50.09"	86˚ 18' 56.67"	N/A	N/A	N/A
Heritage Landing	43˚ 13' 58.33"	86˚ 15' 42.49"	August 2009	April 2011	Shoreline and underwater fill removal*
Grand Trunk	43˚ 12' 57.44"	86˚ 17' 49.19"	July 2009	June 2010	Shoreline and underwater fill removal*

N/A = not applicable
*Fill removal refers to the removal of unnatural fill (i.e., sawmill waste; industrial and/or commercial demolition material, such as broken concrete) at (shoreline) or below (underwater) the ordinary high water mark.

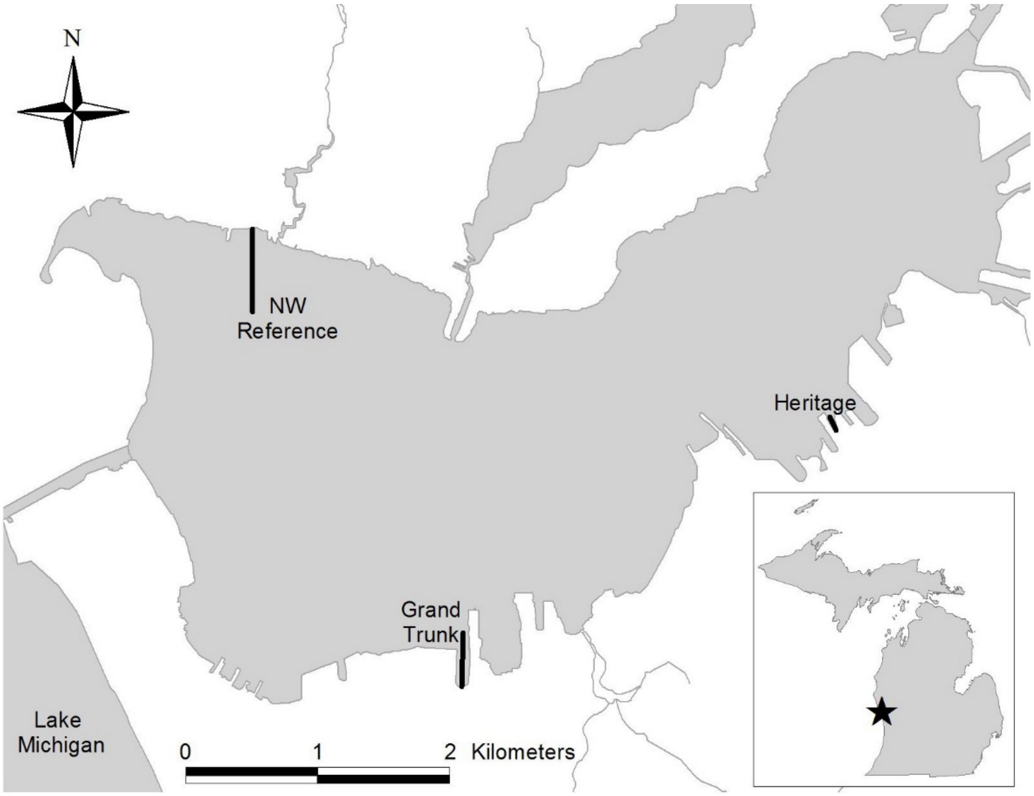

Figure 1. Transect locations and lengths (black lines) for macrophyte assessment in Muskegon Lake. See text for sampling details.

At each point, plant cover was assessed with a ranking system: 0 = Bare; 1 = 1 to 25%; 2 = 26 to 50%; 3 = 51 to 75%; and 4 = 76 to 100%. All plants within a ~5 m radius were identified to species in the field and species percent abundance (0-100%) was estimated. When sites and plants were too deep to be easily seen from the surface, a double-headed rake was tossed three times to aid in recovering and identifying species, assign cover rank, and estimate relative abundance. Voucher specimens for plants that could not be identified in the field were brought back to the lab for later identification.

Plant biomass and sediment were sampled at one randomly selected point in each of the following distance-from-shore categories: 0-20 m, 20-50 m, 50-100 m, 200-300 m, 300-400 m, 400-500 m, etc. Plant biomass was harvested using two garden rakes attached to each other at a pivot point near the middle of each rake's handle. The teeth of the rakes faced each other in order to cut and secure the plants when the handles were pulled together. A chain connected to the rakes fixed the sampling area at 0.6 m^2. A total area of 1.8 m^2 (3 scoops) was sampled at each point along transects; where biomass was very high, only 0.6 or 1.2 m^2 (1 or 2 scoops) was sampled. One sediment core (4-cm diameter, 10 cm deep) per point was collected using a modified hand-held gravity corer (Davis and Steinman 1998). Each sediment sample was placed in a Ziploc bag and placed on ice until brought back to the lab for processing sediment OM and particle size distribution.

Macroinvertebrates were collected at 3 points along each transect (see Table 17 for locations on each transect). At each point, three petite ponar dredges and three D-net 1-m sweeps were taken. After collection, the three ponar grabs were composited per point. Composite ponar grabs were stored in a 5 gallon bucket and brought back to the laboratory, where sediment was gently washed in a 500 µm sieve and preserved in 95% ethanol with Rose Bengal stain to aid in sorting invertebrates from organic debris. D-net samples were separated on 1-inch gridded trays and picked for 30-human min (i.e., 1 person picking for 30 min, or two people picking for 15 min each, etc.) and combined in the field into one composite sample per point, then preserved on-site with 95% ethanol (modified from Uzarski et al. 2017).

Laboratory processing

Plant biomass and sediment samples were refrigerated (4°C) until laboratory processing. Plant samples were cleaned of any sediment, *Dreissena* mussels, and filamentous green algae. Samples were then sorted by species, weighed, dried at 85˚C for 96 hr, and weighed again.

Sediment samples were homogenized by hand and three 5-g subsamples were taken for OM analysis (APHA 2005). Briefly, subsamples were dried for 24 hr at 105˚C, weighed, ashed at 550˚C for 4 hr, and re-weighed. Sediment OM was calculated as the difference between pre- and post-combustion weights, expressed as a percentage of sediment dry weight. Values for each of the three subsamples were averaged for each sampling point. All of the remaining sediment was used for particle size distribution. The remaining sediment was ashed and sequentially sieved into the following size categories: gravel/cobble and larger (>2 mm), very coarse sand (1-2 mm), coarse sand (0.5-1 mm), medium sand (250-500 µm), fine sand (125-250 µm), very fine sand (63-125 µm), and silt/clay and smaller (<63 µm). Sediment was sieved for a minimum of 10 min on medium intensity on an Octagon 200 Sieve Shaker. We report these data as percent sediment dry weight in each of the size categories (% size fraction of total sample).

Macroinvertebrates sampled via ponar were sorted from sample debris in a white enamel pan, aided by bright lights, and 3X magnifying glasses. Using taxonomic keys and an 8X-50X stereomicroscope, insects were identified to family level, while other aquatic taxa (amphipods, arachnids, clams, flatworms, isopods, leeches, mussels, snails, and worms) were identified to as low as practicably possible between subclass and family, and then counted.

Data analysis

Macrophyte biomass within each transect was analyzed by first separately summing the dry mass (g) of all plants collected at each point along a transect and dividing the total dry mass by the area sampled at the point (area sampled = total number of scoops x 0.6 m^2) to calculate biomass density at each location as g/m^2. Transect biomass density was then calculated by summing biomass from sampling points within each transect. Transect total biomass was calculated by multiplying biomass density by the total area of each transect (total area = transect length x 10 m transect width).

Macrophyte taxon relative abundance was calculated for each transect using a weighted mean in order to follow previous study years, which chose to incorporate both percent abundance and cover rank in describing the importance of individual taxa in a given transect. In this calculation, the percent abundance of a taxon at a given sampling location was weighted by its cover rank at that location. Consequentially, taxa with higher cover ranks contribute more to overall mean relative abundance than taxa with lower cover ranks. The calculation process is to (1) multiply the percent abundance of taxon (0-100%) at each sampling location by its cover rank (from 1 to 4) at that location to calculate weighted relative abundance, (2) calculate the sum of weighted relative abundance values for taxon along the transect, and (3) divide by the sum of cover values for the transect using the formula:

$$\overline{\mathrm{A}}_W = \frac{\Sigma \mathrm{AC}}{\Sigma \mathrm{C}}$$

Where *w* stands for weighted, A = taxon relative abundance, and C=cover rank. Table 3 illustrates the difference between calculating unweighted vs. weighted mean relative abundance using example values.

Table 3. Hypothetical data from a macrophyte sampling transect. Mean percent abundance (unweighted) is calculated for each species and compared to weighted mean relative abundance, which accounts for cover rank. Cover ranks: 0 = Bare; 1 = 1–25%; 2 = 26–50%; 3 = 51–75%; or 4 = 76–100%.

Distance from shore	Cover Rank	Species 1	% Abundance	Species 2	% Abundance
5 m	1	*Vallisneria americana*	100	*Najas flexilis*	0
10 m	1	*Vallisneria americana*	100	*Najas flexilis*	0
20 m	3	*Vallisneria americana*	20	*Najas flexilis*	80
30 m	4	*Vallisneria americana*	5	*Najas flexilis*	95
40 m	2	*Vallisneria americana*	0	*Najas flexilis*	100
Mean			45		55
vs.					
Weighted mean			25		75

V. americana = ((100*1)+(100*1)+(20*3)+(5*4)+(0*2))/(1+1+3+4+2) = 25
N. flexilis = ((0*1)+(0*1)+(80*3)+(95*4)+(100*2))/(1+1+3+4+2) = 75

The Coefficient of Conservatism (C) for each species, as determined by the State of Michigan, was applied to each macrophyte species identified at transect sites. C-values range from 0 to 10 and represent the probability that a species will occur within an undisturbed landscape. For example, a species with a C-value of 0 is more likely to be found in highly degraded areas, while a species with C-value of 10 is usually found in higher quality undisturbed areas (Herman et al. 2001). All non-native species were assigned a C-value of 0 (Bourdaghs et al. 2006). A mean C-value was calculated for each transect.

During sediment particle size measurements, several sediment fraction samples were initially reported as negative mass values, which of course defies the laws of physics, and likely were due to machine error of scales. To correct this, prior to conversion from mass (g) into sediment particle fraction (%) of ashed sediment samples, a +0.1 g value was added to all sediment fractions for all samples (this value was selected because the largest negative value for a single sample sediment fraction was -0.09 g) and resulted in a total correction factor adjustment per site sample of +0.7 g of all sediment fractions combined.

Differences in macrophyte cover, sediment OM, and biomass among sites and years were tested using a Kruskal-Wallis One-Way Analysis of Variance (ANOVA) on Ranks with post-hoc multiple pairwise comparisons using Dunn's Test. Normality was tested using the Kolmogorov-Smirnov test. Two multivariate Principal Component Analyses (PCA) were conducted using multiyear environmental (air temperature, organic matter, precipitation, slope, water level, & wind index) and biological data (biomass cover, biomass total density, & species richness) using whole-transect mean data for NW Reference, Heritage, and Grand Trunk. PCA input % data were square root transformed and all other data was log transformed. All statistical analyses were conducted using SigmaPlot (v.14.0; Systat).

Macroinvertebrate community composition for macroinvertebrates was measured using Shannon's Diversity Index, separately calculated for each collection method at each collection site as well as for entire transect lengths using the formula:

$$H' = -\sum_{i=1}^{R} p_i * \ln p_i$$

where *H'* is Shannon's diversity value, richness (*R*) is the total number of taxa in the dataset, and p_i is the proportion of a given taxon from all taxa in a sample. H'_{max} was calculated as the natural log of *H'*. Evenness, the relative abundance of all taxa in a given location, was calculated by dividing H'/H'_{max}.

Results

Water Depth

As seen in previous sampling years, 2018 transects were relatively shallow (<3 m) throughout their length and generally had consistently level bathymetry followed by steep drop-offs, with the continued exception from past years of the NW Reference site, which had a more gradual slope (i.e., gradual increase in water depth) over the entire transect length and was longer than transects at other sites (Figure 2). The maximum depth at which macrophytes were found in each transect responded in different ways in 2018 compared to previous sampling years 2009-2012 at each sampled site, with NW Reference having a shallower maximum macrophyte depth in 2018 (3.70 m vs. 3.65-5.30 m), Heritage Landing having a deeper maximum macrophyte depth (4.30 m vs. 2.40-3.50 m), and Grand Trunk approximating the average of all previous sampling years' maximum macrophyte depths (2.70 m vs. 1.80-4.02 m); however, maximum macrophyte depth at Grand Trunk was more shallow in 2018 compared to 2011 or 2012 (Table 4).

Table 4. Mean water depth for transects in Muskegon Lake and the maximum depth at which macrophytes were found along each transect.

	Mean Water Depth					Max. Macrophyte Depth				
Site	2009	2010	2011	2012	2018	2009	2010	2011	2012	2018
NW Ref.	1.09	1.38	1.28	0.93	1.37	3.65	5.30	4.69	4.10	3.70
Heritage	2.05	2.14	2.27	1.93	1.27	2.40	2.65	3.50	3.15	4.30
G. Trunk	0.82	0.81	1.06	0.59	2.62	1.80	2.68	4.02	3.24	2.70

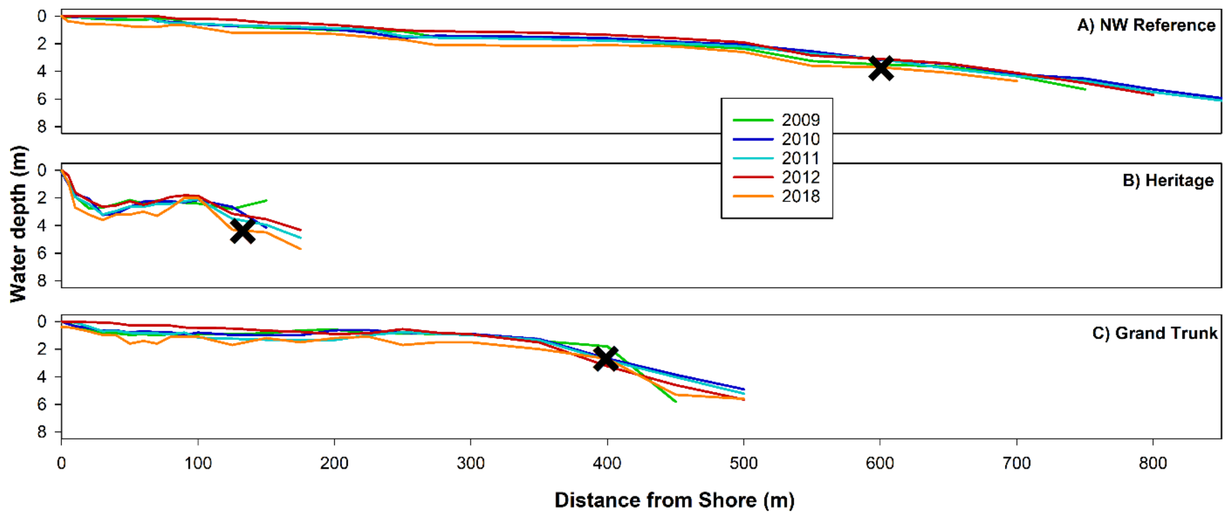

Figure 2. Depth contours at each transect sampled from 2009-2018. "X" indicates the approximate farthest extent of macrophyte growth in the most recent year sampled.

Macrophyte Cover and Biomass

Mean macrophyte cover rank at the NW Reference transect was higher in 2018 than any other previous pre- or post-restoration sampling year, entering the 51-75% cover category for the first time and was significantly greater than in 2011 (p=0.038; Table 5). The Heritage Landing transect cover also exceeded previous mean rank values, but approximated 2009 pre-restoration condition (Table 5). Conversely, the Grand Trunk transect cover ranked at its lowest observed value to date (Table 5). No significant differences in mean cover rank across all years were detected within Heritage Landing or Grand Trunk transects. Within 2018, both the NW Reference and Grand Trunk transects' mean cover rank were significantly higher than that at Heritage Landing (p=0.005 and p=0.012 respectively; Table 5). Macrophyte cover by rank at each site and across the 5 sampling years is illustrated in Appendix Figures A1-3.

Macrophyte density and total biomass had a variety of changes from 2009 to 2018 across the three transects. All transects showed low macrophyte abundance in 2011 (Figure 3), likely due to physical disturbance that was associated with restoration activity. Both NW Reference and Grant Trunk transects exhibited modest increases in density and biomass since 2012, but macrophyte density and biomass declined in 2018 at the Heritage transect compared to 2012 (Figure 3).

Table 5. Mean macrophyte cover rank for transects in Muskegon Lake. Cover ranks: 0=Bare, 1=1–25%, 2=26–50%, 3=51–75%, 4=76–100%.

	Mean Cover Rank				
Site	2009	2010	2011	2012	2018
NW Reference	2.67	2.42	2.33	2.93	3.54
Heritage	3.58	3.23	2.77	3.00	3.64
Grand Trunk	2.77	3.64	3.57	3.27	2.54

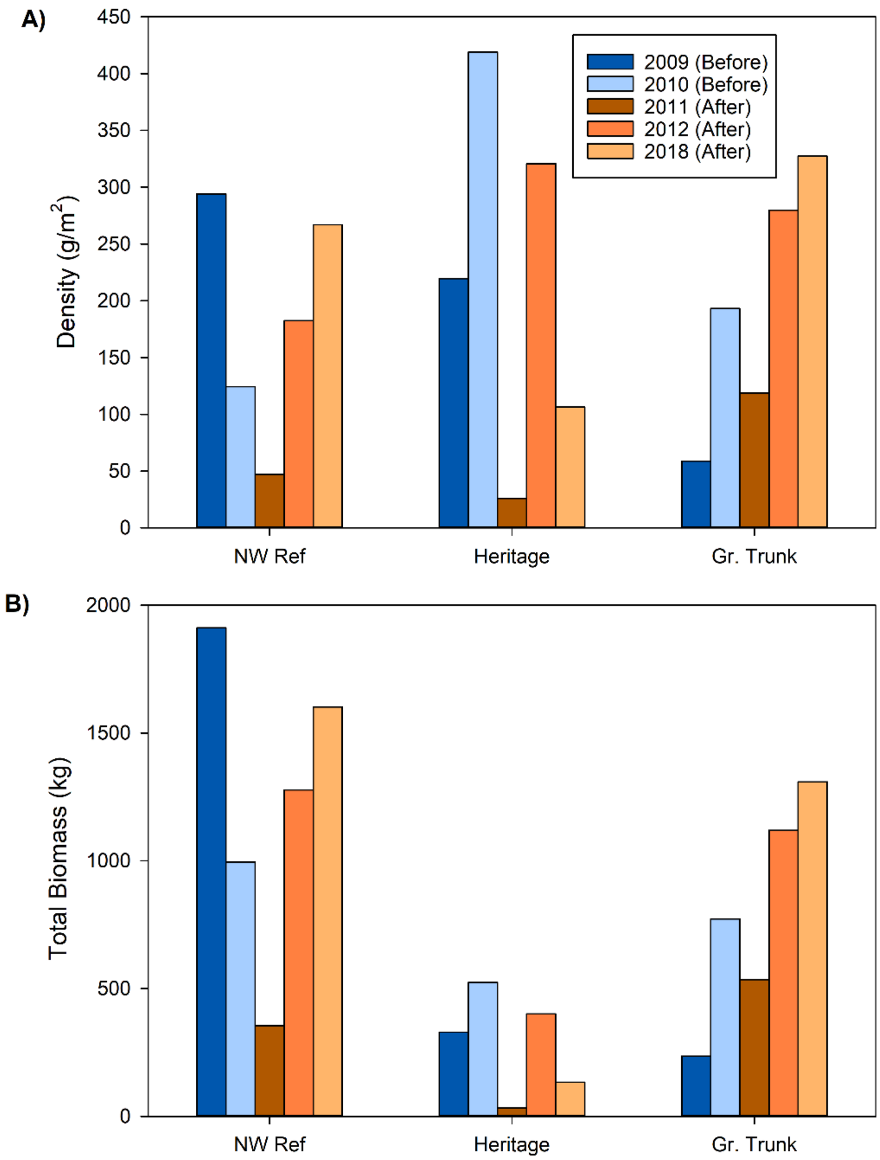

Figure 3. Macrophyte biomass density (g/m^2) (A) and total biomass (kg) (B) at each survey site before (2009 and 2012) and after (2011, 2012, 2018) restoration.

Community Composition

As seen in previous years, 2018 transect species composition nearshore consisted of emergent shallow-water vegetation, chiefly cattail (*Typha angustifolia*); however, a decrease in other emergent species may be related to high water levels in the previous few years. For example, mean water levels in Lakes Michigan-Huron (they are treated as one lake given their hydrologic connection) were between 175.92 and 176.26m in 2009-2012, but between 176.30 and 176.87 in 2014-2018, an increase of up to 3 ft in the past 4 years. In addition, the 2018 increase in filamentous green algae and floating and submergent species, such as coontail (*Ceratophyllum demersum*), watermilfoil (*Myriophyllum sp.*), bladderwort (*Utricularia sp.*), and duckweeds (*Lemna sp.*, *Spirodela sp.*) (Tables 6-10), may have restricted growth of emergents. Notably, common reed (*Phragmites australis*) was not recorded in 2018 (Table 10) despite its regular occurrence at the NW Reference transect in 2009-2012 (Tables 6-9). Additionally, 2018 cattails at Grand Trunk may have all hybridized from *T. angustifolia* to *T.* x *glauca* since 2012 (Table 10).

Overall, macrophyte community composition in 2018 was similar to what was observed in 2011 and 2012. As seen in previous sampling years, *Ceratophyllum demersum* had the greatest weighted relative abundance in 2018 at Heritage and Grand Trunk transects; however, *Vallisneria americana* was generally more abundant at the NW Reference in 2018 compared to prior years (Tables 11-15). Average C-values in 2018 generally fell within ranges observed in 2009-2012 (Tables 11-15, Figure 4). Indeed, among the post-restoration years, transects sampled in 2018 were found to have mean C-values slightly higher than the post-restoration grand means in 2011 and 2012 at the restoration sites, and an equivalent C-value at the NW reference site (Figure 4; Table 16).

Several varieties of high-quality species indicated by C-values of 10, meaning the species require high quality conditions for growth, were found at NW Reference, Heritage, and Grand Trunk transects in 2009-2012 (Tables 11-14). In 2018, the sole high-quality species with a C-value of 10 (*Ranunculus flabellaris*) was identified at the NW Reference with <1% mean relative abundance (Table 15).

Table 6. Dominant taxa based on relative abundance along each of the macrophyte transects in 2009. Loc. = distance from shore in meters. Taxa in bold have Coefficients of Conservation values of zero, indicating non-native or most likely to be found in degraded habitat.

<table>
<tr><th>Loc.</th><th>NW Reference</th><th>Heritage</th><th>Grand Trunk</th></tr>
<tr><td>0</td><td rowspan="11">• Typha angustifolia
• Phragmites australis
• Scirpus americanus
• Utricularia vulgaris</td><td rowspan="4">• Salix exigua
• Vallisneria americana
• Ceratophyllum demersum
• Elodea canadensis</td><td rowspan="4">• Typha angustifolia
• Lythrum salicaria
• Utricularia vulgaris</td></tr>
<tr><td>5</td></tr>
<tr><td>10</td></tr>
<tr><td>20</td></tr>
<tr><td>30</td><td rowspan="8">• Ceratophyllum demersum</td><td>• Ceratophyllum demersum</td></tr>
<tr><td>40</td><td rowspan="12">• Ceratophyllum demersum
• Myriophyllum spicatum
• Nymphaea odorata
• Potamogeton pusillus
• Potamogeton crispus
• Potamogeton perfoliatus
• Elodea canadensis
• Vallisneria americana</td></tr>
<tr><td>50</td></tr>
<tr><td>60</td></tr>
<tr><td>70</td></tr>
<tr><td>80</td></tr>
<tr><td>90</td></tr>
<tr><td>100</td><td rowspan="7">BARE</td></tr>
<tr><td>125</td><td rowspan="15"></td></tr>
<tr><td>150</td></tr>
<tr><td>175</td></tr>
<tr><td>200</td></tr>
<tr><td>225</td></tr>
<tr><td>250</td><td rowspan="5">• Vallisneria americana</td></tr>
<tr><td>275</td><td rowspan="9">• Vallisneria americana
• Macroalgae
• Ceratophyllum demersum</td></tr>
<tr><td>300</td></tr>
<tr><td>350</td></tr>
<tr><td>400</td></tr>
<tr><td>450</td><td rowspan="5"></td></tr>
<tr><td>500</td></tr>
<tr><td>550</td></tr>
<tr><td>600</td></tr>
<tr><td>650</td></tr>
</table>

Table 7. Dominant taxa based on relative abundance along each of the macrophyte transects in 2010. Loc. = distance from shore in meters. Taxa in bold have Coefficients of Conservation values of zero, indicating non-native or most likely to be found in degraded habitat.

<table>
<tr><th>Loc.</th><th>NW Reference</th><th>Heritage</th><th>Grand Trunk</th></tr>
<tr><td>0</td><td rowspan="9">• Typha angustifolia
• Phragmites australis
• Scirpus americanus</td><td>• Salix exigua
• Schoenoplectus tabernaemontani</td><td rowspan="2">• Typha xglauca
• Lythrum salicaria
• Nasturtium microphyllum
• Sparganium eurycarpum</td></tr>
<tr><td>5</td><td>• Nymphaea odorata</td></tr>
<tr><td>10</td><td rowspan="2">• Ceratophyllum demersum
• Elodea canadensis</td><td rowspan="14">• Ceratophyllum demersum
• Myriophyllum spicatum
• Nymphaea odorata</td></tr>
<tr><td>20</td></tr>
<tr><td>30</td><td>BARE</td></tr>
<tr><td>40</td><td rowspan="8">• Ceratophyllum demersum
• Elodea canadensis</td></tr>
<tr><td>50</td></tr>
<tr><td>60</td></tr>
<tr><td>70</td></tr>
<tr><td>80</td><td rowspan="8">BARE</td></tr>
<tr><td>90</td></tr>
<tr><td>100</td></tr>
<tr><td>125</td></tr>
<tr><td>150</td><td rowspan="17"></td></tr>
<tr><td>175</td></tr>
<tr><td>200</td></tr>
<tr><td>225</td><td rowspan="6">• Vallisneria americana</td></tr>
<tr><td>250</td><td rowspan="13">• Vallisneria americana
• Ceratophyllum demersum
• Myriophyllum spicatum
• Najas flexilis</td></tr>
<tr><td>275</td></tr>
<tr><td>300</td></tr>
<tr><td>350</td></tr>
<tr><td>400</td></tr>
<tr><td>450</td><td rowspan="2">BARE</td></tr>
<tr><td>500</td></tr>
<tr><td>550</td><td rowspan="6"></td></tr>
<tr><td>600</td></tr>
<tr><td>650</td></tr>
<tr><td>700</td></tr>
<tr><td>750</td></tr>
<tr><td>800</td></tr>
</table>

Table 8. Dominant taxa based on relative abundance along each of the macrophyte transects in 2011. Loc. = distance from shore in meters. Taxa in bold have Coefficients of Conservation values of zero, indicating non-native or most likely to be found in degraded habitat.

<table>
<tr><th>Loc.</th><th>NW Reference</th><th>Heritage</th><th>Grand Trunk</th></tr>
<tr><td>0</td><td rowspan="9">• Typha angustifolia
• Phragmites australis
• Schoenoplectus pungens
• Utricularia intermedia</td><td>• Salix exigua
• Impatiens capensis</td><td rowspan="3">• Typha angustifolia
• Lythrum salicaria</td></tr>
<tr><td>5</td><td rowspan="6">• Nymphaea odorata
• Ceratophyllum demersum
• Vallisneria americana</td></tr>
<tr><td>10</td></tr>
<tr><td>20</td><td rowspan="13">• Ceratophyllum demersum
• Myriophyllum spicatum
• Nymphaea odorata
• Elodea canadensis</td></tr>
<tr><td>30</td></tr>
<tr><td>40</td></tr>
<tr><td>50</td></tr>
<tr><td>60</td><td rowspan="5">• Elodea canadensis
• Ceratophyllum demersum
• Vallisneria americana</td></tr>
<tr><td>70</td></tr>
<tr><td>80</td><td rowspan="7">• Najas flexilis
• Chara sp.
• Filamentous green algae</td></tr>
<tr><td>90</td></tr>
<tr><td>100</td></tr>
<tr><td>125</td><td>• Ceratophyllum demersum</td></tr>
<tr><td>150</td><td rowspan="16"></td></tr>
<tr><td>175</td></tr>
<tr><td>200</td></tr>
<tr><td>225</td><td rowspan="13">• Vallisneria americana
• Ceratophyllum demersum
• Myriophyllum spicatum
• Najas flexilis
• Potamogeton pusillus
• Potamogeton perfoliatus</td><td rowspan="7">• Vallisneria americana
• Ceratophyllum demersum
• Potamogeton perfoliatus</td></tr>
<tr><td>250</td></tr>
<tr><td>275</td></tr>
<tr><td>300</td></tr>
<tr><td>350</td></tr>
<tr><td>400</td></tr>
<tr><td>450</td></tr>
<tr><td>500</td><td rowspan="6"></td></tr>
<tr><td>550</td></tr>
<tr><td>600</td></tr>
<tr><td>650</td></tr>
<tr><td>700</td></tr>
<tr><td>750</td></tr>
</table>

Table 9. Dominant taxa based on relative abundance along each of the macrophyte transects in 2012. Loc. = distance from shore in meters. Taxa in bold have Coefficients of Conservation values of zero, indicating non-native or most likely to be found in degraded habitat.

<table>
<tr><th>Loc.</th><th>NW Reference</th><th>Heritage</th><th>Grand Trunk</th></tr>
<tr><td>0</td><td rowspan="10">• Typha angustifolia
• Phragmites australis
• Schoenoplectus pungens</td><td>• Salix exigua
• Impatiens capensis</td><td rowspan="3">• Typha angustifolia
• Typha x glauca
• Lythrum salicaria
• Impatiens capensis</td></tr>
<tr><td>5</td><td>• Filamentous green algae</td></tr>
<tr><td>10</td><td rowspan="10">• Ceratophyllum demersum
• Elodea nutallii</td></tr>
<tr><td>20</td><td rowspan="15">• Ceratophyllum demersum
• Nymphaea odorata
• Elodea nuttallii
• Myriophyllum spicatum</td></tr>
<tr><td>30</td></tr>
<tr><td>40</td></tr>
<tr><td>50</td></tr>
<tr><td>60</td></tr>
<tr><td>70</td></tr>
<tr><td>80</td></tr>
<tr><td>90</td><td rowspan="6">• Najas flexilis
• Chara sp.
• Filamentous green algae
• Potamogeton pectinatus</td></tr>
<tr><td>100</td></tr>
<tr><td>125</td><td>• Ceratophyllum demersum</td></tr>
<tr><td>150</td><td rowspan="15"></td></tr>
<tr><td>175</td></tr>
<tr><td>200</td></tr>
<tr><td>225</td><td rowspan="8">• Vallisneria americana
• Myriophyllum spicatum
• Najas flexilis
• Potamogeton perfoliatus
• Filamentous green algae</td></tr>
<tr><td>250</td></tr>
<tr><td>275</td><td rowspan="4">• Ceratophyllum demersum
• Elodea nuttallii
• Myriophyllum spicatum
• Vallisneria americana
• Najas guadalupensis
• Potamogeton pusillus</td></tr>
<tr><td>300</td></tr>
<tr><td>350</td></tr>
<tr><td>400</td></tr>
<tr><td>450</td><td rowspan="6"></td></tr>
<tr><td>500</td></tr>
<tr><td>550</td><td rowspan="4">• Ceratophyllym demersum
• Najas flexilis</td></tr>
<tr><td>600</td></tr>
<tr><td>650</td></tr>
<tr><td>700</td></tr>
</table>

Table 10. Dominant taxa based on relative abundance along each of the macrophyte transects in 2018. Loc. = distance from shore in meters. Taxa in bold have Coefficients of Conservation values of zero, indicating non-native or most likely to be found in degraded habitat.

<table>
<tr><th>Loc.</th><th>NW Reference</th><th>Heritage</th><th>Grand Trunk</th></tr>
<tr><td>0</td><td rowspan="7">• Ceratophyllum demersum
• Lemna minor
• Macroalgae
• Spirodela polyrhiza
• Typha angustifolia
• Utricularia vulgaris
• Wolffia sp.</td><td rowspan="4">• Ceratophyllum demersum
• Macroalgae
• Myriophyllum spicatum
• Various grasses</td><td rowspan="4">• Cephalanthus sp.
• Ceratophyllum demersum
• Lemna minor
• Spirodela polyrhiza
• Typha x glauca</td></tr>
<tr><td>5</td></tr>
<tr><td>10</td></tr>
<tr><td>20</td></tr>
<tr><td>30</td><td>BARE</td><td rowspan="10">• Ceratophyllum demersum
• Elodea canadensis
• Potamogeton zosteriformus</td></tr>
<tr><td>40</td><td rowspan="2">• Ceratophyllum demersum</td></tr>
<tr><td>50</td></tr>
<tr><td>60</td><td rowspan="5">• Chara sp.
• Najas flexilis
• Potomogeton zosteriformus</td><td rowspan="4">• Ceratophyllum demersum
• Elodea spp.
• Najas flexilis</td></tr>
<tr><td>70</td></tr>
<tr><td>80</td></tr>
<tr><td>90</td></tr>
<tr><td>100</td><td rowspan="2">• Ceratophyllum demersum</td></tr>
<tr><td>125</td><td rowspan="5">• Chara sp.
• Potamogeton perfoliatus
• Vallisneria americana</td></tr>
<tr><td>150</td><td rowspan="2">BARE</td></tr>
<tr><td>175</td></tr>
<tr><td>200</td><td rowspan="13"></td><td rowspan="6">• Myriophyllum spicatum
• Vallisneria americana</td></tr>
<tr><td>225</td></tr>
<tr><td>250</td><td rowspan="6">• Potamogeton pucillis
• Vallisneria americana</td></tr>
<tr><td>275</td></tr>
<tr><td>300</td></tr>
<tr><td>350</td></tr>
<tr><td>400</td></tr>
<tr><td>450</td><td rowspan="2">BARE</td></tr>
<tr><td>500</td><td rowspan="3">• Ceratophyllum demersum
• Vallisneria americana</td></tr>
<tr><td>550</td><td rowspan="4"></td></tr>
<tr><td>600</td></tr>
<tr><td>650</td><td rowspan="2">BARE</td></tr>
<tr><td>700</td></tr>
</table>

Non-native species were again assigned C-values of 0 (Bourdaghs et al. 2006) and transects in 2018 included species that have all been reported in previous sampling years (Tables 11-14), including purple loosestrife (*Lythrum salicaria*), Eurasian watermilfoil (*Myriophyllum spicatum*), watercress (*Nasturtium spp*.), curly-leaf pondweed (*Potamogeton cripsus*), narrow-leaf cattail (*Typha angustifolia*), and hybrid cattail (*Typha* x *glauca*) (Table 15). As was already noted above, another non-native species, common reed (*Phragmites australis*), was not recorded during the 2018 study, although it previously accounted for 10-14% of relative abundance at the NW Reference in 2009-2012 (Tables 11-14). Higher water levels may have been responsible.

Total species richness in 2018 declined substantially at the NW reference site (Table 16; Figure 4). Given that submerged species richness increased slightly at this site in 2018, the decline was largely due to loss of emergent species (from 42 to 6 species; Tables 11-15). This suggests that environmental factors (such as sustained high water levels) may have been responsible. Possibly due to the decreased number of emergent macrophytes and resulting increase in space and light availability, floating macrophytes species, including duckweeds (*Lemna spp.*, *Spirodela polyrhiza*, *Wolffia spp.*), water lilies (*Nuphar lutea*, *Nymphaea odorata*), and floating pondweed (*Potamogeton natans*), were recorded at the NW Reference transect in 2018, some of which were observed for the first time at this site in project history (Table 15). The decline in 2018 species richness at the NW Reference transect led to generally similar total richness values at all sampling transects (Table 16, Figure 4). Despite the potentially negative impact of high water levels on macrophytes, species richness was relatively steady at Grand Trunk and Heritage sites compared to past years, suggesting that restoration activities helped maintain habitat in the littoral zone.

Table 11. Coefficient of Conservatism (C) values and weighted mean relative abundance (%) for taxa found along each macrophyte transect in 2009. E = emergent, S = submergent, F = floating. – indicates that no C-value was available for that taxon.

Species	**Type**	**C**	**NW Ref**	**Heritage**	**Grand Trunk**
Carex hystericinia	E	2	1		
Ceratophyllum demersum	S	1	13	63	23
Chara sp.	S	—		<1	
Cicuta bulbifera	E	5	<1		
Elodea Canadensis	S	1	<1	23	6
Filamentous green algae	—	—	7		<1
Heteranthera dubia	S	6	<1	1	1
Impatiens capensis	E	2	<1		
Juncus articulatus	E	3	<1		
Juncus canadensis	E	6	<1		
Juncus sp.	E	—	<1		
Lemna minor	F	5	<1		<1
Lemna trisulca	F	6			<1
Lythrum salicaria	E	0	<1		4
Myriophyllum spicatum	S	0	2	5	10
Najas flexilis	S	5	6	<1	
Najas guadalupensis	S	7			1
Nasturtium microphyllum	E	0			2
Nymphaea odorata	F	6	<1	1	10
Peltandra virginica	E	6			<1
Phragmites australis	E	0	10		
Potamogeton crispus	S	0			3
Potamogeton nodosus	S	6			<1
Potamogeton pectinatus	S	3	<1	<1	3
Potamogeton perfoliatus	S	6		<1	5
Potamogeton pusillus	S	4	3	<1	4
Potamogeton zosteriformis	S	5		1	<1
Ranunculus flabellaris	S	10	<1		
Sagittaria sp.	E	—			<1
Sagittaria latifolia	E	1	<1		
Salix sp.	E	—			<1
Salix exigua	E	1		2	
Schoenoplectus acutus	E	5	4		
Schoenoplectus pungens	E	5	6		
Schoenoplectus tabernaemontani	E	4	<1	1	
Spirodela polyrhiza	F	6			<1
Typha angustifolia	E	0	27		8
Utricularia vulgaris	S	6	8		5
Vallisneria americana	S	7	12	3	14
Mean C			3.6	3.8	3.9
Submergent Richness			10	11	13
Total Richness			26	14	24

Table 12. Coefficient of Conservatism (C) values and weighted mean relative abundance (%) for taxa found along each macrophyte transect in 2010. See Table 11 for table explanation.

Species	**Type**	**C**	**NW Ref**	**Heritage**	**Grand Trunk**
Carex comosa	E	5	<1		
Ceratophyllum demersum	S	1	2	38	33
Chara sp.	S	–	2		
Cicuta bulbifera	E	5	<1		<1
Cladium mariscoides	E	10	<1		
Cuscuta gronovii	E	3	<1		
Elodea canadensis	S	1	<1	31	3
Elodea nuttallii	S	5	<1		2
Eupatorium perfoliatum	E	4	<1		
Filamentous green algae	–	–	3		5
Galium tinctorium	E	5	<1		
Heteranthera dubia	S	6	1	6	2
Hydrocotyle umbellata	E	10	<1		
Impatiens capensis	E	2	<1	<1	<1
Juncus articulatus	E	3	<1		
Juncus canadensis	E	6	2		
Juncus debilis	E	–			<1
Lemna minor	F	5	<1		<1
Lemna trisulca	F	6	<1		<1
Lythrum salicaria	E	0	<1		2
Myriophyllum spicatum	S	0	7	9	10
Najas flexilis	S	5	7	<1	
Najas guadalupensis	S	7			2
Nasturtium microphyllum	E	0	<1		2
Nymphaea odorata	F	6		7	9
Phragmites australis	E	0	10		
Polyganum punctatum var. *confertiflorum*	E	5			<1
Potamogeton crispus	S	0			<1
Potamogeton pectinatus	S	3	<1		2
Potamogeton perfoliatus	S	6	2	<1	2
Potamogeton pusillus	S	4	2	<1	1
Potamogeton zosteriformis	S	5			<1
Ranunculus flabellaris	S	10			<1
Salix sp.	E	–			<1
Salix exigua	E	1		1	
Salix petiolaris	E	1	<1		
Schoenoplectus pungens	E	5	6		
Schoenoplectus tabernaemontani	E	4	<1	1	<1
Sparganium eurycarpum	E	5			1
Typha angustifolia	E	0	19		
Typha x *glauca*	E	0			3
Utricularia geminiscarpa	S	8	2		
Utricularia intermedia	S	10	2		
Utricularia minor	S	10	2		
Utricularia vulgaris	S	6			2
Unknown sedge	E	–		<1	
Vallisneria americana	S	7	28	7	16
Various grasses	E	–	2		
Mean C			4.5	3.6	4.0
Submergent Richness			14	8	13
Total Richness			34	13	28

Table 13. Coefficient of Conservatism (C) values and weighted mean relative abundance (%) for taxa found along each macrophyte transect in 2011. See Table 11 for table explanation.

Species	**Type**	**C**	**NW Ref**	**Heritage**	**Grand Trunk**
Carex comosa	E	5	<1		
Carex hystericinia	E	2	<1		
Ceratophyllum demersum	S	1	3	57	47
Chara sp.	S	–	2		
Cicuta bulbifera	E	5	<1		
Cirsium muticum	E	6	<1		
Cladium mariscoides	E	10	<1		
Cuscuta gronovii	E	3	<1		
Eleocharis sp.	E	–	<1		
Elodea canadensis	S	1	<1	11	4
Elodea nuttallii	S	5	<1		1
Filamentous green algae	–	–	6	<1	3
Galium tinctorium	E	5	<1		
Heteranthera dubia	S	6	2	<1	2
Hydrocotyle umbellata	E	10	<1		
Impatiens capensis	E	2	<1	1	<1
Juncus sp. 1	E	–	<1		
Juncus sp. 2	E	–	<1		
Juncus sp. 3	E	–	<1		
Juncus sp. 4	E	–	<1		
Juncus articulatus	E	3	1		
Juncus effusus	E	3	<1		
Lemna minor	F	5	1		1
Lemna trisulca	F	6			<1
Lythrum salicaria	E	0	1		3
Myriophyllum spicatum	S	0	6	2	2
Myosotis laxa	E	6	<1		
Najas flexilis	S	5	8	2	
Najas guadalupensis	S	7			1
Nasturtium microphyllum	E	0	<1		<1
Nymphaea odorata	F	6	<1	6	4
Peltandra virginica	E	6	<1		<1
Phragmites australis	E	0	14		
Pilea pumila	E	5	<1		
Polyganum virginianum	E	4	<1		
Potamogeton crispus	S	0			2
Potamogeton illinoensis	S	5			
Potamogeton pectinatus	S	3	1		1
Potamogeton perfoliatus	S	6	2	<1	2
Potamogeton pusillus	S	4	3	5	2
Rumex sp.	E	–	<1		
Salix exigua	E	1		1	
Salix petiolaris	E	1	<1		
Sagittaria latifolia	E	1	<1		
Schoenoplectus acutus	E	5	2	<1	
Schoenoplectus pungens	E	5	7		
Schoenoplectus tabernaemontani	E	4	<1		
Scutellaria galericulata	E	5	<1		
Spirodela polyrhiza	F	6			<1
Typha angustifolia	E	0	18		9
Typha x *glauca*	E	0	1		<1
Typha latifolia	E	1	<1		
Utricularia sp.	S	–			1
Utricularia intermedia	S	10	3		
Vallisneria americana	S	7	16	13	13
Various grasses	E	–	<1		
	Mean C		3.9	3.7	3.4
	Submergent Richness		12	8	12
	Total Richness		49	13	23

Table 14. Coefficient of Conservatism (C) values and weighted mean relative abundance (%) for taxa found along each macrophyte transect in 2012. See Table 11 for table explanation.

Species	Type	C	NW Ref	Heritage	Grand Trunk
Carex comosa	E	5	<1		
Ceratophyllum demersum	S	1	10	63	36
Chara sp.	S	–	3		
Cirsium muticum	E	6	<1		
Cladium mariscoides	E	10	<1		
Cuscuta gronovii	E	3	<1		
Eleocharis sp.	E	–	<1		
Elodea canadensis	S	1	<1	<1	1
Elodea nuttallii	S	5	<1	22	9
Epilobium coloratum	E	3			<1
Eupatorium perfoliatum	E	4	<1		
Eutrochium maculatum	E	4	<1		
Filamentous green algae	–	–	4	3	3
Galium tinctorium	E	5	<1		
Heteranthera dubia	S	6	1	1	2
Hydrocotyle umbellata	E	10	<1		
Impatiens capensis	E	2	<1	1	4
Juncus sp. 1	E	–	<1		
Juncus sp. 2	E	–	<1		
Juncus sp. 3	E	–	<1		
Juncus sp. 4	E	–	<1		
Juncus sp. 5	E	–	<1		
Juncus acuminatus	E	8	<1		
Juncus articulatus	E	3	<1		
Juncus brachycephalus	E	7	<1		
Juncus effusus	E	3	<1		
Leersia oryzoides	E	3	<1		
Lemna minor	F	5	<1		<1
Lemna trisulca	F	6			<1
Lycopus sp.	E	–	<1		
Lythrum salicaria	E	0	<1		4
Moss	E	–	<1		
Myriophyllum spicatum	S	0	6	4	8
Myosotis laxa	E	6	<1		
Najas guadalupensis	S	7	13		2
Nasturtium microphyllum	E	0	<1		<1
Nuphar variegata	F	7			<1
Nymphaea odorata	F	6		1	11
Peltandra virginica	E	6	<1		<1
Phragmites australis	E	0	14	<1	
Pilea pumila	E	5	<1		
Polyganum punctatum	E	5	<1		<1
Pontederia cordata	E	8	<1		<1
Potamogeton crispus	S	0		<1	<1
Potamogeton illinoensis	S	5	<1		
Potamogeton pectinatus	S	3	1	<1	2
Potamogeton perfoliatus	S	6	2	1	<1
Potamogeton pusillus	S	4	<1	<1	1
Potamogeton zosteriformis	S	5		<1	1
Rumex sp.	E	–	<1		
Salix exigua	E	1		1	
Sagittaria latifolia	E	1	<1		
Schoenoplectus acutus	E	5	<1		
Schoenoplectus pungens	E	5	3		
Schoenoplectus tabernaemontani	E	4	<1		
Scutellaria lateriflora	E	5	<1		
Sparganium eurycarpium	E	5			<1
Spirodela polyrhiza	F	6			<1
Typha angustifolia	E	0	25		4
Tyhpa x glauca	E	0	<1		3
Unknown emergent 1	E	–	<1		
Unknown emergent 2	E	–	<1		
Utricularia vulgaris	S	6			1
Vallisneria americana	S	7	13	2	4
Various grasses	E	–	<1		
Verbena hastata	E	4	<1		
Mean C			4.2	3.1	3.9
Submergent Richness			12	11	13
Total Richness			56	16	29

Table 15. Coefficient of Conservatism (C) values and weighted mean relative abundance (%) for taxa found along each macrophyte transect in 2018. See Table 11 for table explanation.

Species	Type	C	NW Ref	Heritage	Grand Trunk
Cephalanthus occidentalis	E	1			1
Ceratophyllum demersum	S	1	16	56	20
Chara sp.	S	–	8		1
Elodea Canadensis	S	1	<1	5	9
Elodea nuttallii	S	5	<1	10	3
Filamentous green algae	–	–	4	3	5
Heteranthera dubia	S	6			2
Impatiens capensis	E	2		1	
Lemna minor	F	5	5		4
Lemna trisulca	F	6	2		4
Lythrum salicaria	E	0	<1		
Myriophyllum spicatum	S	0	2	5	6
Najas flexilis	S	5	13	6	1
Nasturtium spp.	E	0	1		
Nuphar lutea	F	7	<1		
Nymphaea odorata	F	6	<1	<1	1
Potamogeton crispus	S	0		<1	<1
Potamogeton natans	F	5		1	
Potamogeton pectinatus	S	3	<1	1	1
Potamogeton perfoliatus	S	6	3	<1	2
Potamogeton pusillus	S	4	10	2	<1
Potamogeton zosteriformis	S	5	2	5	6
Ranunculus flabellaris	S	10	<1		<1
Salix exigua	E	1		<1	
Schoenoplectus pungens	E	5	<1		
Schoenoplectus tabernaemontani	E	4	<1		
Spirodela polyrhiza	F	6	4		3
Typha angustifolia	E	0	5		
Typha x *glauca*	E	0			6
Utricularia vulgaris	S	6	2	<1	1
Vallisneria Americana	S	7	18	1	24
Various grasses	E	–	<1	1	
Wolffia spp.	F	5	3		1
Mean C			4.2	3.6	4.2
Submergent Richness			13	12	15
Total Richness			26	18	23

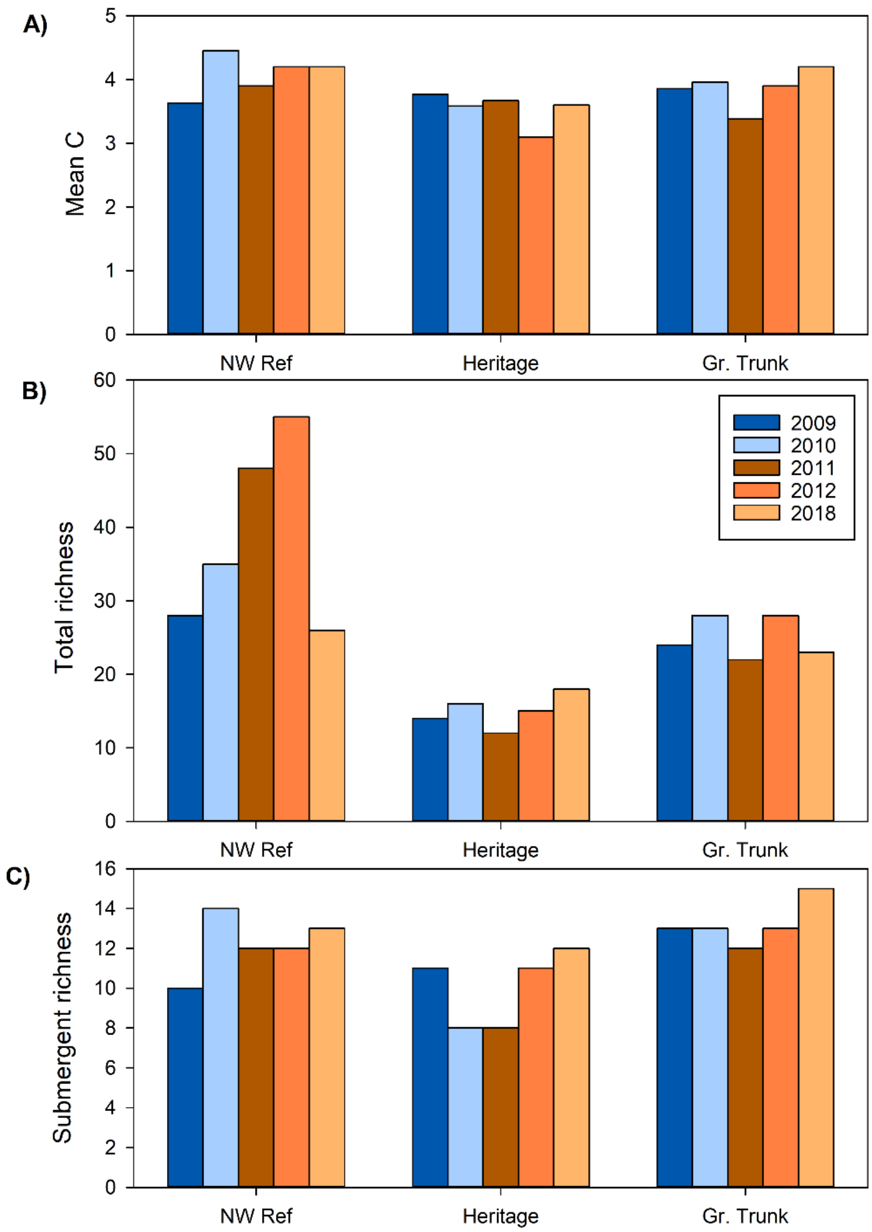

Figure 4. Mean coefficient of conservatism [C] values (A), total richness (B), and submergent richness (C) at each transect before (2009-2010) and after (2011, 2012, and 2018) restoration.

Table 16. Grand means (±SD) of mean coefficient of conservatism (C) values, submergent richness, and total species richness at each transect pre- (2009-2010) and post-restoration (2011, 2012, and 2018). ND = no data; NA = not applicable. The "other richness" parameter summarizes non-vascular plants, such as macroalgae, including filamentous green algae.

Grand Means	Time	NW Ref	Heritage	Grand Trunk
Sample Size (n=years)	Pre	2	2	2
	Post ('11-'12)	2	2	2
	Post ('18)	1	1	1
Mean C	Pre	4.0 (0.6)	3.7 (0.1)	3.9 (0.1)
	Post ('11-'12)	4.2 (0.2)	3.1 (0.4)	3.9 (0.4)
	Post ('18)	4.2 (NA)	3.6 (NA)	4.2 (NA)
Submergent Richness	Pre	12.0 (2.8)	9.5 (2.1)	13.0 (0.0)
	Post ('11-'12)	12.0 (0.0)	9.5 (2.1)	12.5 (0.7)
	Post ('18)	13.0 (NA)	12.0 (NA)	15.0 (NA)
Emergent Richness	Pre	15.0 (2.8)	3.0 (1.4)	8.0 (2.8)
	Post ('11-'12)	38.0 (5.7)	3.0 (0.0)	8.0 (2.8)
	Post ('18)	6.0 (NA)	3.0 (NA)	2.0 (NA)
Floating Richness	Pre	2.0 (0.0)	1.0 (0.0)	3.5 (0.7)
	Post ('11-'12)	1.5 (0.7)	1.0 (0.0)	4.5 (0.7)
	Post ('18)	6.0 (NA)	2.0 (NA)	5.0 (NA)
Other Richness	Pre	1.0 (0.0)	0.0 (0.0)	1.0 (0.0)
	Post ('11-'12)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
	Post ('18)	1.0 (NA)	1.0 (NA)	1.0 (NA)
Total Richness	Pre	30.0 (5.7)	13.5 (0.7)	26.0 (2.8)
	Post ('11-'12)	52.5 (4.9)	14.5 (2.1)	26.0 (4.2)
	Post ('18)	26.0 (NA)	18.0 (NA)	23.0 (NA)

The multivariate analysis of environmental data (Figure 5) indicated that Axis 1 accounted for 39% of the variation and axis 2 accounted for an additional 29% of the variation (Figure 5A). Of the environmental variables, OM, water level, and precipitation had the most explanatory power. The environmental data separated transect sites cleanly, with NW Reference associated with high OM and low slope, while Heritage associated with the reverse (Figure 5B). The environmental data also separated very strongly by year, with 2018 being associated with higher water levels and warmer water temperatures compared to prior years (Figure 3C). Finally, there was separation of transect type, with NW reference and 2018 restoration transects differentiated in ordination space from the pre-restoration and early post-restoration transects; again, reference transects were associated with OM, whereas the 2018 transects were associated with high water levels (Figure 3D).

Unfortunately, we were unable to generate PCA biplots for the macrophyte data, as there were no significant differences between Eigenvectors in the analysis.

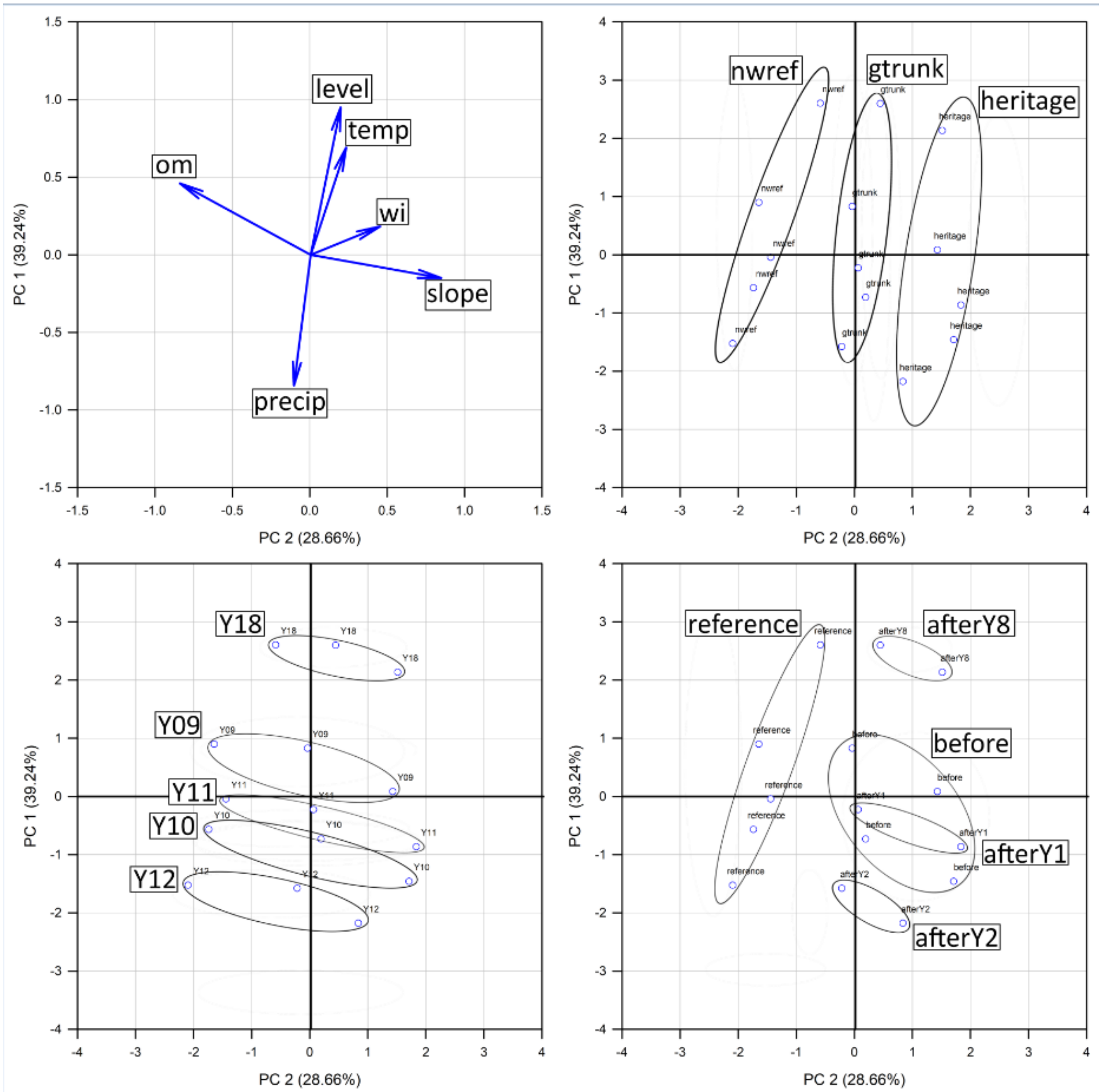

Figure 5. (A) PCA biplot of environmental data (organic matter [OM], precipitation [precip], air temperature [temp], slope, wind index [wi], and water level relative to the long-term mean [level]). Vector length is positively related to explanatory power for each variable. (B) Environmental data clustered by site (Northwest Reference [nwref], Grand Trunk [gtrunk], and Heritage Landing [heritage]. (C) Environmental data clustered by year. (D) Environmental data clustered by site type (reference, before restoration [before], 1 year post-restoration [afterY1], 2 years post-restoration [afterY2]), and 8 years post-restoration [afterY8].

Sediment Characterization

Mean OM percent (OM%) from all NW Reference transect sediment sampling points increased in 2018 compared to prior years (Figure 6). This increase, and its associated variability, were driven largely by a single point with high and variable OM% levels (11%, 73%, and 85%), sampled 30 m from shore with 50% coverage from cattails (*Typha angustifolia*) and 30% coontail (*Ceratophyllum demersum*). Field technicians noted that the sediment visibly contained notable amounts of vegetation and OM% (data not shown). Grand Trunk and Heritage Landing transect mean OM% values in 2018 fell within the range of previous sampling efforts, with the highest OM% once again at Grand Trunk (Figure 6). Both Grand Trunk and Heritage Landing had statistically greater grand mean OM% than the NW Reference in 2018 alone and for all sampling years pooled (post-hoc Dunn's Tests: p<0.001 for both tests; Figure 6).

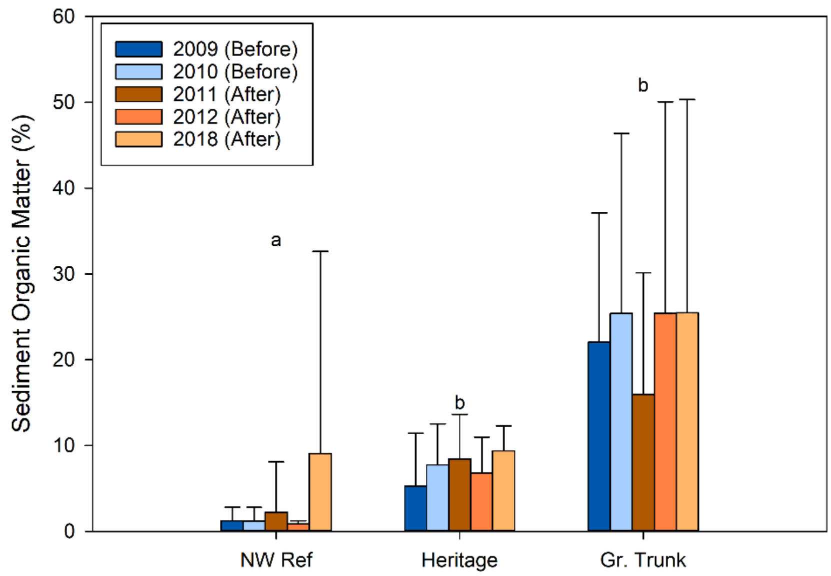

Figure 6. Mean (±SD) sediment organic matter (%) at survey site before (2009 and 2010) and after (2011, 2012, and 2018) restoration. Letters above error bars indicate statistically significant differences between grand means (all years pooled) across sites sampled in 2018 (p<0.001).

Sediment particle size analysis determined that the NW Reference transect, medium sand (125-250 µm) composed 60-80% of sediment at all sites sampled except at the site 30 m from shore, which was more evenly split between medium sand (48%) and fine sand; 40%) (Figure 7). Medium sand was also the main component of Grand Trunk sites (48-80%), except at a site 150 m from shore which was composed of more finely grained silt and clay particles (<63 µm; 46%) (Figure 9). Sediment from the three Heritage Landing sites were all sampled closer to shore (10, 30, and 60 m away) due to the shorter overall length of the Heritage transect compared to the other 2018 transects and perhaps due to shoreline proximity. Heritage sites all contained a majority of finer sediments, silt and clay (40%) and fine sand (31-32%) (Figure 8).

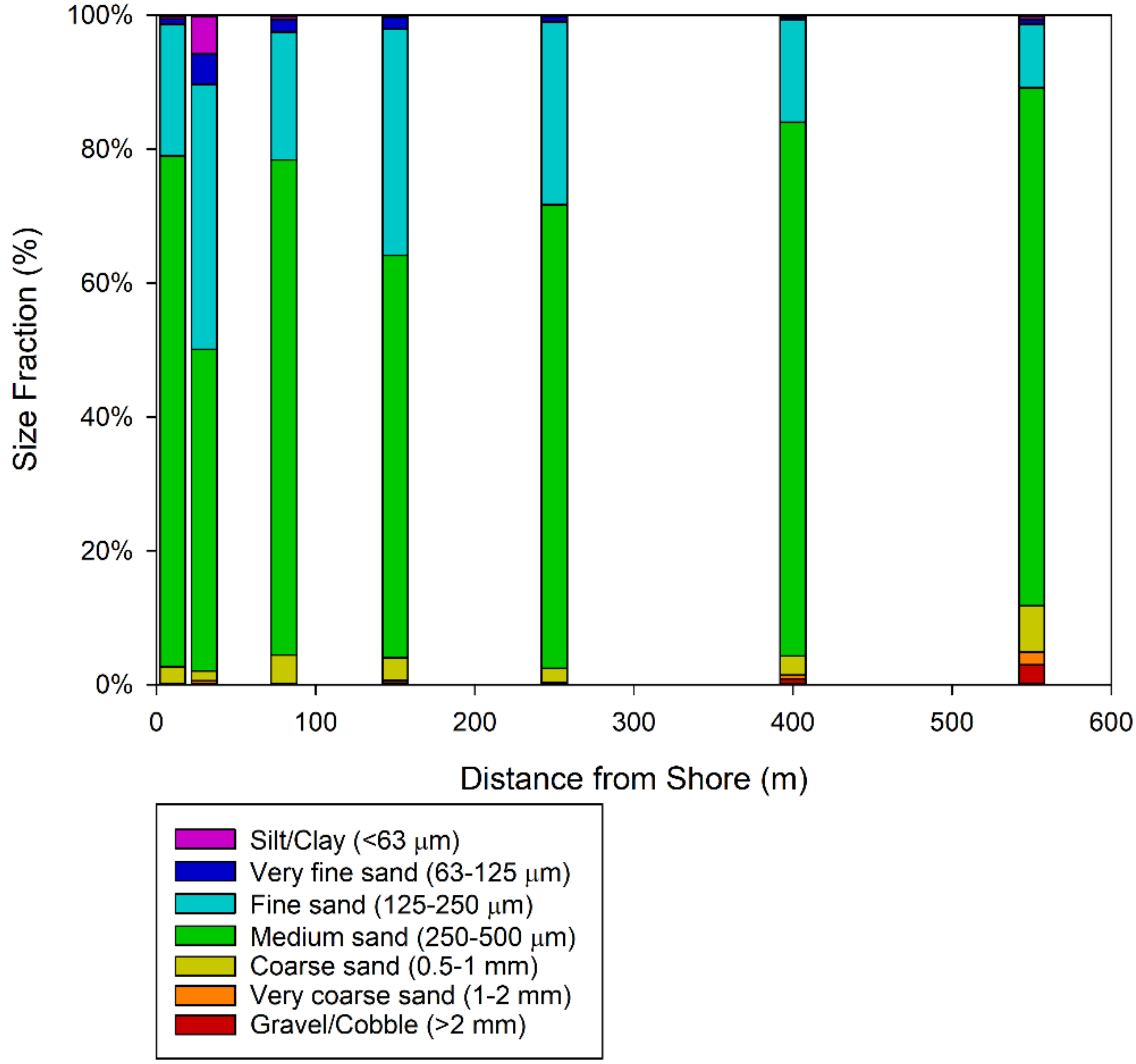

Figure 7. Sediment particle size analysis at NW Reference transect sites in 2018. A full list of sediment fraction values is given in Appendix Table A1.

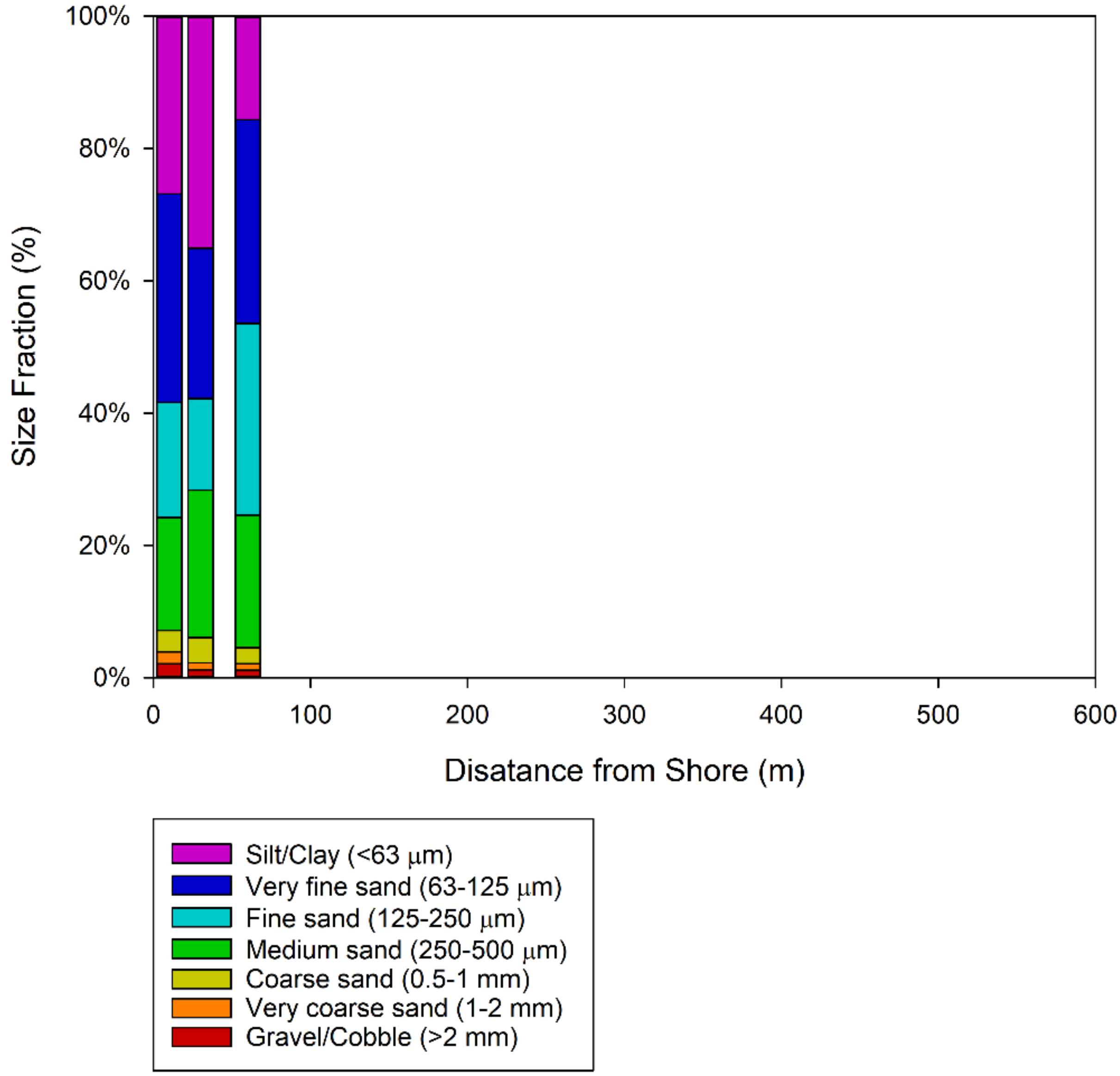

Figure 8. Sediment particle size analysis at Heritage Landing transect sites in 2018. A full list of sediment fraction values is given in Appendix Table A1.

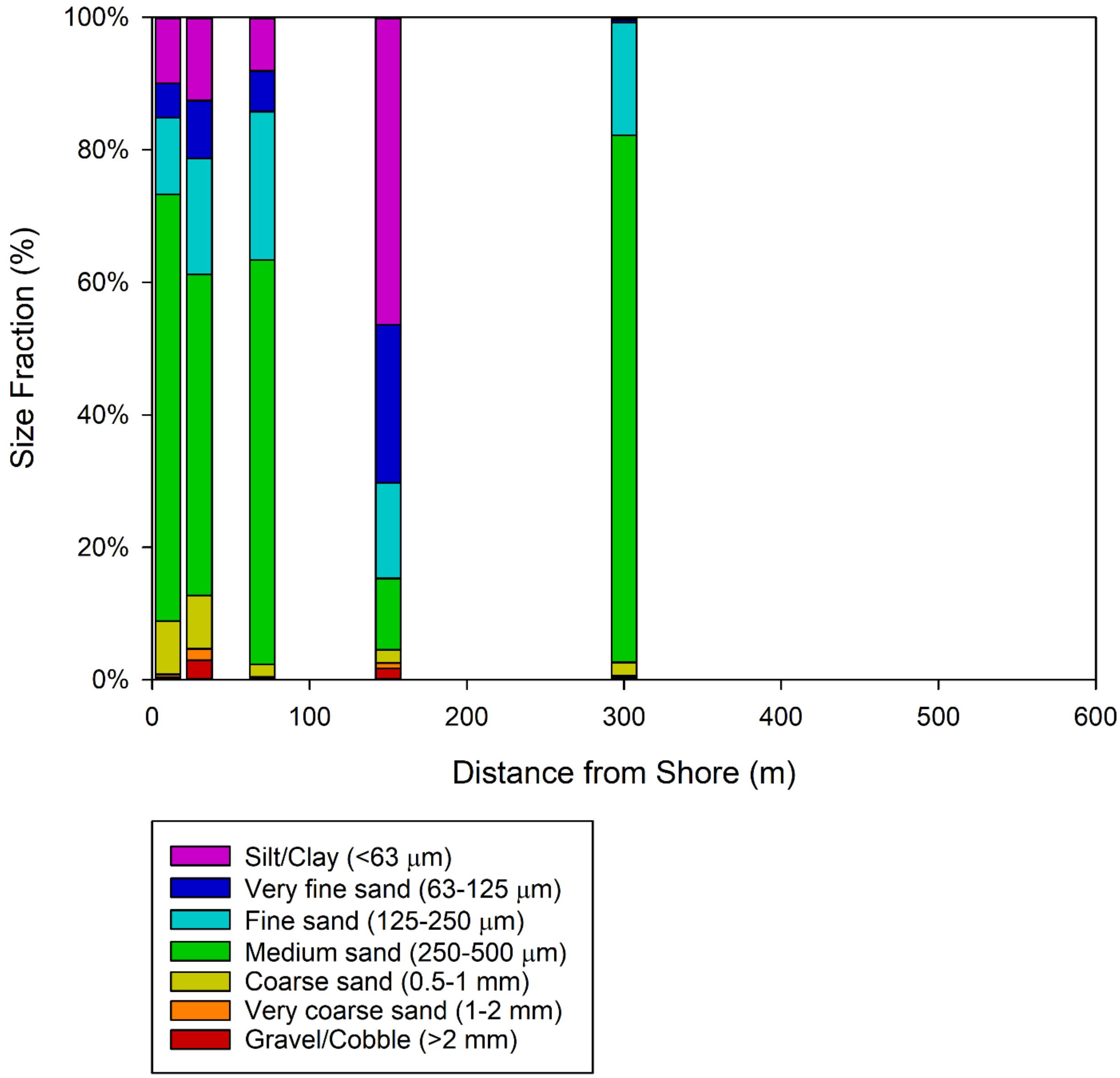

Figure 9. Sediment particle size analysis at Grand Trunk transect sites in 2018. A full list of sediment fraction values is given in Appendix Table A1.

Macroinvertebrate Community Structure Characterization

Macroinvertebrate community composition was not sampled as part of the original habitat restoration assessment, so the 2018 data provide a baseline for future assessments. Community structure at points within transects varied by depth and, to some extent, by sampling method (Table 17). For sites where no macrophytes were found, D-net sweeps were still conducted by skimming the sediment surface, but 0 invertebrates were found during the field picking. This only occurred at the Heritage transect at 30 m and 150 m from shore. Full summaries of captured taxa and count data are presented in Appendix Tables A2, A3, and A4. Species richness was higher at NW Reference and Grand Trunk than at Heritage Landing, irrespective of sampling type; ponar samples from Heritage were noted to be highly organic, had an oily appearance, and smelled of volatile compounds.

Total abundance of organisms at each point was highly variable but was highest when sampling by ponar, with a maximum number of 1,197 organisms in the NW Reference transect at 30 m from shore; about 30% of the cumulative ponar sample catch was composed of benthic Dreissenid mussels (Tables 17, A2-A4). Shannon's Diversity taxa richness (H') cumulatively for sites was similar among most transects and sampling methods (H' ranging 1.676 to 2.287), but was noticeably lower for D-net at Heritage Landing (H'=0.874), possibly due to sampling only one site (Table 17). NW Reference had both the highest maximum taxa richness (H'_{max}) and lowest evenness for an entire transect (Table 17).

Table 17. Muskegon Lake 2018 transect macroinvertebrate community composition based on D-net and ponar sampling techniques. Shannon's Diversity Index was used to calculate taxa richness (*H'*), maximum richness (H'_{max}), and evenness within each sampling site as well as totals calculated for each transect as a whole (gray highlighted text). NA = not applicable. Full abundance count summaries of taxa are presented in Appendix Tables A2, A3, and A4.

		D-net					Ponar				
Transect	Site	Total Species	Total Abundance	*H'*	H'_{max}	Evenness	Total Species	Total Abundance	*H'*	H'_{max}	Evenness
NW Ref	30 m	10	155	1.543	2.303	0.670	20	1197	1.681	2.996	0.561
	250 m	12	61	1.917	2.485	0.771	16	874	1.634	2.773	0.589
	550 m	8	453	1.033	2.079	0.497	8	309	1.300	2.079	0.625
	total	19	669	1.676	2.944	0.569	24	2380	2.002	7.775	0.257
Heritage	30 m	0	0	NA	NA	NA	1	3	0.000	0.000	NA
	60 m	8	125	0.874	2.079	0.420	13	482	1.468	2.565	0.572
	150 m	0	0	NA	NA	NA	4	91	0.628	1.386	0.453
	total	8	125	0.874	2.079	0.420	14	576	1.718	2.639	0.651
Grand Trunk	30 m	15	179	1.659	2.708	0.613	18	297	1.181	2.890	0.409
	150 m	17	289	1.818	2.833	0.642	9	73	1.379	2.197	0.628
	300 m	17	261	1.969	2.833	0.695	10	942	1.242	2.303	0.539
	total	24	729	2.287	3.178	0.720	19	1312	1.811	2.944	0.615

Discussion

The ecological significance of aquatic macrophytes is considerable. The structural complexity of macrophytes provides essential habitat for invertebrates, fish, and breeding marsh birds (Jude and Pappas 1992, Thomaz et al. 2008, Cvetkovic et al. 2010, Grabas et al. 2012, Jurca et al. 2012) in addition to other ecosystem services, such as sediment stabilization and nutrient cycling (Barko et al. 1991, Madsen et al. 2001). Although fish distribution in Great Lakes coastal wetlands is significantly affected by both macrophytes and water quality, macrophytes have been shown to be the better predictor of fish community (Cvetkovic et al. 2010). Fish depend on macrophytes for refugia from predators, protection from wind and wave disturbances, shelter from sunlight, and cooler water temperatures (Jude and Pappas 1992, Lougheed et al. 2001, Cvetkovic et al. 2010). The high primary productivity of macrophyte beds also supports a rich zooplankton and invertebrate food source (Jude and Pappas 1992). The macrophyte communities of Great Lakes coastal wetlands, such as those found in Muskegon Lake, are particularly attractive to fishes due to their connection with both a major river and a Great Lake (Jude and Pappas 1992, Larson et al. 2013).

Our prior analysis of the macrophyte community in Muskegon Lake revealed that biomass was within the mean range of 55-170 g/m^2 reported for temperate lakes (Squires and Lesack 2003), but was quite variable throughout the lake. Differences in littoral zone morphology (i.e., slope; Duarte and Kalff 1986, Barko et al. 1991, Partanen et al. 2009) and exposure (i.e., protection from waves and wind; Keddy 1983, Cvetkovic at al. 2010, Cooper et al. 2012) among transects likely played a role in the spatial variability observed in biomass.

The PCA output indicated that organic matter composition, precipitation, and water level were the environmental factors explaining most of the variation in the data. OM was particularly important at the NW Reference site, which is consistent with the undisturbed nature of this site and its high macrophyte biomass. Our previous study (Ogdahl and Steinman 2015) also revealed a strong relationship between macrophyte biomass and sediment OM; furthermore, the accumulation of OM was influenced by site exposure, as sites with a lower wind index (WI in Figure 5) had greater sediment OM.

It is surprising to see the opposite positions of precipitation and water level in ordination space, as one would expect them to be positively related, as they were in our prior analysis (Ogdahl and Steinman 2015). However, that was not the case in the current study, with 2018 data included (Figure 5). It is possible that the inclusion of 2018 data, which resulted in more years overall but half the number of transects in 2018, may have influenced the PCA output. In addition, water levels the past 5 years have been much higher compared to the 2009-2013 period (Table 18).

Table 18. Lake Michigan-Huron mean water level data (NOAA-GLERL: https://www.glerl.noaa.gov/data/dashboard/GLWLD.html).

Year	Lake-wide annual mean surface water elevation (m)
2009	176.26
2010	176.11
2011	176.04
2012	175.92
2013	175.90
2014	176.30
2015	176.59
2016	176.70
2017	176.77
2018	176.87

Comparisons of the pre-restoration data in 2009 and 2010, as well as the 2011 and 2012 post-restoration data, with those collected in 2018 are therefore confounded by differences in water levels over that time period. Hence, the data provided at the NW Reference transect provides a mechanism to tease out the impacts of natural variability (e.g., water level changes) from those associated with restoration. In other words, we can use the following logic steps to assess the impact of restoration on macrophyte biomass:

i. If: $B_{rest-18} > B_{rest-11/12}$ but $B_{ref-18} > B_{ref-11/12}$, then increase cannot be attributed to restoration activity

ii. If: $B_{rest-18} > B_{rest-11/12}$ and $B_{ref-18} \leq B_{ref-11/12}$, then increase is likely associated with restoration activity

Where:

$B_{rest-18}$ = macrophyte biomass in 2018 at the restoration transect

$B_{rest-11/12}$ = macrophyte biomass in 2011/2012 at the restoration transect

B_{ref-18} = macrophyte biomass in 2018 at the reference transect

$B_{ref-11/12}$ = macrophyte biomass in 2011/2012 at the reference transect

Using this approach, the increases in macrophyte density and biomass seen in 2018 at Grand Trunk cannot unequivocally be attributed to prior restoration activity because similar increases were observed at NW reference transect. Indeed, the decline in density and biomass at Heritage Landing suggests restoration activities have not had a sustainable effect on these response variables. Of course, successful habitat restoration involves more than macrophyte biomass; species composition is also critical for habitat (Slagle and Allen 2018). High biomass levels of undesirable macrophyte species, such as Eurasian watermilfoil, can have quite negative impacts on lake habitat and the associated economic value of lake property (Goodenberger and Klaiber 2016).

Average C-values have been shown to be effective indicators of condition in Great Lakes coastal wetlands (Bourdaghs et al. 2006). In a survey of 55 Great Lakes coastal wetlands, Bourdaghs et al. (2006) reported an average C-value of 5.42 based on the State of Michigan's values, higher than what we observed in Muskegon Lake. Based on 2018 mean C-values, Grand Trunk and NW reference have the highest species quality (both 4.2), whereas Heritage Landing is more degraded (3.6). As noted in the prior report, if the appropriate environmental conditions are provided in restored areas, there is a readily available species pool present to colonize these regions. Nonetheless, the C-values improved in 2018 compared to 2012 at both Heritage Landing (from 3.1 to 3.6) and Grand Trunk (from 3.9 to 4.2) transects, and remained the same at NW reference transect (4.2), suggesting improved habitat quality. At the taxon level, two taxa of particular interest in Muskegon Lake are the desirable *Vallisneria americana* and the undesirable *Typha* spp. In 2018, relative abundance of *V. americana* increased dramatically from 2012 at Grand Trunk (4 to 24%) but declined at Heritage Landing (2 to 1%). *Typha angustfolia* relative abundance declined at the NW reference transect (25 to 4%) and Heritage Landing (4% to not present) from 2012 to 2018; the trends in these two taxa are suggestive of improved habitat, despite the counteracting influence of high water levels on species richness.

Overall, all three transect sites are relatively protected compared to more exposed locations in Muskegon Lake. In our previous report, we recommended close monitoring of the hybrid cattail (*Typha* x *glauca*) and common reed (*Phragmites australis*), as both species are known to expand into structurally uniform and monotypic stands to the detriment of wet meadow habitat (Frieswyk and Zedler 2007, Tulbure et al. 2007). We saw no evidence of significant expansion, at least at our monitored transects; indeed, *Phragmites* wasn't observed at all, at least in our lakeward transects.

Once again, filamentous green algae were relatively abundant at all sites throughout the study. A consortium of different taxa was found entangled among the vascular macrophytes. We did not identify the filamentous green algae by species, although the growth dynamics of these autotrophs clearly bear watching, given concerns over their abundance and putative role in botulism and beach fouling (Auer et al. 2010; Chun et al. 2013).

We cautioned previously that the increases in macrophyte metrics observed at most sites in 2012, with or without restoration actions, could have meant that 2012 was simply a "good year" for macrophytes in Muskegon Lake. Water levels in Lake Michigan were ~60 cm below the long-term average in 2012, while they were ~75 cm above the long-term average in 2018, which clearly plays an impact in macrophyte growth and vigor. A long-term study of shallow, eutrophic lakes in Sweden concluded that water level was among the most important factors causing fluctuations in coverage of submersed macrophytes (Blindow 1992).

Finally, climate change models predict an increase in extreme events and conditions (Changnon 2007; Notaro et al. 2015), it is likely that we will see continued fluctuations in Muskegon Lake water levels, and therefore our restoration efforts should take into account both adaptation and resilience (cf. Folke et al. 2010). Minimizing hardened features along shorelines, thereby allowing coastal wetland vegetation to migrate both landward and lakeward, depending on lake levels, will maximize structural and functional diversity in these systems. In addition, changing water levels may have significant implications for sediment nutrient release, also influencing system responses (cf. Steinman et al. 2012). Future monitoring of the macrophyte community in Muskegon Lake will be instrumental in teasing out environmental effects and changes resulting from restoration.

Acknowledgements

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APPENDICES

Appendix A: Macrophyte, Particle Size Fraction, and Macroinvertebrate Data

Appendix B: Fish Survey

Appendix A: Table of Contents

NW Reference

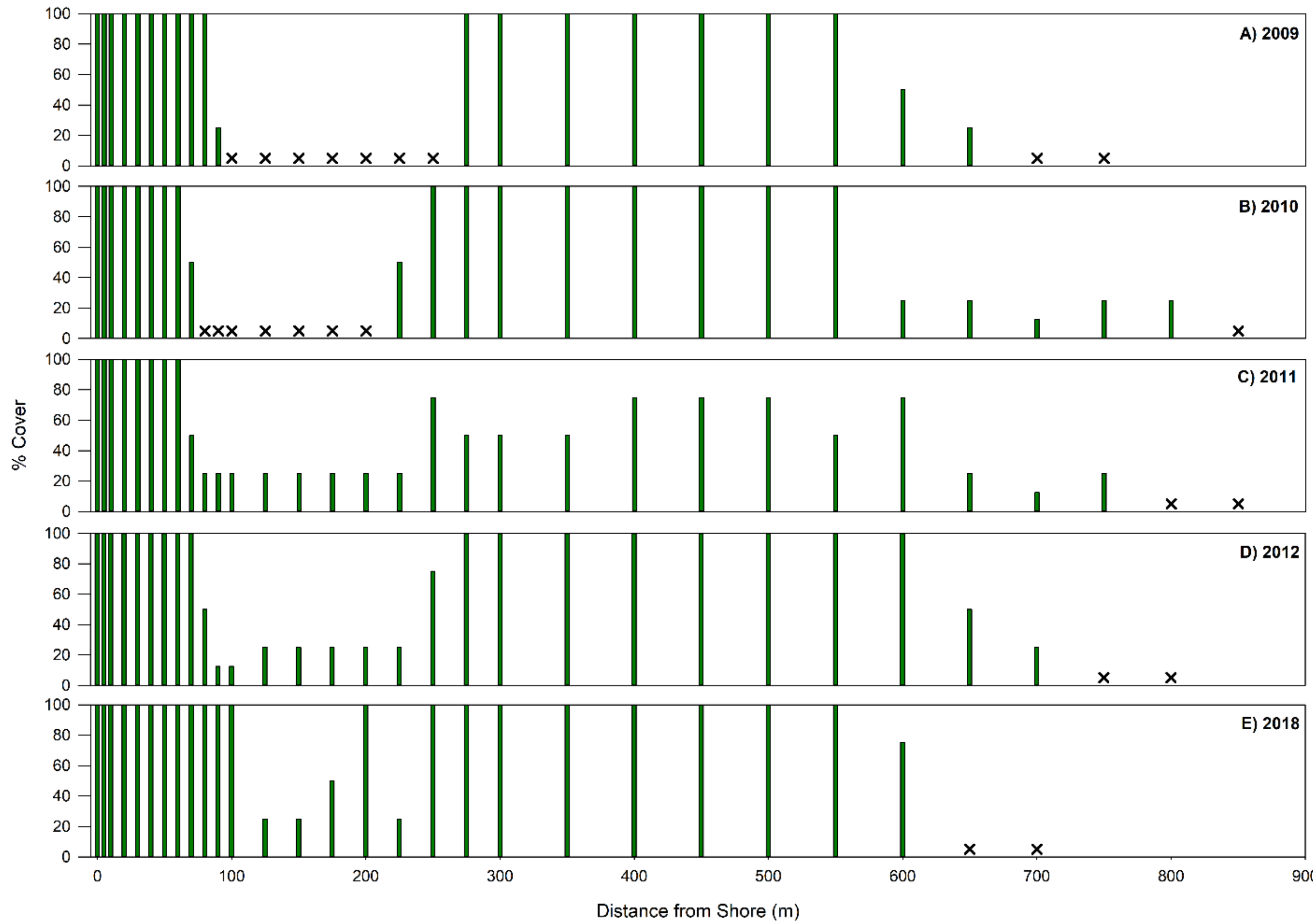

Figure A1. Macrophyte % cover (based on cover ranks) at the NW Reference site from 2009-2018. X indicates 0% cover for a given point along the transect.

Heritage Landing

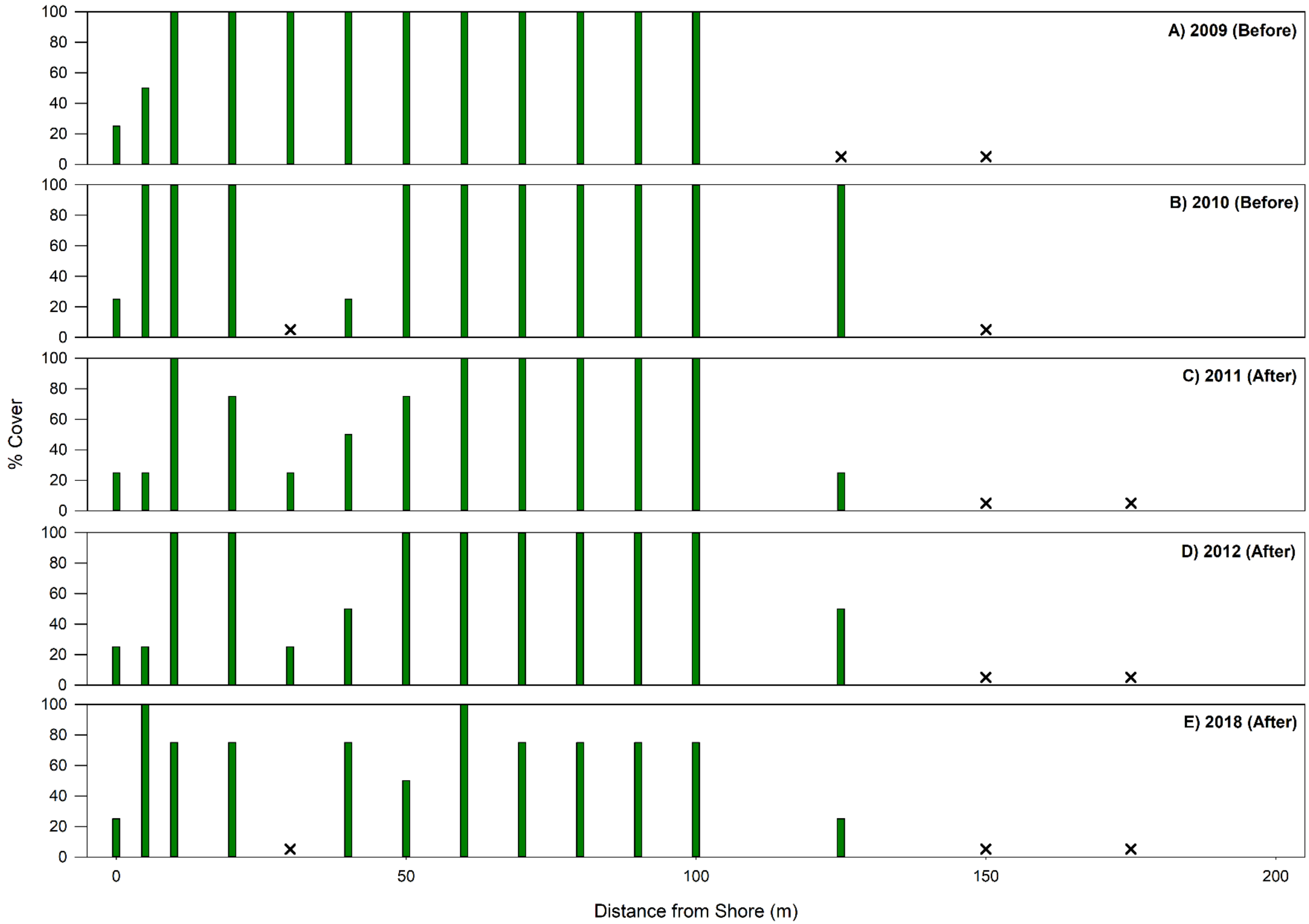

Figure A2. Macrophyte % cover (based on cover ranks) at the Heritage Landing site from 2009-2018. X indicates 0% cover for a given point along the transect.

Grand Trunk

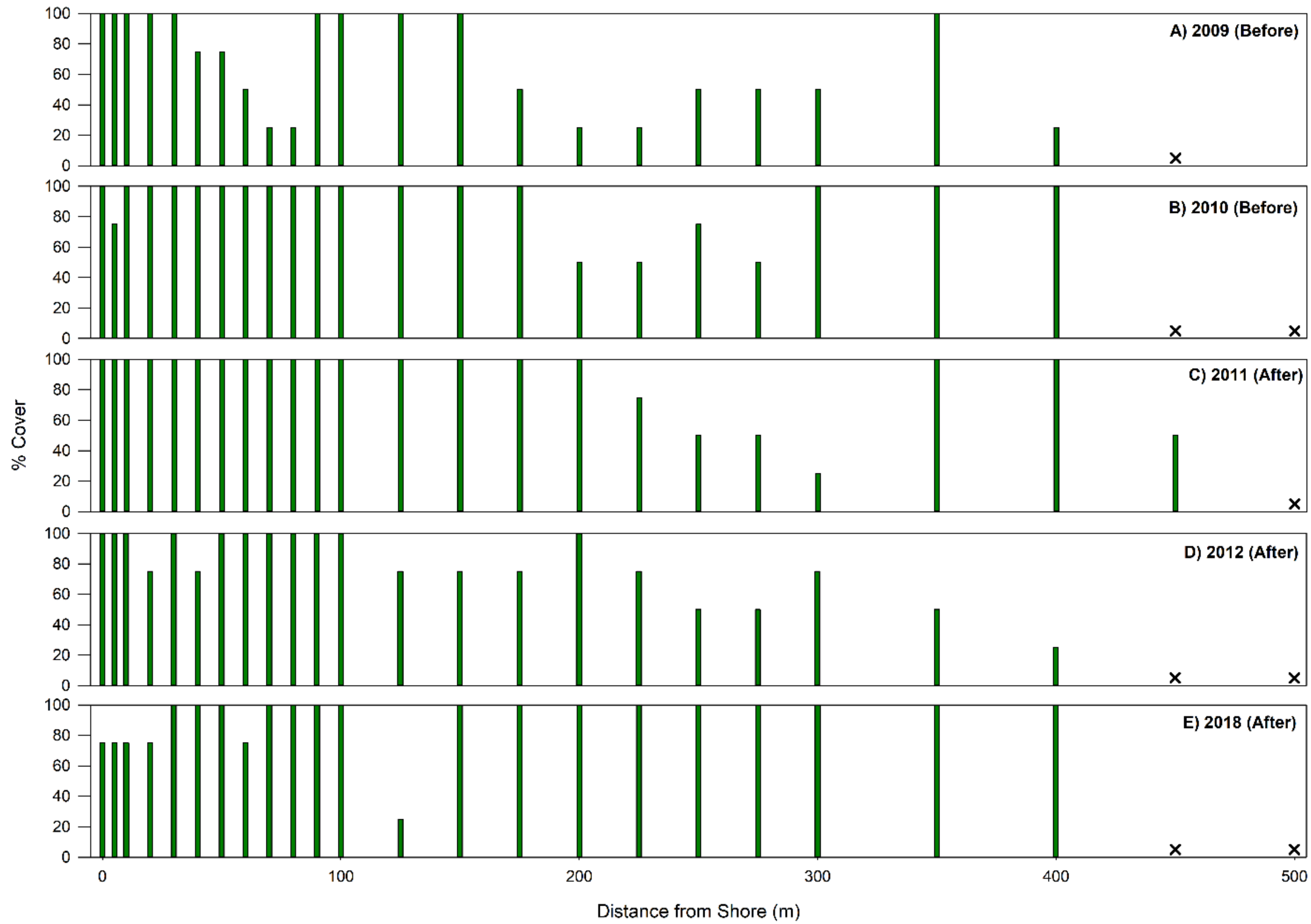

Figure A3. Macrophyte % cover (based on cover ranks) at the Grand Trunk site from 2009-2018. X indicates 0% cover for a given point along the transect.

Table A1. Particle size fractions from 2018 transect sediment, organized by distance from shore.

Transect	Distance (m)	Gravel/Cobble (>2 mm)	Very coarse sand (1-2 mm)	Coarse sand (0.5-1 mm)	Medium sand (250-500 µm)	Fine sand (125-250 µm)	Very fine sand (63-125 µm)	Silt/Clay (<63 µm)
NW Ref	10	0.1%	0.1%	2.5%	76.3%	19.7%	0.8%	0.6%
	30	0.1%	0.5%	1.4%	48.0%	39.6%	4.6%	5.8%
	80	0.0%	0.2%	4.3%	73.9%	19.0%	1.8%	0.7%
	150	0.2%	0.4%	3.4%	60.1%	33.8%	1.8%	0.3%
	250	0.1%	0.2%	2.2%	69.3%	27.3%	0.8%	0.2%
	400	0.9%	0.6%	2.9%	79.7%	15.3%	0.4%	0.3%
	550	2.9%	2.0%	6.9%	77.4%	9.5%	0.7%	0.7%
Heritage	10	2.1%	1.8%	3.3%	17.1%	17.4%	31.6%	26.8%
	30	1.2%	1.1%	3.8%	22.3%	13.8%	22.8%	35.1%
	60	1.1%	1.0%	2.4%	20.0%	29.0%	30.8%	15.7%
Grand Trunk	10	0.4%	0.4%	8.1%	64.4%	11.6%	5.2%	9.9%
	30	3.0%	1.7%	8.0%	48.5%	17.5%	8.7%	12.6%
	70	0.2%	0.2%	1.9%	61.1%	22.4%	6.2%	8.1%
	150	1.7%	0.8%	1.9%	10.8%	14.4%	23.9%	46.4%
	300	0.3%	0.3%	2.0%	79.6%	17.0%	0.4%	0.4%

Table A2. NW Reference 2018 transect macroinvertebrate abundance counts collected via D-net and Ponar sampling techniques.

			D-net				Ponar			
Class/Subclass	Order/Suborder/clade	Family	30 m	250 m	550 m	Total	30 m	250 m	550 m	Total
Acari			21	16	4	41	12			12
Bivalvia	Veneroida	Dreissenidae		4	131	135	137	233	106	476
Bivalvia	Veneroida	Sphaeridae						21	5	26
Clitellata	Rhynchobdellida	Glossiphoniidae					4	3		7
Clitellata	Rhynchobdellida	Piscicolidae					1	1		2
Gastropoda	Hygrophila	Physidae					39			39
Gastropoda	Hygrophila	Planorbidae	3		1	4	28	21	1	50
Gastropoda	Littorinimorpha	Bithyniidae	2			2				
Gastropoda	Littorinimorpha	Rissooidae			22	22	144	126	3	273
Insecta	Coleoptera	Curculionidae		1		1				
Insecta	Diptera	Ceratopogonigae						1		1
Insecta	Diptera	Chironomidae	1	9	12	22	3	373	43	419
Insecta	Diptera	Culicidae		6		6				
Insecta	Ephemeroptera	Baetidae		1		1				
Insecta	Ephemeroptera	Caenidae		1		1	1	14		15
Insecta	Hemiptera	Corixidae	4			4	3			3
Insecta	Hemiptera	Naucoridae	1			1				
Insecta	Hemiptera	Nepidae	2			2				
Insecta	Hemiptera	Pleidae	8			8	3			3
Insecta	Lepidoptera	Crambidae		1		1				
Insecta	Odonata	Coenagrionidae		1		1	4			4
Insecta	Trichoptera	Hydroptilidae		1		1		16		16
Insecta	Trichoptera	Leptoceridae	1	8		9				
Malacostraca	Amphipoda	Crangonyctidae	1			1	1			1
Malacostraca	Amphipoda	Gammaridae	78	2	2	82	442	36	4	482
Malacostraca	Amphipoda	Hyalellidae	27	18	276	321	23	3	10	36
Malacostraca	Isopoda	Asellidae	10	1		11	347	2	137	486
Oligochaeta					5	5	1	15		16

Table A3. Heritage Landing 2018 transect macroinvertebrate abundance counts collected via D-net and Ponar sampling techniques.

			D-net				Ponar			
Class/Subclass	Order/Suborder/clade	Family	30 m	60 m	150 m	Total	30 m	60 m	150 m	Total
Acari				6				1		1
Bivalvia	Veneroida	Dreissenidae		5				263	1	264
Gastropoda	Hygrophila	Physidae						9		9
Gastropoda	Hygrophila	Planorbidae		7				40		40
Gastropoda	Littorinimorpha	Rissooidae						11		11
Insecta	Diptera	Ceratopogonidae		1			3	1		4
Insecta	Diptera	Chironomidae		4				10	70	80
Insecta	Ephemeroptera	Caenidae						3		3
Insecta	Odonata	Coenagrionidae		1						
Insecta	Trichoptera	Hydroptilildae						9		9
Insecta	Trichoptera	Leptoceridae						2		2
Malacostraca	Amphipoda	Gammaridae		2				8		8
Malacostraca	Amphipoda	Hyalellidae		99				104	1	105
Malacostraca	Isopoda	Asellidae						21		21
Oligochaeta									19	19

Table A4. Grand Trunk 2018 transect macroinvertebrate abundance counts collected via D-net and Ponar sampling techniques.

			D-net				Ponar			
Class/Subclass	Order/Suborder/clade	Family	30 m	150 m	300 m	Total	30 m	150 m	300 m	Total
Acari			14	25	21	60				
Bivalvia	Veneroida	Dreissenidae		11	39	50	6		519	525
Bivalvia	Veneroida	Sphaeriidae			1	1				
Clitellata	Rhychobdellida	Glossiphoniidae	1	6		7	1	1		2
Gastropoda	Hygrophila	Physidae	1	3		4	17			17
Gastropoda	Hygrophila	Planorbidae	1	2	2	5	18	7	1	26
Gastropoda	Littorinimorpha	Rissooidae		4	109	113	1		141	142
Insecta	Coleoptera	Hydrophilidae	2			2				
Insecta	Diptera	Ceratopogonidae	5	7	7	19		2		2
Insecta	Diptera	Chironomidae	1	5	17	23	2	11	193	206
Insecta	Ephemeroptera	Baetidae		7		7				
Insecta	Ephemeroptera	Caenidae	10	1	4	15	3		17	20
Insecta	Hemiptera	Macrovellidae					2			2
Insecta	Hemiptera	Pleidae	14			14	3			3
Insecta	Odonata	Aeshnidae					1			1
Insecta	Odonata	Coenagrionidae	25	11	3	39	5			5
Insecta	Odonata	Corduliidae	1	2		3				
Insecta	Odonata	Libellulidae	6			6				
Insecta	Trichoptera	Hydroptilidae		4	24	28	2	1	65	68
Insecta	Trichoptera	Leptoceridae		55	2	57	2		1	3
Insecta	Trichoptera	Polycentropodidae			1	1				
Malacostraca	Amphipoda	Gammaridae			2	2	1		1	2
Malacostraca	Amphipoda	Hyalellidae	95	139	17	251	220	5	1	226
Malacostraca	Isopoda	Asellidae		2	1	3	9	43	3	55
Oligochaeta			1		9	10	2	2		4
Turbellaria			2	5	2	9	2	1		3

Appendix B:

Fish Monitoring of the Littoral Zone at Shoreline Restoration Sites in Muskegon Lake

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Introduction

Monitoring fish assemblages can provide information on the ecological health of freshwater habitats (Uzarski et al. 2005; Cooper et al. 2018). As such, fish monitoring can be used as a tool for assessing the effects of habitat restoration activities. An extensive shoreline restoration project was completed in Muskegon Lake during 2010 and 2011 (Ogdahl and Steinman 2014), which provided an opportunity to evaluate the ecological outcome of habitat restoration on the littoral fish assemblage. Fish surveys were conducted in Muskegon Lake during 2009-2011 as part of the original shoreline restoration project (Janetski and Ruetz 2015), providing pre-restoration data. The purpose of this survey was to evaluate the response of the littoral fish assemblage post restoration in Muskegon Lake.

Methods

Study sites.—Muskegon Lake is a large drowned river mouth that connects the Muskegon River to Lake Michigan (Steinman et al. 2008; Janetski and Ruetz 2015). Fish surveys were conducted at two restoration sites along the south shoreline: Heritage Landing and Grand Trunk (Table 1; Figure 1). One reference site (NW Reference) was sampled along the north shoreline (Table 1; Figure 1) to represent more natural shoreline conditions. In contrast, much of the wetland along the south shore of Muskegon Lake has been filled and shoreline hardened because of industrial activity and urban development (Alexander 2006; Steinman et al. 2008; Ogdahl and Steinman 2014).

Fish and environmental monitoring.—We sampled fish via fyke netting at each study site during 17-18 July 2018. Fyke nets were set during daylight hours and fished an average of 23.8 h (range = 22.8-24.3 h) at an average water depth of 87.7 cm (Table 2). Three fyke nets (4-mm mesh) were fished at each site following the protocol of Janetski and Ruetz (2015). Briefly, two fyke nets were set parallel to the shoreline with mouths facing each other and connected at the leads. The third fyke net was placed about 30-50 m from the parallel nets, perpendicular to the shoreline, with the net's mouth facing the shoreline. A detailed description of the fyke nets is provided in Breen and Ruetz (2006), and the type of fyke nets we used select for small-bodied fish

(Ruetz et al. 2007). Each fish captured was identified to species, measured (total length), and released in the field; however, some specimens were preserved to confirm identifications in the laboratory. We calculated a fish-based index of biotic integrity (IBI) score for each site using an IBI developed by Uzarski et al. (2005) for Great Lakes coastal wetlands that was modified to better represent anthropogenic disturbance (based on land use and water quality) across a gradient of drowned river mouths (Appendix A). A high score suggests a "healthier" ecosystem, whereas a low score suggests a "degraded" ecosystem.

Environmental conditions were measured at each site. We measured water temperature (°C), dissolved oxygen (mg/L and % saturation), specific conductivity (µS/cm), total dissolved solids (g/L), turbidity (NTU), pH, and chlorophyll *a* (µg/L) in the middle of the water column using a YSI 6600 multi-parameter data sonde near the mouth of each fyke net. We measured water depth at the mouth of each fyke net, organic sediment depth (see Cooper et al. 2007b), and visually estimated the percent cover of submerged aquatic vegetation (SAV) for the length of the lead between the wings of each fyke net.

Results and Discussion

2018 Monitoring.—Environmental conditions were fairly consistent among the three fish sampling sites, although we tended to measure conditions more indicative of better water quality at the reference site compared with the two restoration sites (Table 2). Across the three sites, mean water temperature was 25.6 °C, dissolved oxygen concentration was 9.1 mg/L, specific conductivity was 355 µS/cm, total dissolved solids was 0.231 g/L, turbidity was 3.7 NTU, pH was 8.5, chlorophyll *a* was 8.0 µg/L, % SAV was 62, and organic sediment depth was 1.6 cm (Table 2). These values were within the range commonly recorded during summer in littoral habitats of Muskegon Lake (Bhagat and Ruetz 2011; Janetski and Ruetz 2015). The main difference among sites was that the reference site had the lowest specific conductivity and turbidity (Table 2), which was consistent with better water quality (Uzarski et al. 2005; Janetski and Ruetz 2015). However, percent coverage of SAV also was lowest where we set fyke nets at the reference site (Table 2).

We captured 801 fish comprising 18 species at three sites in Muskegon Lake during July 2018 (Table 3). The most abundant fishes across all sites were yellow perch (35%), largemouth bass (21%), round goby (17%), golden shiner (9%), bluntnose minnow (5%), bluegill (4%), pumpkinseed (3%), and rock bass (2%), which accounted for nearly 96% of the total catch (Table 3). Of the 18 fish species captured in 2018, two species were non-native to the Great Lakes basin (Bailey et al. 2004)—round goby (17%) and white perch (<1%; Table 3).

We observed difference in catch among the three sites in 2018. Catch was highest at the reference site followed by the restoration sites Grand Trunk and Heritage Landing (Table 3). The two most common species in the catch at each site during 2018 were yellow perch (68%) and largemouth bass (17%) at the reference site, golden shiner (29%) and largemouth bass (25%) at Grand Trunk, and round goby (53%) and largemouth bass (23%) at Heritage Landing (Table 3; Figure 2). Most of the fish captured were small (<10 cm TL; Table 3), which is common with the type of fyke net we used for monitoring (Ruetz et al. 2007). With respect to yellow perch and largemouth bass—two species important to recreational anglers (Becker 1983)—the size suggests these were young of the year and juveniles (Becker 1983; Janetski et al. 2013). Finally, we documented evidence of variation in the species composition of the catch among years at the three sites (Figure 2). The inter-annual variation was most obvious at the reference site (Figure 2a) and Heritage Landing (Figure 2b).

Fish-based IBI and assessing habitat restoration.—The IBI scores at the three sites ranged from 37-44 in 2018 (Figure 3) with a mean IBI score of 41 (Figure 4). The mean IBI score in 2018 was above the Muskegon Lake Area of Concern target of 36 (Figure 3) established for two fish-related beneficial use impairments: loss of fish habitat and degradation of fish populations. This is a positive in terms of evaluating the overall health of littoral habitats and fishes in Muskegon Lake, although this optimism should be tempered in that most drowned river mouth wetlands are considered to be at least moderately degraded when compared with coastal wetlands across the Great Lakes basin (Cooper et al. 2018). Among the three sites we sampled in Muskegon Lake during 2018, Grand Trunk had the highest IBI score, Heritage Landing had the lowest, and the reference site was intermediate to the two restoration sites (Figure 3). When we compared the mean IBI score in 2009 and 2010 (i.e., pre-restoration monitoring) with the IBI score for post-restoration monitoring for each site in 2018, we found no difference at the reference site and a modest decline at the two restoration sites (Figure 3). Based on the fish-based IBI, we did not find evidence that the fish assemblage positively responded to the restoration activities (see Table 1) at Heritage Landing and Grand Trunk.

We think the lack of a detectable response of the fish assemblage to habitat restoration in Muskegon Lake—measured based on the IBI score—could be due to (1) the fish sampling effort (i.e., three fyke nets fished annually) may be insufficient to overcome natural temporal (e.g., day to day) variability in the catch. If this is the case, then background “noise” may prevent “signal” detection. We found evidence of variation in the fish assemblage at the reference site over the 4 years of sampling (Figure 2a). For instance, yellow perch was the most common species in the catch during 2018 but was largely absent from the catch in previous years at the reference site (Figure 2a). (2) At Heritage Landing, the location within the site where fyke nets were set differed between pre-restoration (2009-2010) and post-restoration (2018) monitoring because the area sampled pre-restoration was too deep for fyke netting in 2018. (3) The fish-based IBI for drowned river mouths was devised as a crude tool to assess the ecological health of littoral habitats at the spatial scale of the lake. This tool was developed with limited data from drowned river mouths and should be used cautiously. Future assessments of these habitat restoration activities should consider using other fish-based IBIs (e.g., Cooper et al. 2018) or multivariate statistical analyses to examine changes in the fish assemblage pre- versus post-restoration. Although the restoration activities at these sites (see Table 1) may not be of sufficient magnitude to expect a detectable response in the littoral fish assemblage given background levels of variation, fish mobility and sampling effort, cumulatively these habitat restoration efforts should improve the overall health of the ecosystem, especially over longer temporal scales (e.g., decades).

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Table 1. Latitude (N) and longitude (W) for each fish sampling site in July 2018 as well as restoration details for the site (Ogdahl and Steinman 2014). Coordinates are the mean of the three fyke nets set at each site. Site locations are depicted in Figure 1.

Site	Lat (°)	Long (°)	Date of Restoration	Type of Restoration
NW Reference	43.24623	86.31478	NA	Reference site
Heritage Landing	43.23349	86.26202	April 2011	Shoreline & underwater fill removal
Grand Trunk	43.21865	86.29628	June 2010	Shoreline wetland restoration & unnderwater fill removal

Table 2. Mean ± 1 standard error (n = 3) of environmental conditions measured in July 2018. Water depth, water temperature (Temp), dissolved oxygen (DO), specific conductivity (SpecCond), total dissolved solids (TDS), turbidity, pH, chlorophyll *a* (Chl *a*), submerged aquatic vegetation (SAV; %), and organic sediment depth were measured at each fyke net.

Site	Depth (cm)	Temp (°C)	DO (mg/L)	DO (%)	SpecCond (µS/cm)	TDS (g/L)	Turbidity (NTU)	pH	Chl *a* (µg/L)	SAV (%)	Organic sediment depth (cm)
NW Reference	90±2	24.61±0.05	9.31±0.27	111.9±2.9	346±0	0.225±0.000	0.4±0.2	8.56±0.03	4.4±0.1	38±16	1.0±0.0
Heritage Landing	88±2	27.98±0.18	11.91±0.54	152.4±7.3	357±2	0.230±0.002	9.8±2.3	8.82±0.05	14.1±1.9	75±5	1.0±0.0
Grand Trunk	85±4	24.27±0.07	6.08±0.34	72.8±4.1	362±1	0.235±0.000	0.9±0.1	8.12±0.10	5.5±0.6	73±22	2.7±0.3

Table 3. Number and mean total length (TL; ranges reported parenthetically) of fishes captured by fyke netting at three sites (n = 3 nets/site) in Muskegon Lake during 18 July 2018.

		Grand Trunk		Heritage Landing		NW Reference	
Common name	Scientific name	Catch	TL (cm)	Catch	TL (cm)	Catch	TL (cm)
rock bass	*Ambloplites rupestris*	7	11.9 (2.7-17.8)	5	13.1 (2.7-21.4)	5	12.5 (7.5-21.3)
black bullhead	*Ameiurus melas*	0	--	1	28.4	1	31.1
yellow bullhead	*Ameiurus natalis*	2	4.2 (3.7-4.6)	0	--	0	--
bowfin	*Amia calva*	2	48 (38.1-57.9)	1	66.2	0	--
northern pike	*Esox lucius*	1	68.3	0	--	0	--
banded killifish	*Fundulus diaphanus*	4	7.9 (7.4-8.1)	2	5.2 (3.9-6.5)	1	7.8
pumpkinseed	*Lepomis gibbosus*	3	11.6 (8.3-15.7)	15	9.8 (6.1-16.6)	6	11.1 (6.1-18.4)
bluegill	*Lepomis macrochirus*	0	--	7	8.2 (7.6-9.3)	20	13.9 (6.1-18.3)
longnose gar	*Lepisosteus osseus*	0	--	0	--	1	18.1
smallmouth bass	*Micropterus dolomieu*	13	4.6 (3.8-5.5)	0	--	1	4.8
largemouth bass	*Micropterus salmoides*	64	4.3 (2.5-6.1)	46	4.4 (2.2-24.1)	59	4.7 (3.6-6.7)
white perch	*Morone americana*	1	18.0	0	--	0	--
silver redhorse	*Moxostoma anisurum*	0	--	1	50.1	1	54.2
round goby	*Neogobius melanostomus*	27	6.7 (3.3-8.5)	105	6.5 (2.5-11.3)	2	7.0 (4.7-9.3)
golden shiner	*Notemigonus crysoleucas*	74	4.8 (3.9-5.7)	0	--	0	--
tadpole madtom	*Noturus gyrinus*	1	5.9	0	--	0	--
yellow perch	*Perca flavescens*	31	8.0 (4.7-19.1)	16	8.8 (4.0-18.8)	237	6 (4.2-23.9)
bluntnose minnow	*Pimephales notatus*	22	6.1 (5.5-7.2)	1	7.5	15	6.3 (5.6-7.4)
	Total	252		200		349	

Figure 1. Map of Muskegon Lake showing the three sites surveyed for fishes. The latitude and longitude for each site is reported in Table 1.

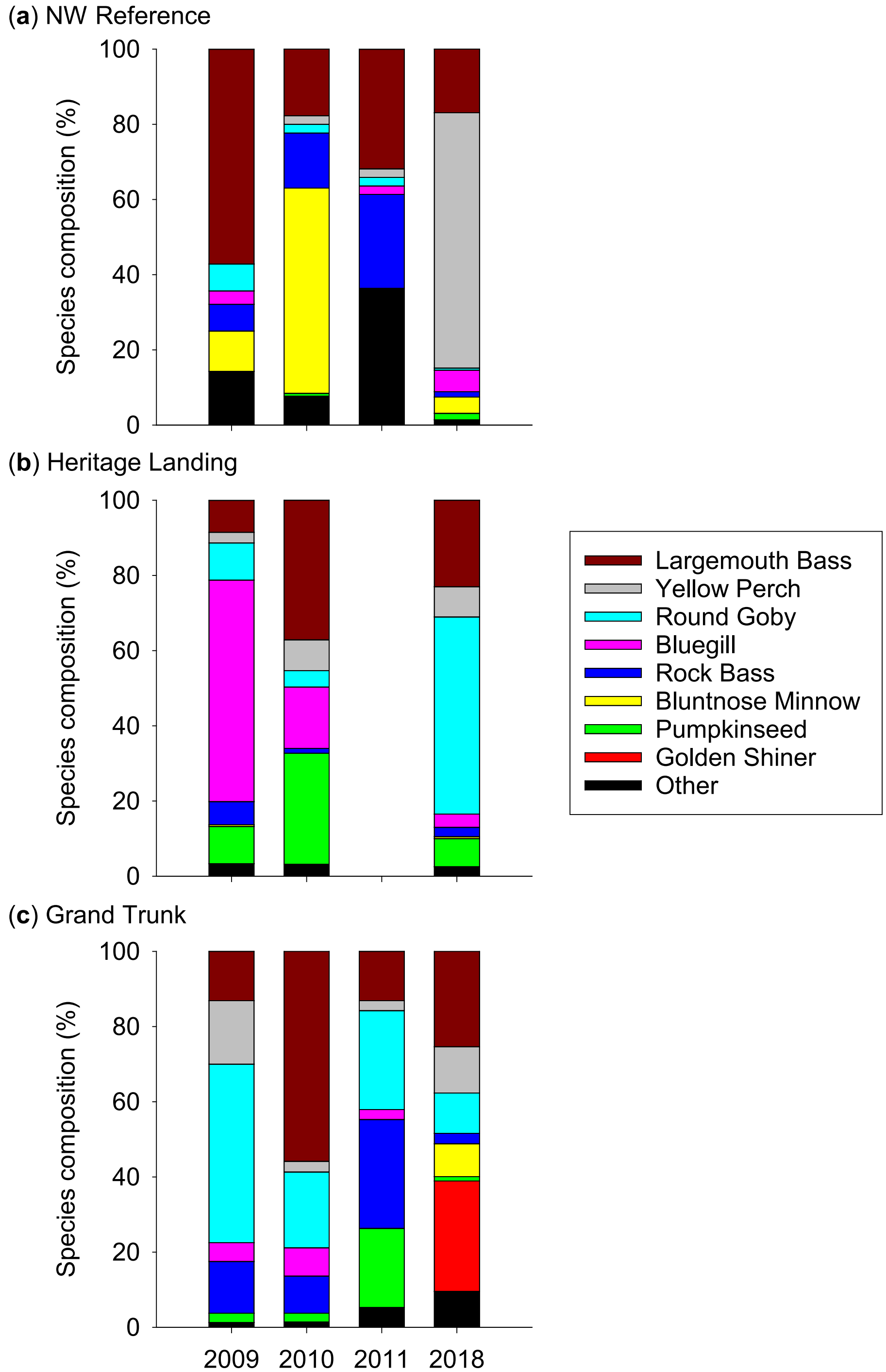

Figure 2. Fish species composition in the catch at three sites in Muskegon Lake over four years: (**a**) NW Reference, (**b**) Heritage Landing, and (**c**) Grand Trunk. Pre-restoration monitoring was conducted during 2009-2010 and post-restoration monitoring in 2011 and 2018 at the two restoration sites (i.e., Heritage Landing and Grand Trunk). "Other" includes all fish species not listed in the legend. Three fyke nets were fished at each site. The number of fish captured varied among sampling events (Appendix B).

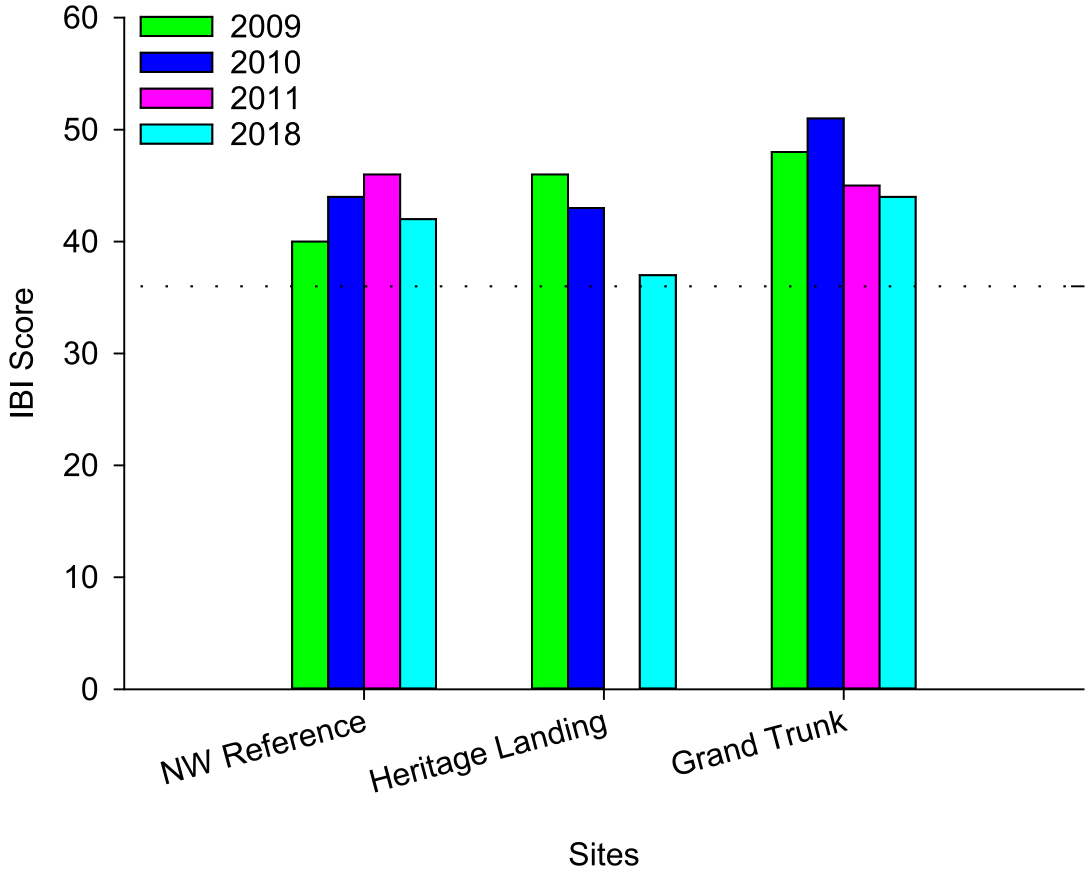

Figure 3. Scores from the fish-based index of biotic integrity (IBI) for three sampling sites in Muskegon Lake. The dashed line represents the numerical delisting target of 36 for the Muskegon Lake Area of Concern (Appendix A). Note that Heritage Landing was not sampled in 2011 due to dredging at the site.

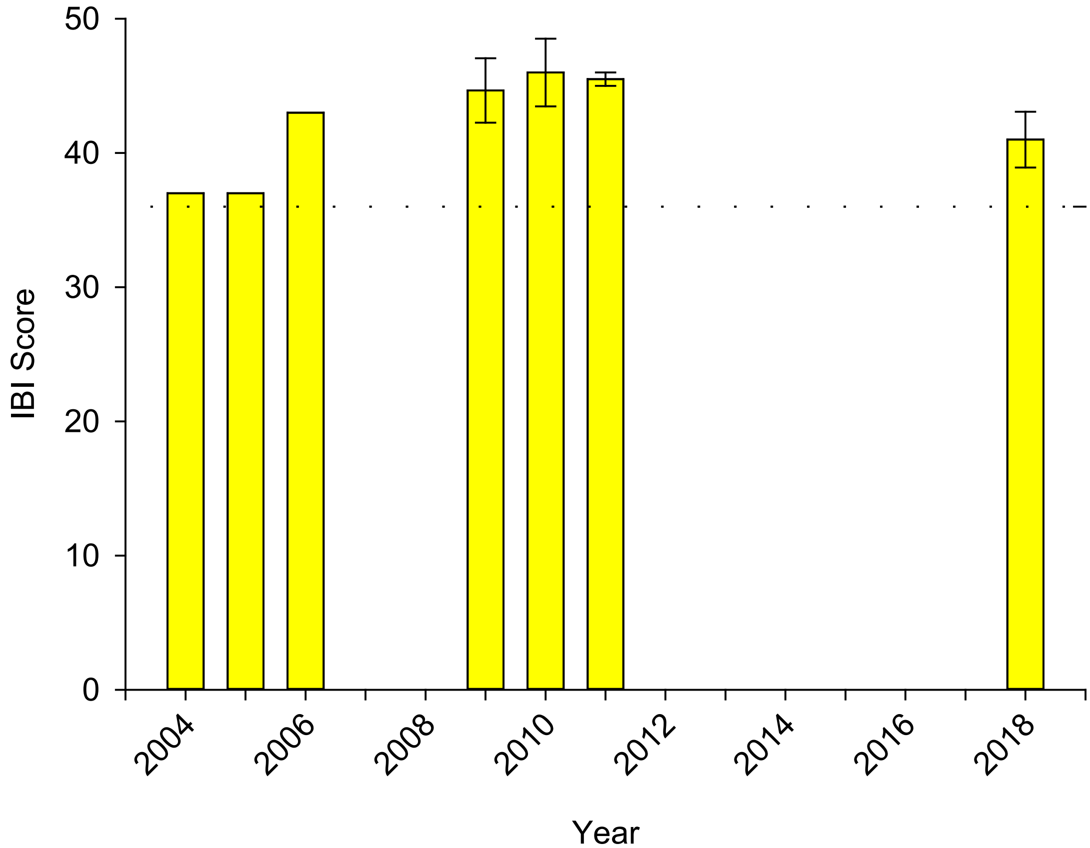

Figure 4. Scores from the fish-based index of biotic integrity (IBI) for Muskegon Lake. The dashed line represents the numerical delisting target of 36 for the Muskegon Lake Area of Concern (Appendix A). Bars are missing for years without fish data. The IBI scores calculated for 2004-2006 were based on one sampling site (see Cooper et al. [2007a] for location of site with submerged aquatic vegetation) that was not part of fish sampling in later years. Mean values (± 1 standard error) were reported for 2009 (n = 3 sites), 2010 (n = 3 sites), 2011 (n = 2 sites), and 2018 (n = 3 sites) based on data for the three sites that were the subject of this report.

Appendix A

We provide additional details regarding the development of a fish-based index of biotic integrity (IBI) used in this report as well as a description of how the IBI was used to set a delisting target for two beneficial use impairments (BUIs; loss of fish habitat and degradation of fish populations) in the Muskegon Lake Area of Concern (see Ruetz [2011] for additional details).

A multi-metric index—termed IBI—was used to set quantitative delisting targets for Muskegon Lake based on annual fish-sampling records collected by the Annis Water Resources Institute (AWRI) in 2004-2006. The IBI approach is widely used across the United States to monitor water quality. Fish are integrators of the overall habitat and water quality; fish also respond to both episodic and cumulative anthropogenic disturbances in an ecosystem. Fish sampling for calculating IBI scores only was required annually because the fish themselves are integrators of time (i.e., the fish assemblage is there continuously). A fish-based IBI can be used to address questions concerning both fish populations and habitat because the IBI is an indicator of both fish community health and overall ecological health of the water body.

A typical IBI includes metrics such as number and composition of species sampled, focuses on indicator species that are particularly sensitive to water quality and habitat alterations, and considers groups of organisms that have similar feeding modes. Once the sampling is complete, a "score" is calculated for each metric in the IBI. The final IBI score is the total of all metrics and is indicative of ecosystem health. A high score suggests a "healthier" ecosystem, whereas a low score is indicative of a "degraded" ecosystem.

The IBI used for setting delisting targets in Muskegon Lake is modified from a fish-based IBI developed for Great Lakes coastal wetlands (Uzarski et al. 2005). The IBI developed by Uzarski et al. (2005) was modified to better represent anthropogenic disturbance (based on land use and water quality) across a gradient of drowned river mouth lakes. The modified, fish-based IBI consisted of 11 metrics (Table A1). A revised fish-based IBI was recently published by Cooper et al. (2018) for Great Lakes coastal wetlands, which could be considered in future assessments.

At least three pieces of evidence suggested that fish populations and, therefore, habitat were no longer severely degraded in Muskegon Lake at the time the target was developed prior to 2009 (Ruetz 2011). First, the fish-based IBI scores calculated based on data collected during 2004-2006 suggested that the ecosystem health of Muskegon Lake was comparable to Pentwater Lake, a drowned river mouth lake that did not suffer the types of severe environmental degradation experienced by Muskegon Lake. Second, the 1987 Remedial Action Plan noted that Muskegon Lake experienced marked improvements in water and habitat quality, including an excellent fishery for numerous fish species, following the construction of a wastewater treatment system. Finally, assessments by the Michigan Department of Natural Resources suggested that Muskegon Lake supported good fishing for several fish species with self-sustaining populations (O'Neal 1997; Hanchin et al. 2007). Therefore, the proposed target for delisting the loss of fish habitat and degradation of fish populations BUIs in Muskegon Lake was to maintain or improve the lake's ecosystem health over a 3-year time span beginning in 2009. The numerical target was set as the average IBI score of ≥36, which was determined based on the mean IBI score during 2004-2006 minus one standard deviation. This target was achieved based on sampling during 2009-2011 (Figure 3).

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Table A1. Metrics for fish-based index of biotic integrity (IBI) for drowned river mouths. The IBI is modified from Uzarski *et al*. (2005). Fish sampling should be conducted with fyke nets (Cooper *et al*. 2007a) at shallow (depth ≤1 m) sites with submerged aquatic vegetation. At least three fyke nets should be fished at each site. The catch of fish is then standardized across nets at a site to calculate IBI scores.

Preliminary Drowned River Mouth Lake IBI – SAV habitat only

1. Percent omnivore abundance:
   >70% score = 0 | 50 to 70% score = 3 | <50% score = 5

2. Percent piscivore richness:
   <25% score = 0 | 25 to 35% score = 3 | >35% score = 5

3. Percent carnivore (insectivore+piscivore+zooplanktivore) richness:
   <70% score = 0 | 70-80% score = 3>80% score = 5

4. Smallmouth bass (*Micropterus dolomieu*) mean catch per net-night:
   0 score = 0 | >0 to 5 score = 3 | >5 score = 5

5. Insectivorous Cyprinidae richness:
   >3 score = 0 | >1 to 3 score = 3 | 0 to 1 score = 5

6. Percent Centrarchidae abundance:
   0-30 score = 0 | >30 to 60 score = 3 | >60 to 80 score 5 | >80 score = 7

7. Centrarchidae richness:
   0 to 1 score = 0 | >1 to 3 score = 3 | >3 score = 5

8. Mean evenness:
   <0.2 score = 0 | 0.2 to 0.6 score = 3 | >0.6 score = 5

9. Rock Bass (*Ambloplites rupestris*) catch per net-night:
   0 to 1 score = 0 | >1 to 5 score = 3 | >5 score = 5

10. Bluegill (*Lepomis macrochirus*) abundance per net-night:
    0 to 3 score = 0 | >3 to 20 score = 3 | >20 to 30 score = 5 | >30 score = 7

11. *Lepomis* catch per net-night:
    >50 score = 0 | >20 to 50 score= 3 | >5 to 20 score = 5 | 0 to 5 score = 7

Table B1. Number of fish captured in three fyke nets fished at each site (NW Reference, Heritage Landing, and Grand Trunk) over four years. No sampling was conducted at Heritage Landing in 2011.

Year	NW Reference	Heritage Landing	Grand Trunk
2009	28	212	160
2010	130	159	213
2011	44	--	38
2018	349	200	252