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LAKE ERIE BENTHOS SURVEY COOPERATIVE SCIENCE AND MONITORING INITIATIVE 2019

Technical Report

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TECHNICAL REPORT

LAKE ERIE BENTHOS SURVEY

COOPERATIVE SCIENCE AND MONITORING INITIATIVE 2019

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COOPERATIVE SCIENCE AND MONITORING INITIATIVE 2019

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CHAPTER 1. MAJOR FINDINGS FROM THE CSMI BENTHIC MACROINVERTEBRATE SURVEY IN LAKE ERIE IN 2019 WITH AN EMPHASIS ON LONG-TERM TRENDS IN BENTHIC COMMUNITY

INTRODUCTION

In this report, we present results of a benthic survey of Lake Erie conducted as part of the United States Environmental Protection Agency (U.S. EPA) Great Lakes National Program Office (GLNPO) Great Lakes Biology Monitoring Program (GLBMP). The benthic monitoring component of GLBMP includes sample collections from long-term monitoring stations (9 - 16 depending on the lake) sampled every year for each of the five Great Lakes and a much more intensive lake-wide survey conducted on each lake every 5 years as part of the Cooperative Science and Monitoring Initiative (CSMI). Consistent with the sampling scheme of previous CSMI benthic surveys, a lake-wide benthic survey was conducted in 2019 at 77 stations in Lake Erie to assess the status of the benthic macroinvertebrate community. The primary focus of this survey was the status of benthic community, including the invasive zebra mussel (*Dreissena polymorpha*) and quagga mussel (*D. rostriformis bugensis*) in comparison with historic data.

This report contains detailed descriptions of benthic communities in Lake Erie from 1930 to 2019, including information on sampling design (station locations, sampling and laboratory procedures) and the taxonomy and abundance of benthic invertebrates. Primary information (number and biomass of each taxon in each replicate sample) for the 2019 sampling year can be requested from U.S. EPA GLNPO. Detailed analysis of results for this study are provided in Karatayev et al. (2021a) and Karatayev et al. (in preparation).

Although all Great Lakes suffered negative consequences from anthropogenic eutrophication, pollution, and overfishing, Lake Erie, being the shallowest and most productive, was perhaps the most affected (Beeton, 1965; Makarewicz and Bertram, 1991; Reutter, 2019). The degradation of Lake Erie reached a maximum in the 1960s and 1970s, when the lake was declared the “North America’s Dead Sea” (Beeton, 1965; Sweeney, 1993, 1995). In 1969, the Cuyahoga River caught fire and similar fires occurred in the Detroit and Buffalo areas (Reutter, 2019). The burning rivers and the "dead" lake were the major events forcing the Federal government to step in and to deal with water pollution. In 1972, Congress passed the Clean Water Act that tightened regulations on industrial dumping. The Great Lakes Water Quality Agreement (GLWQA) was signed in 1972 to coordinate the actions of Canada and the U.S. "…to restore and maintain the chemical, physical, and biological integrity of the Waters of the Great Lakes". Under this binational agreement, extensive measures were undertaken to reduce and eliminate industry discharge, including bans on the sale of phosphorous detergents, and improvements of wastewater treatment (Dolan, 1993; Sweeney, 1993). These actions led to a dramatic improvement in Lake Erie water quality (Sweeney, 1995), the impacts of which were evident across various aquatic communities, including phytoplankton (Makarewicz, 1993) and benthos (Krieger and Ross, 1993; Schloesser et al., 1995).

The improvement in the water quality of Lake Eire and associated rivers, however, has coincided with a dramatic increase in the number of successful invasions of exotic species, preventing restoration of the native communities (Mills et al., 2003). Lake Erie became the hot spot for exotic species introductions and experienced strong impacts from aquatic invasions. It was also the first waterbody in North America where two especially aggressive freshwater invaders, exotic bivalves *Dreissena polymorpha*, the zebra mussel (Carlton, 2008), and *D. rostriformis bugensis*, the quagga mussel (Mills et al., 1993), were detected. The round goby (*Neogobius melanostomus*), another Ponto-Caspian fish invader, was first reported near Cleveland in 1994 and had spread throughout the lake by 1998 (Johnson et al., 2005).

Lake Erie has the longest history of benthic studies among the Great Lakes (Wright, 1955; Carr and Hiltunen, 1965; Schloesser et. al., 1995, 2017; Manny and Schloesser, 1999). Several studies analyzed the long-term dynamics of benthos in various basins (Britt et al., 1980; Schloesser et al., 2017), or in the last decades (Dermott, 1994; Burlakova et al., 2014). However, to date, no studies have followed the dynamics of benthos for the whole studied period, and none have investigated major factors that impacted benthic communities in the entire lake. In this study, we compare results of our 2019 lake-wide survey with historical data to examine long-term changes in the benthic community of all three basins of Lake Erie.

METHODS

2019 sampling protocol

In 2019, a total of 249 benthic samples were collected at 77 stations, including 55 stations sampled aboard R/V *Lake Guardian* in July during the Lake Erie Cooperative Science and Monitoring Initiative (CSMI https://www.epa.gov/great-lakes-monitoring/cooperative-science-and-monitoring-initiative-csmi) benthic survey and 10 stations during the U.S. EPA Great Lakes Biology Monitoring Program Long-Term

Monitoring (LTM, https://www.epa.gov/great-lakes-monitoring) summer survey in August using a Ponar grab (sampling area 0.0523 m^2) (Appendix). Three shallow stations (973, DO2, ER03) in the western basin were sampled by a NOAA small vessel on July 11 (Fig. 1).

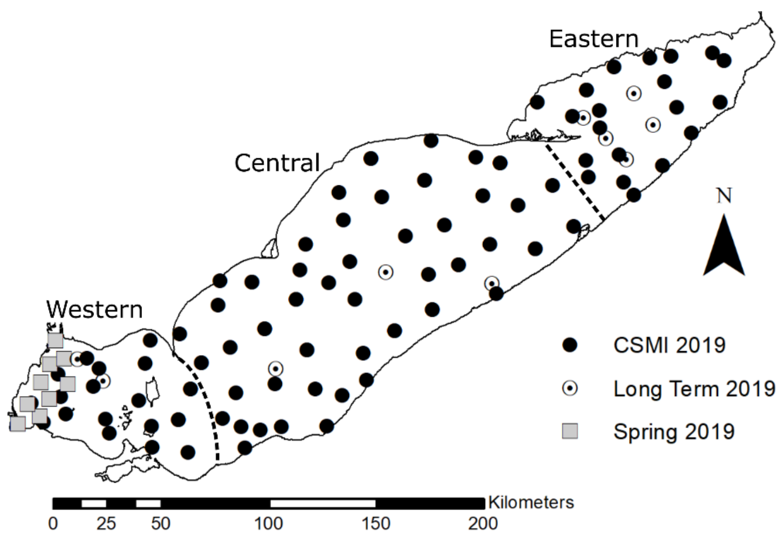

Figure 1. Location of CSMI stations (black circles) and Long-term Monitoring stations (open circles) stations sampled in July, August, and April (grey squares) in Lake Erie in 2019.

An additional 25 stations were sampled aboard the R/ V *Lake Guardian* in July only for the assessment of the distribution and population size of *Dreissena.* Nine more stations in the west basin were sampled on April 24, 2019, abord SUNY Buffalo State's R/V *John J Friedhoff* using a petit Ponar (sampling area 0.0231 m^2) (Appendix). These 9 stations (3D, 8D, 15D, 2L, 6L, 1M, 7M, 8M, and 4R) were sampled consistently over the last 90 years (see detail description below). All field operations were conducted according to the US EPA Standard Operating Procedures for Benthic Invertebrate Field Sampling SOP LG406 (US EPA, 2018). Three replicate samples were collected from each station to determine benthic species richness, density (number of individuals per m^2) and wet biomass (g/m^2). All samples collected in 2019 were elutriated through a 500 µm mesh sieve and preserved with neutral buffered formaldehyde with Rose Bengal stain to a final formalin concentration of 5 - 10% (Karatayev et al., 2021a).

Details of laboratory sample processing are described in Standard Operating Procedure for Benthic Invertebrate Laboratory Analysis SOP LG407 (US EPA, 2015) and in Burlakova et al. (2021). In brief, all benthic invertebrates were picked out of samples under low magnification using a dissecting microscope. All *Dreissena* were identified to species, counted, and measured using a digital caliper (0.01

mm), after which all mussels in each replicate were combined into 5 mm size groups and weighed with shells to the nearest 0.0001 g after being blotted dry on absorbent paper. Other invertebrates (Amphipoda, Chironomidae, Oligochaeta, Mollusca) were identified, counted, and weighed after being blotted dry. Adult oligochaetes were identified to species; immatures were taken to the lowest taxonomic level possible, usually family, and included in abundance estimates. Oligochaete fragments, though counted, were excluded from density but used for biomass estimates because they could be weighed but not attributed to individuals. Density and biomass of immature oligochaetes (in cocoons) were recorded but were not considered in density nor in biomass. Other invertebrates were identified to species or genus, when possible. Meiobenthic organisms (e.g. Nematoda, Hydracarina, Ostracoda, benthic Cladocera, Copepoda, and Harpacticoida) were not recorded in our samples and excluded from historical data, if present.

Historic data

Western basin

A total of 17 benthic surveys were conducted in the western basin of Lake Erie between 1929 and 2019 (Table 1). These surveys varied in the number of stations sampled (8-63), number of sampling events (1-24 cruises) and duration (from a few days to three years, Karatayev et al., in preparation). Surveys also varied in sampling gear (Ekman, Petersen, Franklin-Anderson, Shipek, and Ponar grabs), the mesh size of the sieve used to wash sediments (180 - 760 µm), and the level of taxonomic identification and taxa reported (from reporting only Oligochaeta and *Hexagenia* to reporting all species collected, Table 1).

Table 1. Lake-wide (basin-wide) benthic surveys conducted in Lake Erie from 1929-2019. Surveys marked with shading were omitted from the analysis due to small sample sizes or incompatible methods.

Sampling Date	Number of stations	Sampler	Mesh size, µm	Taxonomic resolution	Author
Western Basin					
1929 (June-September)	14(13)*	Ekman	500	Groups, genera	Wright, 1955
1930 (June-September)	79(67)*	Petersen	500	Groups, genera	Wright, 1955
1961 (May-June)	40	Petersen	600	Groups, genera, species	Carr and Hiltunen, 1965
1963-1965	11	Franklin-Anderson	500-600	Groups, genera, species	Barton, 1988
1967 (April-August)**	42	Ponar	650	Species	Veal and Osmond, 1968
1970 (July-August)	12	Ponar	760	Groups	Schelske and Roth, 1973

Sampling Date	Number of stations	Sampler	Mesh size, µm	Taxonomic resolution	Author
June 1973 - December 1975 Only 1973 data available	13	Ponar	425	Species	Herdendorf, 1979 Britt et al., 1980
1979 (October)	52	Shipek	153	Species	Dermott, 1994
1982 (June)	40	Ponar	600	Groups, genera	Manny and Schloesser, 1999
1992 (July-August)	9(1)***	Ponar	580/180	Species	Dermott personal communication
1993 (September)	9(2)***	Ponar	250	Groups, genera	Dermott and Dow, 2008
1993 (June)	47****	Ponar	600	Species	USGS Great Lakes Science Center, Ann Arbor, MI
1998 (April-June)	7	Ponar	250	Groups, genera	Dermott and Dow, 2008
2003 (April-May)	60	Ponar	600	Species	USGS Great Lakes Science Center, Ann Arbor, MI
2010 (March-April)	31****	Ponar	600	Species	USGS Great Lakes Science Center, Ann Arbor, MI
2009-2012	13	Ponar	500	Species	Burlakova et al., 2014
2014 (April, August)	52(1)***	Ponar	500	Species	Our data
2019 (April, July, August)	26(3)***	Ponar	500	Species	Our data
Central Basin					
1963-1965	45	Franklin-Anderson	500-600	Groups, genera, species	Barton, 1988
June 1973 - December 1975. Only 1973 data available	36	Ponar	425	Species	Herdendorf, 1979; Britt et al., 1980
1978 (October)	52	Shipek	153	Species	Dermott, 1994
1979 (October)	17	Shipek	153	Species	Dermott, 1994
1992 (July-August)	22	Ponar	580/180	Species	Demott, personal communication
1993 (September)	20(4)***	Ponar	250	Groups, genera	Dermott and Dow, 2008
1998 (April-June)	9	Ponar	250	Groups, genera	Dermott and Dow, 2008
2009-2012	30	Ponar	500	Species	Burlakova et al., 2014
2014 (August)	31(11)***	Ponar	500	Species	Our data
2019 (July-August)	32(17)***	Ponar	500	Species	Our data
Eastern Basin					
1963-1965	27	Franklin-Anderson	500-600	Groups, genera, species	Barton, 1988
1973-1975	26	Ponar	600	Species	Mullin, 1980
1976 (September)	25	Ponar	600	Species	GLL, 1978

Sampling Date	Number of stations	Sampler	Mesh size, µm	Taxonomic resolution	Author
1978 (October)	37	Shipek	153	Species	Dermott, 1994
1992 (July-August)	15	Ponar	580/180	Species	Demott, personal communication
1993 (September)	10	Ponar	250	Groups, genera	Dermott and Dow, 2008
1998 (April-June)	13(15)***	Ponar	250	Groups, genera	Dermott and Dow, 2008
2009-2012	21	Ponar	500	Species	Burlakova et al., 2014
2014 (August)	28(15)***	Ponar	500	Species	Burlakova et al., 2017
2019 (July-August)	19(5)***	Ponar	500	Species	Our data

* The number of stations where samples were collected successfully (given in parenthesis) and data are available

**No primary data available

***The number of additional stations where samples were collected for *Dreissena* only (given in parenthesis)

**** No data for *Dreissena* spp.

Central and eastern basins

A total of 10 benthic basin-wide surveys were conducted during 1963-2019 in each of the central and eastern basins (Table 1). As we mentioned above, data collected by the Great Lakes Institute, University of Toronto in 1963-1965 and by the GLC in 2009-2012 were excluded from the analysis due to incompatible methods. In 1973 and 1975, the central basin was repeatedly (4-5 times per year) surveyed by Britt et al. (1980) at 36 stations. Although we were not able to locate primary data for 1974 and 1975, data for 1973 were reported by Herdendorf (1979). In 1973-1976 the eastern basin was surveyed by Flint and Merckel (1978) at 26 stations 1-3 times per year, however we were able to locate only averaged data for 1973-1975 (Mullin, 1980) and another set of data reported by species and stations averaged for all surveys conducted in 1976 (GLL, 1978 report) (Table 1). Another survey conducted in 1998 had fewer than 10 stations sampled (Dermott and Dow, 2008) and was thus excluded from the analysis (Table 1).

The weight of benthic invertebrates was measured only in a few surveys and different units were used to report biomass, including volume wet ml/sample in 1962-1965 (Barton, 1988), dry weight in 1978, 1978 (Dermott, 1994), and wet weight in 2009-2012, 2014, and 2019 (Burlakova et al., 2014, 2017). To reconstruct the benthic wet biomass for all years except 2014 and 2019, we multiplied density of the major taxa (Oligochaeta, Chironomidae, Sphaeriidae *Dreissena polymorpha* and *D. r. bugensis,* and *Hexagenia*) by their individual wet weights. Individual wet weights were estimated separately for each taxon and each basin by dividing taxon average biomass for 2019 by their average density. For 2014 data, we used actual measured biomass because it was available at the same resolution as 2019 data.

RESULTS AND DISCUSSION

A total of 107 species and higher taxa of benthic macroinvertebrates were found in Lake Erie in 2019, and the most diverse lake-wide were Oligochaeta (40 taxa), Chironomidae (27), and Gastropoda (17) (excluding unidentified taxa). Species with the highest occurrence included chironomid *Procladius* spp. (found in 91% of all benthic samples), oligochaete *Limnodrilus hoffmeisteri* (86%) followed by exotic bivalve *Dreissena r. bugensis* (75%), chironomid *Chironomus* sp. (71%), bivalve *Pisidium* spp. (60%), and oligochaete *Limnodrilus profundicola* (51%). All other species were found in less than 50% of the samples.

Oligochaeta were the most abundant taxa comprising 61% of lake-wide benthos densities, followed by Chironomidae (13%), quagga mussels (11%), and by Sphaeriidae (10%) (Table 2). Quagga mussels dominated lake-wide benthos by biomass (94% of total wet biomass) (Table 2). The rest of the benthic biomass was mainly represented by zebra mussels (2%), Oligochaeta (2%), and Chironomidae (1%).

The three basins of Lake Erie differed significantly by environmental parameters ($R = 0.45$, $P = 0.001$, 1-way ANOSIM), and the largest difference was found between the eastern and western basins ($R = 0.80$, $P = 0.001$), while the central basin was more similar to the others ($R < 0.40$, $P = 0.001$) (Fig. 2). Eastern, central, and western basin stations mostly differed along the first PC axis that positively correlated with conductivity, surface remote chlorophyll, turbidity, and temperature ($0.37 < r < 0.43$), and negatively correlated with depth and oxygen ($r = -0.41$, $r = -0.35$, respectively). Sediment nutrient concentrations correlated positively with PC2 ($0.28 < r < 0.67$) and were higher in the central basin.

The difference among three basins of Lake Erie in morphometry, nutrient load, and oxygen regime determined differences in benthic communities (Table 2, Fig. 2). The highest diversity of benthic invertebrates was found in the central basin (75 species and higher taxa), including 35 species and higher taxa of Oligochaeta, 13 Chironomidae and 10 Gastropoda. Similar species richness was found in the shallow, warm, and most productive western basin (74) with 22 species of Oligochaeta, 16 – Chironomidae, 13 species of Gastropoda, and 6 species of Hirudinea. The least diverse was the eastern basin (55 taxa), where Oligochaeta were represented by 23 species, Chironomidae – by 19, and Gastropoda – by only 2 species.

The highest basin-wide average benthos density in 2019 was found in the central basin, followed by the eastern and western basins. *Dreissena* spp. dominated benthos densities only in the western basin (31%), while oligochaetes were the most dominant group in both eastern (63%) and central (68%) basins. *Dreissena*, however, was the dominant species in terms of wet biomass in all basins, where its relative proportion increased from 81% in central basin to 89% in western basin and to >99% in the eastern basin.

Excluding dreissenids, the highest benthos density and biomass was recorded in the central basin, while the lowest biomass was recorded in eastern basin.

There was a significant difference in benthic communities among basins both with and without consideration of *Dreissena* (with *Dreissena*: R = 0.75, P = 0.001; without *Dreissena*: R = 0.74, P= 0.001, 1-way ANOSIM, Fig. 2). The largest differences were found between communities in the eastern and western basins (R = 0.94, P = 0.001, pairwise tests after ANOSIM), but differences between central and western basins (R = 0.76) and eastern and central basins (R = 0.54) were significant as well (P = 0.001).

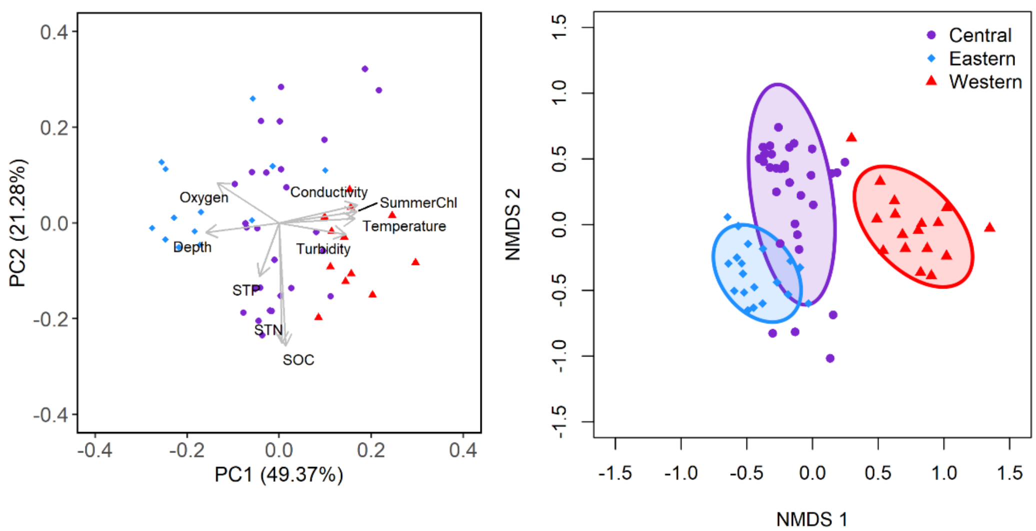

Figure 2. PCA plot of environmental parameters (left) and NMDS ordination plot of benthic community structure (right) of Lake Erie in 2019. Environmental parameters included depth (m), bottom temperature (°C), bottom dissolved oxygen (mg/L), bottom beam attenuation (as a measure of turbidity, 1/m), bottom specific conductance (µS/cm), and the surface remote-sensed summer chlorophyll a (µg/L). Sediment characteristics included total phosphorus (STP; mgP/g), organic carbon (SOC; mgC/g), and total nitrogen (STN; mgN/g). Vector length is proportional to loading of each environmental parameter. All parameters were centered and scaled prior to PCA analysis. The first three PC axes described 88% of variance in parameters. NMDS ordination based on Bray-Curtis similarities (using 4th root transformed density), stress = 0.15. There were significant differences in environmental parameters and benthic community structure among basins (ANOSIM, P = 0.001).

Table 2. Average (± standard error) density (ind./m^2) and wet biomass (g/m^2) of major taxonomic groups of benthic invertebrates collected at 68 all-benthos stations in Lake Erie in summer 2019 averaged by basin and lake-wide. *Dreissena* spp. was collected at additional 25 "*Dreissena*-only" stations (provided in parentheses). "Others" includes Ceratopogonidae, Hydrozoa, Isopoda, Nemertea, and Trichoptera. Percentages of each taxa of total benthos and of *Dreissena*-free benthos are provided in parentheses. *Dreissena* spp. average density and biomass were calculated separately for all-benthos stations as well as for all stations together (all-benthos and additional *Dreissena*-only stations, in bold in parentheses).

Density (ind./m^2):

Taxa	Western	Central	Eastern	Lake-wide
Number of Stations	*17 (3)*	*32 (17)*	*19 (5)*	*68 (25)*
Amphipoda	27±7	29±23	2±1	21±11
Chironomidae	525±161	1151±198	293±182	754±122
D. polymorpha	496±189 **(515±169)**	16±6 **(27±16)**	0±0 **(6±4)**	132±53 **(126±42)**
D. r. bugensis	285±98 **(270±85)**	470±296 **(357±196)**	1084±215 **(1047±177)**	596±157 **(516±118)**
Gastropoda	169±47	25±6	1±1	54±14
Hexagenia	105±21	0±0	0±0	26±7
Hirudinea	112±30	83±28	0±0	67±16
Oligochaeta	628±161	5978±709	2972±519	3800±453
Others	20±5	410±193	10±5	201±93
Platyhelminthes	23±13	106±54	19±9	61±26
Polychaeta	1±1	34±27	0±0	16±13
Sphaeriidae	128±45	1229±204	0±0	610±119
All benthos w/o *Dreissena*	1737±331	9046±1065	3297±530	5612±660
All benthos	2518±434	9532±1254	4381±621	6339±724

Biomass (g/m^2):

Taxa	Western	Central	Eastern	Lake-wide
Amphipoda	0.052±0.019	0.042±0.027	0.003±0.002	0.034±0.014
Chironomidae	1.322±0.509	6.812±1.356	0.232±0.090	3.601±0.745
D. polymorpha	24.76±10.05 **(22.47±8.64)**	1.84±0.91 **(1.29±0.60)**	0.00±0.00 **(0.75±0.51)**	7.06±2.79 **(5.71±2.07)**
D. r. bugensis	40.85±13.34 **(34.85±11.75)**	79.89±45.93 **(94.93±46.49)**	880.87±196.30 **(917.95±207.84)**	293.93±73.21 **(294.40±69.74)**
Gastropoda	1.017±0.207	0.208±0.057	0.019±0.019	0.357±0.075
Hexagenia	2.900±0.646	0.001±0.001	0.000±0.000	0.726±0.220
Hirudinea	0.308±0.067	0.184±0.052	0.004±0.004	0.164±0.032
Oligochaeta	1.670±0.790	8.576±1.463	2.541±0.444	5.163±0.821
Others	0.020±0.009	0.490±0.243	0.003±0.002	0.237±0.117
Platyhelminthes	0.040±0.029	0.067±0.026	0.005±0.003	0.043±0.014
Polychaeta	0.000±0.000	0.009±0.008	0.000±0.000	0.004±0.004
Sphaeriidae	0.602±0.374	2.500±0.416	0.001±0.001	1.327±0.255
All benthos w/o *Dreissena*	7.930±1.072	18.889±2.685	2.807±0.452	11.656±1.549
All benthos	73.538±21.437	100.621±44.976	883.678±196.406	312.645±72.474

LONG-TERM TRENDS IN LAKE ERIE BENTHIC COMMUNITY

Western basin

Historically, the benthic community of the western basin was dominated by larvae mayfly *Hexagenia* spp. (Wright and Tidd, 1933; Shelford and Boesel, 1942; Britt, 1955; Wright, 1955; Manny, 1991, Table 3, Fig. 3). During the first basin-wide study in 1929-1930, eutrophication and accumulation of organic matter in sediments were still local. In 1930, oligochaete density, the most abundant taxa in the basin, was very low and coincided with high densities of mayflies *Hexagenia.* Drastic degradation of water and sediment quality in the following decades resulted in increased density of pollution-tolerant tubificids, chironomids, and sphaeriids, while pollution intolerant species (e.g. mayflies, caddisflies, amphipods) declined (Carr and Hiltunen, 1965; Beaton, 1961, 1969). By 1961 when the second basin-wide survey was conducted, the average density of *Hexagenia* plummeted to 1 ind./m^2, while basin-wide density of oligochaetes increased 7-fold along with their relative abundance in benthic community (Fig. 3, Table 3). Density of chironomids, gastropods and sphaeriids had doubled in 1961, but their relative proportions in benthos had declined. In the next decade (in the 1970s), the density of benthic invertebrates declined substantially, mostly due to the decrease in oligochaetes density, about 2-fold compared to 1961, while density of other taxa did not change substantially (Fig. 3). By 1982 benthic density increased again, compared to 1979, by a factor of 7 and reached the highest density ever reported in the basin. As before, this increase was exclusively due to a strong increase in oligochaete density. By the next survey in 1990s community dominants had shifted: zebra and quagga mussels became important players in the community, while density and relative abundance of oligochaetes declined from 1982 to 2003 by a factor of 15, returning to pre-eutrophication level of the 1930s. *Hexagenia* showed first signs of recovery in 1982 (basin-wide average density 7 ± 4 ind./m^2), and in 2003 reached densities (295 ± 56 ind./m^2) higher than those reported in 1930. *Hexagenia* densities in 2019 were not significantly different from densities in 1930 (Tukey's HSD: $P = 0.99$ following permutational ANOVA: $P < 0.001$).

Analysis of density dynamics based on nine consistently sampled stations revealed a largely similar pattern (Fig. 3). Densities of benthic invertebrates fluctuated 7- to 8- fold between 1930 and 2019. The lowest benthos density was recorded in 1930 (1,737 ind./m^2) but it was increasing in the next decades: 4-fold by 1961 (to 7,008 ind./m^2) and almost 2-fold between 1961 and 1982 (13,211 ind./m^2) which was the highest basin-wide benthos density recorded before the introduction of *Dreissena* spp.

Table 3. Average density of major taxa of benthic invertebrates (mean ± standard error) in the western basin of Lake Erie. For the data sources see Table 1. Average *Dreissena* density in 2002 from Patterson et al. (2005).

Taxa	**1930**	**1961**	**1970**	**1973**	**1979**	**1982**	**1992**	**1993**
Stations sampled	*N = 67*	*N = 40*	*N = 12*	*N = 13*	*N = 52*	*N = 40*	*N =10*	*N =11*
Amphipoda	NA	12±4	55±28	5±5	6±3	5±3		46±9
Chironomidae	137±32	355±46	341±108	544±107	419±42	538±59		416 ± 47
D. polymorpha	0±0	0±0	0±0	0±0	0±0	0±0	839±620	1201±615
D. r. bugensis	0±0	0±0	0±0	0±0	0±0	0±0	2±2	8±8
Gastropoda	66±12	159±45	104±79	51±33	4±2	22±8		
Hexagenia	155±24	1	0±0		1±1	7±4		10±2
Hirudinea	64±16	31±7	51±27	22±5	23±6	13±4		11±2
Oligochaeta	1163±520	5990±1292	2699±724	2893±349	1614±259	12410±2336		5801±2521
Sphaeriidae	307±83	600±117	403±213	231±86	347±114	227±31		
All Benthos	1891	7159±1308	3653±937	3748±423	2414±274	17068±3160		9437
Benthos w/o *Dreissena*	1891	7159±1308	3653±937	3748±423	2414±274	17068±3160		8228±3257

Taxa	**2002**	**2003**	**2004**	**2010**	**2014**	**2019**
Stations sampled	*N = 49*	*N = 60*	*N =87*	*N = 31*	*N = 52*	*N = 26*
Amphipoda		60±27		27±12	221±78	33±7
Chironomidae		353±35		628±69	263±58	556±107
D. polymorpha	270±127	NA	357±88	42±16	369±122	843±270
D. r. bugensis	258±123	NA	1105±177	1349±608	2475±1317	393±118

Taxa	**2002**	**2003**	**2004**	**2010**	**2014**	**2019**
Stations sampled	*N = 49*	*N = 60*	*N =87*	*N = 31*	*N = 52*	*N = 26*
Gastropoda		14±5		141±24	248±120	242±77
Hexagenia		295±56		307±41	234±35	121±29
Hirudinea		14±3		63±11	87±24	88±21
Oligochaeta		1158±133		1924±443	751±210	770±169
Sphaeriidae		91±23		148±58	91±20	104±33
All Benthos		NA		4743±903	3917±NA	3199±NA
Benthos w/o *Dreissena*		2082±187		3351±579	2231±503	1962±251

Between 1982 and 2003 non-dreissenid benthos decreased by 5.3-fold and has fluctuated since: increased 2.7-fold by 2014 and again decreased by 2.9-fold in 2019. Because these 9 stations were not sampled between 1961 and 1982, we cannot confirm the decline in benthos density recorded in 1973-1979 using a larger but less consistent dataset (Fig. 3).

Analysis of benthic biomass revealed even more dramatic changes in the community than the density dynamics (Fig. 3). In 1930, *Hexagenia* alone formed 48% of the whole community biomass, while oligochaetes comprised only 28%. Other common taxa were gastropods (7% of the total wet biomass) and sphaeriids (5%). In 1961 the proportion of major taxa had changed drastically: *Hexagenia* had virtually disappeared, and oligochaetes became the dominant taxa forming 74% of all benthic biomass, followed by Gastropoda and Sphaeriidae. The role of oligochaetes further increased in 1982 and 1993 to > 90%, but then dramatically declined to <20% by 2003. In contrast, *Hexagenia* again became the dominant component in non-dreissenid benthos comprising 69% of the whole biomass in 2003. These changes in benthic biomass coincided with the introduction of zebra and quagga mussels. Since 1992 zebra and later quagga mussels became the solo dominant taxon of the benthic community comprising over 92% of its biomass.

Most recently (2010-2019) the species richness, density, and wet biomass of non-dreissenid benthos have changed and are now more similar to those recorded in the 1930s, suggesting community recovery (Fig. 3). For the first time from 2014 and 2019 oligochaete contribution to native benthos density dropped below 40%, while contribution of amphipods, gastropods, and leeches increased. Biomass-wise, *Hexagenia* once again became the dominant species (37-69% of all non-dreissenid biomass), followed by oligochaetes (20-23%) and chironomids (6-19%). Since 2010 *Hexagenia* density and biomass reached, and in most cases exceeded, 1930 levels, suggesting that population of mayflies is currently stable. Consistently low oligochaetes density in 2003-2019 may indicate a trend toward a more mesotrophic condition in western Lake Erie (Fig. 3). However, low *Dreissena* biomass, along with relatively high density and lack of large mussels during 2010-2019, suggest periodic mass mortality most likely caused by hypoxia (Burlakova et al., 2017; Karatayev et al., 2018a, 2021b) that occurs in the western basin during extensive periods of calm weather (Ackerman et al., 2001; Bridgeman et al., 2006). Changes in *Dreissena* population from 2010-2019, along with the decline in Secchi depth, increase in total phosphorus, and total dissolved phosphorus during 1999-2013 compared to the previous decade (1989-1998, Karatayev et al., 2018b), suggest that de-eutrophication trend in the basin is fragile and can be reversed.

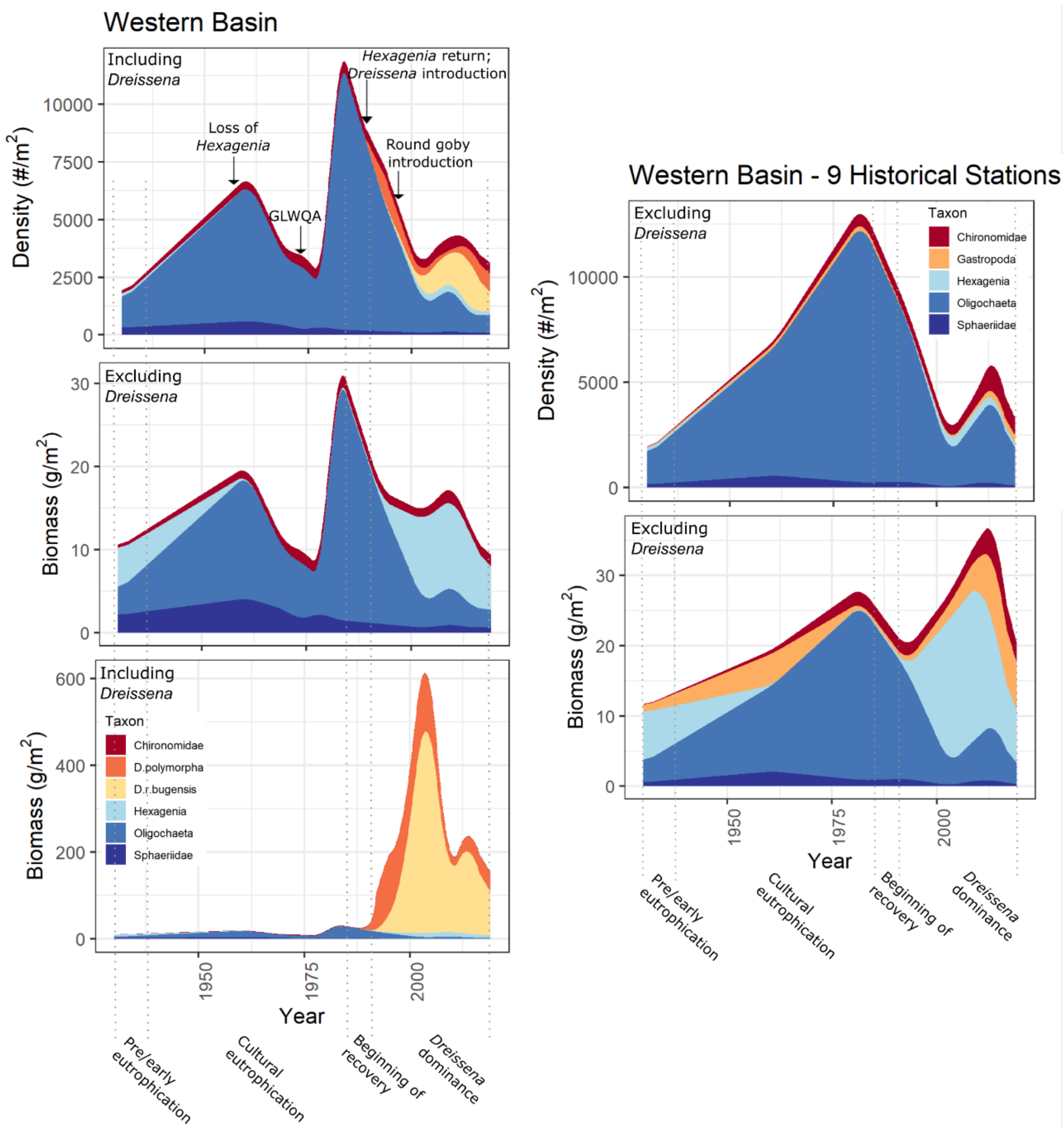

Figure 3. Average densities and biomass of major benthic taxonomic groups in the western basin of Lake Erie in 1930-2019 that were consistently counted for the entire lake with major events highlighted. Missing data were simulated using splines then all data were smoothed using a five-year moving average. Displayed data are additive (stacked). "GLWQA" indicated the Great Lakes Water Quality Agreement.

Central basin

In Lake Erie's central basin, bottom hypoxia is the major driver of benthic community structure, and even the introduction of dreissenids has not changed the major dominant taxa, but rather their density and/or relative abundance (Fig. 4, Table 4). Historically, the central basin has always experienced seasonal hypoxic conditions (Beeton, 1961, 1963; Delorme, 1982), but the extent of hypoxic zone substantially increased in the 1950s and 1960s during the cultural eutrophication and then shrank again after the implementation of phosphorus reduction (Makarewicz and Bertram, 1991; Beeton, 1963; Bertram, 1993; Burlakova et al., 2017). Three major groups of invertebrates – oligochaetes, sphaeriids, and chironomids – routinely contributed >90% of all benthic density in the central basin before the introduction of *Dreissena* spp. (Fig. 4). The lowest total benthic invertebrate densities were recorded in 1973. By the time of the next survey in 1978, benthic density increased by ca. 50% and more than doubled by 1979. In the next 40 years (1979-2019) density of major taxa in the central basin was relatively stable, except for the 1990s, when dreissenid density exceeded 20% of all benthos for a brief time. During the last two surveys, dreissenid density did not exceed 7% of the whole benthos. In contrast to density, chironomids were more important than oligochaetes in non-dreissenid benthic biomass (25-48% of wet biomass) due to the high abundance of large bodied *Chironomus*. Another important taxon was Sphaeriidae, representing 6-23% of benthic biomass excluding dreissenids. Similar to the western basin, after establishment of zebra and later quagga mussels, dreissenids became the major component of benthos in the central basin, forming up to 90-95% biomass during 1990s, but their share declined to 83-84% of the total benthos wet biomass in 2014-2019.

Eastern basin

The deepest and most oligotrophic basin of Lake Erie, which has a hypolimnion that never goes hypoxic due to its large volume and low inputs of suspended solids and nutrients (Kemp et al., 1977; Mortimer, 1987; Karatayev et al., 2018a), is also the least polluted part of the lake. In the 1960s and 1970s, the eastern basin supported deep cold-water oligotrophic benthic crustaceans *Diporeia* and *Mysis relicta* and lumbriculid *Stylodrilus heringianus* (Beeton, 1965, 1969; Cook and Johnson, 1974; Flint and Merckel, 1978, Table 5). Oligochaetes were the dominant group by density during 1973-1976, comprising on average 59-68% of the whole benthos per year, followed by *Diporeia* (13-17%), sphaeriids (8-14%), and chironomids (6%). Other taxa did not exceed 1% of benthic density. Most major taxa in the eastern basin showed significant differences among years, including *D. polymorpha* ($P < 0.001$; $R^2_{adj} = 0.10$), *D. r. bugensis* ($P < 0.001$; $R^2_{adj} = 0.25$), oligochaetes ($P < 0.001$; $R^2_{adj} = 0.12$), and sphaeriids ($P < 0.001$; $R^2_{adj} = 0.29$). Chironomidae, however, remained consistent and did not show a significant difference among years ($P = 0.12$). The next survey was conducted in 1978 and, although a different bottom grab was used (Shipek instead of Ponar) along with a different mesh size (Table 1), data where very much in line with 1973-1976 surveys.

Table 4. Average density of major taxa of benthic invertebrates (mean ± standard error) in the central basin of Lake Erie. For the data sources see Table 1. Average *Dreissena* density in 2002 from Patterson et al. (2005).

Taxa	**1973**	**1978**	**1979**	**1992**	**1993**	**2002**	**2004**	**2014**	**2019**
Stations sampled	*N = 36*	*N = 52*	*N = 17*	*N = 22*	*N = 20 (24)*	*N = 41*	*N =121*	*N = 42*	*N = 32 (49)*
Amphipoda	1±0	4±3	0±0	10±6	169±52			29±26	29±23
Chironomidae	335±68	343±75	436±85	1315±314	983±269			1073±244	1151±198
Diporeia	2±2	3±1	0±0	NA	2±2			0±0	0±0
D. polymorpha	0±0	0±0	0±0	997±604	767±226	25±10	5±2	15±7	27±16
D. r. bugensis	0±0	0±0	0±0	134±83	1980±668	540±200	350±88	593±223	357±196
Gastropoda	8±3	29±22	7±5	12±5	30±15			25±8	25±6
Hirudinea	3±2	10±4	2±2	6±4	4±4			24±8	83±28
Oligochaeta	2531±275	3460±453	7183±1861	4993±892	6935±1341			7856±1284	5978±709
Sphaeriidae	554±78	1098±131	702±205	930±215	579±236			1114±245	1229±204
All Benthos	3519±331	5227±539	8414±1972	8704	11521			11611	9440
Benthos excluding *Dreissena*	3519±331	5227±539	8414±1972	7573±1107	8774±1508			11002±1485	9056±1063

Table 5. Average density of major taxa of benthic invertebrates (mean ± standard error) in the eastern basin of Lake Erie. For the data sources see Table 1. Average *Dreissena* density in 2002 from Patterson et al. (2005).

Taxa	**1974**	**1976**	**1978**	**1992**	**1993**	**1998**	**2002**	**2004**	**2014**	**2019**
Stations sampled	*N = 26*	*N = 25*	*N = 37*	*N = 15*	*N = 10 (10)*	*N = 13 (15)*	*N =17*	*N = 76*	*N =28 (43)*	*N = 19 (24)*
Amphipoda	232±60	76±34	21±13	237±138	2±1	561±328			86±47	2±1
Chironomidae	255±34	430±115	373±100	1319±1088	293±182	1353±606			633±207	293±182
Diporeia	1313±339	1754±556	787±196	90±77	0±0	0±0			0 ± 0	0±0
D. polymorpha	0±0	0±0	0±0	4544±2120	1203	502±390	0±0	0±0	4 ± 3	2±2
D. r. bugensis	0±0	0±0	0±0	1463±484	3615	5284±2071	9481±2710	1622±290	2283±468	1011±181
Gastropoda	NA	130±45	27±11	237±147	1±1	1016±678			3±2	1±1
Hirudinea	NA	67±29	48±14	32±22	0±0	204±155			1±1	0±0
Oligochaeta	4658±1006	9567±3936	3901±609	16926±3912	2972±519	18121±6958			5552±795	2972±519
Sphaeriidae	1104±207	1074±179	425±66	517±257	0±0	182±97			20±19	0±0
All Benthos	7905±1167	14015±3988	6131±723	25776	4354	57757			8842	4314
Benthos excluding *Dreissena*	7905±1167	14015±3988	6131±723	19769±3723	3301±530	51971±12936			6555±887	3301±530

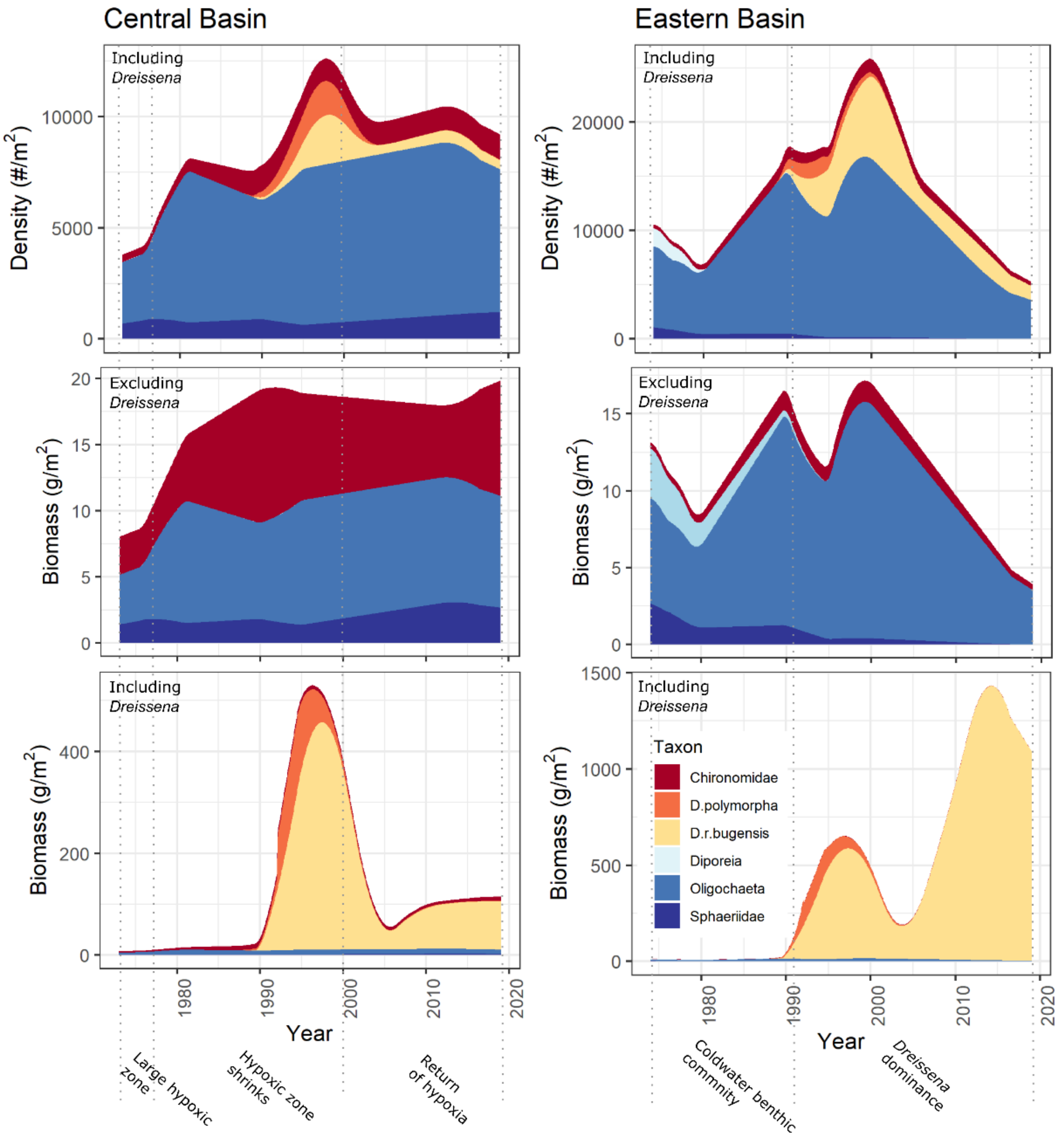

Figure 4. Average depth-weighted densities and biomass of major benthic taxonomic groups that were consistently counted in the central and eastern basins of Lake Erie in 1973-2019 with major events highlighted. Missing data were simulated using splines then all data were smoothed using a five-year moving average. Displayed data are additive (stacked).

Again, the most common groups were oligochaetes (64% of the whole benthos density), *Diporeia* (13%), sphaeriids (7%), and chironomids (6%). By the time of the next survey (1992), zebra mussels had already reached their maximum density (4544 ± 2120 ind./m^2), causing dramatic changes in the whole community

(Fig. 4). *Diporeia* density declined 8.7-fold and the species had not been reported after 1993 (Dahl et al., 1995; Dermott and Kerec 1997; Dermott and Dow, 2008). Other changes associated with the introduction of dreissenids in 1990s include a decline in sphaeriids and an increase in amphipods, gastropods, and chironomids (Dermott and Kerec 1997; Fig. 3, 4). These are changes typically associated with the introduction of dreissenids (see above). Strong declines in non-dreissenid benthos including oligochaetes, amphipods, gastropods, sphaeriids, and leeches by 2014-2019 compared to 1998 was unexpected. This decline may be due to increased consumption of benthic invertebrates by round gobies, whose densities dramatically increased in the basin during 1999-2002 (Barton et al., 2005; Johnson et al., 2005). Dreissenids became the second most abundant component of benthos density-wise in the 1990s (Burlakova et al., 2014). Again, initially dreissenids were dominated by zebra mussels until 1998, when they were almost completely outcompeted by quagga mussels (Patterson et al., 2005; Karatayev et al., 2014, 2021a, 2021b). After reaching a maximum in 2004, quagga mussels density declined to the minimum in 2019, along with the decline of non-dreissenid benthos.

SUMMARY

The three Lake Erie basins differ significantly in community structure, density, and biomass of benthic macroinvertebrates, as well as in major environmental factors that shape these communities. Eutrophication and *Dreissena* spp. introduction were the major drivers of changes in benthos in the western basin, while hypoxia was most important in the central basin, and dreissenid introduction was the dominant factor in the eastern basin. Non-dreissenid community composition of the western basin has dramatically changed over the last 90 years from benthos indicative of good water quality in the 1930s, with a community that was healthy, highly diverse, and dominated by *Hexagenia*, to one of low diversity dominated by pollution-tolerant species in the 1960s, followed by recovery to a state comparable to that of the early 20th century by the early 2000s. In contrast, the non-dreissenid benthic community of the central basin over the last 60 years was the most stable and was always dominated by the same taxa, signifying the persistence of the major community driver – hypoxia. The Eastern basin community has changed dramatically over the same period, including the disappearance of *Diporeia* after the introduction of *Dreissena* in the 1990s, followed by a recent decline in oligochaetes, amphipods, gastropods, sphaeriids, and leeches. *Dreissena* spp. became an important component of benthos in all Lake Erie basins, but their role is the most important in the eastern, and the least significant in the western basin.

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CHAPTER 2. RAPID ASSESSMENT OF *DREISSENA* POPULATION IN LAKE ERIE USING UNDERWATER VIDEOGRAPHY

INTRODUCTION

In this study, we developed a novel sampling method by using the Benthic Imaging System (BIS, a drop frame equipped with two GoPro cameras) across all three Lake Erie basins to estimate *Dreissena* populations (presence/absence, coverage, and density) in near real-time (during a typically two-week survey) to allow production of lake-wide maps of mussel distribution and preliminary population estimations. These preliminary data used to generate the distribution maps were later compared with dreissenid data obtained from traditional Ponar grabs to assess the advantages and disadvantages of both methods. As Lake Erie consists of three basins that differ dramatically in morphometry, turbidity, and productivity, as well as in *Dreissena* distribution, density, and mussel length-frequency distribution (Karatayev et al., 2018a), it provides an excellent model to test the applicability of our rapid assessment method for *Dreissena* long-term monitoring across large and dynamic environmental gradients (Karatayev et al., 2021a, https://link.springer.com/content/pdf/10.1007/s10750-020-04481-x.pdf).

METHODS

Dreissena sampling protocol

In July - August 2019, *Dreissena* spp. presence, density (number of individuals/m^2), total wet biomass (total wet weight, tissue with shell, g/m^2), and length-frequency distribution were measured at 95 stations, including 82 stations sampled aboard R/V *Lake Guardian* during the Lake Erie CSMI benthic survey in July, 10 stations sampled aboard the *Lake Guardian* during the U.S. EPA Great Lakes Biology Monitoring Program Long-Term Monitoring (LTM) summer survey in August, and three shallow stations (973, DO2, ER03) in western basin sampled by a NOAA small vessel on July 11 (Fig. 5). During this survey two types of samples were collected to study *Dreissena*: 1) Ponar (sampling area 0.0523 m^2, coefficient used to recalculate density per m^2 = 19.12) samples that were processed for mussel presence, density, size-frequency distribution, and sediment analysis; 2) video images collected using BIS (sampling area 0.2154 m^2, coefficient used to recalculate density per m^2 = 5.16) that were processed for mussel presence, bottom coverage (%), and density from 92 stations sampled aboard the R/V *Lake Guardian* (Fig. 5). Sampling details are described in Standard Operating Procedure for Benthic Invertebrate Field Sampling SOP LG406 (US EPA, 2019).

Three replicate Ponar samples for *Dreissena* were successfully collected at 93 stations from a total of 95 planned CSMI and LTM stations (samples were not collected at stations 948 and J31 due to hard substrate, Appendix), and a total of 279 samples were analyzed for *Dreissena* population assessment. Because no video images were collected at stations sampled by NOAA, we did not use Ponar samples from these three shallow western basin stations in our BIS *vs*. Ponar comparison, but we did use these Ponars for calculation of *Dreissena* density and biomass. All *Dreissena* were identified to species, counted, and measured using a digital caliper (0.01 mm). All shell length measurements were rounded to the nearest mm, after which all *Dreissena* in each replicate were combined into 5 mm size groups and weighed to the nearest 0.001 g after being blotted dry on absorbent paper. Details are described in Standard Operating Procedure for Benthic Invertebrate Laboratory Analysis SOP LG407 (US EPA, 2015).

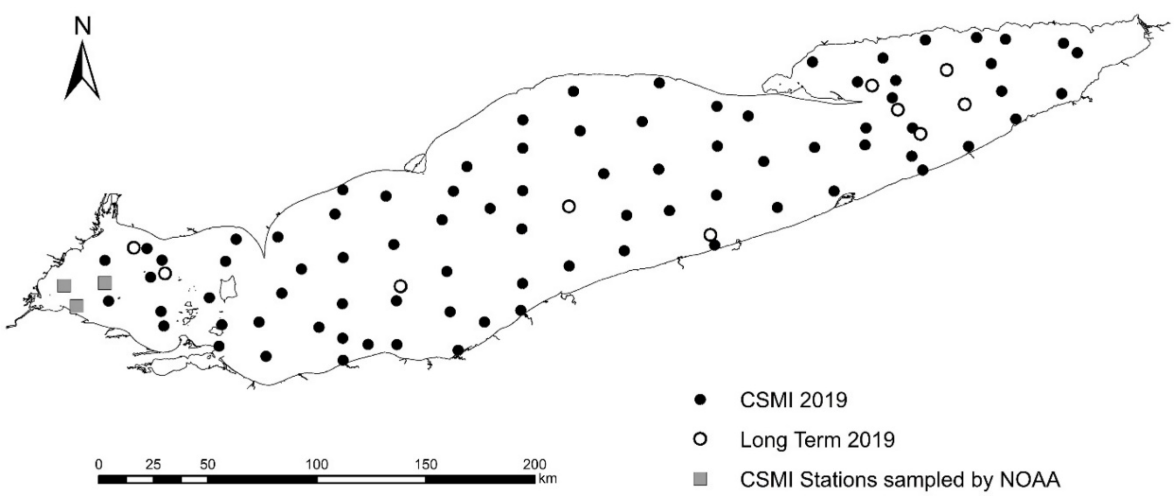

Figure 5. Location of stations in Lake Erie in 2019 sampled for *Dreissena* during July CSMI and August LTM cruises aboard the R/V *Lake Guardian* and NOAA research vessel.

Video image analysis

Video images were collected from 92 stations during LTM and CSMI surveys using a BIS equipped with two GoPro Hero 5 Black cameras (one down-looking camera and one oblique (i.e., side-looking) camera; frame rate: 60 frames/s; screen resolution: 1920 x 1080 pixels; housing certified to a depth of 60 m) and two underwater lights per camera (Suptig 84-LED dive lights) attached to a custom-built stainless-steel carriage (for details see Angradi, 2018; Wick et al., 2020; Karatayev et al., 2021a, 2021b). The down-looking camera was fixed 56 cm above substrate, and the side-looking camera was fixed 30 cm above substrate at an angle of about 45 degrees, resulting in a horizontal distance from the lens to the substrate of 1 m. At each station the BIS was lowered from the starboard side of R/V *Lake Guardian* down to the lake bottom (SOP LG410; US EPA, 2019). The BIS remained on the lake bottom for one minute (the first replicate, or RFS). This time duration was enough to increase the probability that a clear view of the area within the marked scale would be obtained, as any resuspended sediment was allowed to settle or clear from view. After one minute, the BIS was lifted 1 - 2 m from the bottom for 30 seconds, then lowered again to remain on the lake bottom for another minute (second replicate - FD1), lifted again for 30 seconds and then lowered to remain on the lake bottom for another minute (third replicate - FD2). All replicate BIS and Ponar grab samples were collected within the boundaries of an EPA station, with only one GPS record for each station. An EPA station is defined as “a bottom area of approximately 300 m in diameter. If, due to weather and currents, the *Lake Guardian* drifts far off the station, the boat will be re-positioned and sampling will resume” (SOP LG100; US EPA, 2021). After the frame was retrieved from the water, videos from both cameras were immediately downloaded to an external hard drive for onboard analysis. A total of 552 images were initially collected from both down and side-looking cameras (three replicates of each camera from each of the 92 stations). Of these, 482 images from the down- and/or side-looking cameras were used to record *Dreissena* presence/absence, while 235 and 232 images from the down-looking camera were used to record *Dreissena* coverage and to calculate mussel density, respectively. For each station we used averaged data from three replicates both for coverage and density.

For each replicate we used the clearest still image (screen shot) to estimate *Dreissena* coverage and density. Occasionally (at 10 stations with soft sediments) the frame sunk into the sediment; to avoid erroneous estimation of *Dreissena* size and counts we used the screen shot taken exactly at the moment immediately before the frame hit the lakebed. Mussel druses in each video screen shot were manually highlighted in Photoshop CS6 (Fig. 6). In all digitized images *Dreissena* were black and the background was white (Fig. 6, C). *Dreissena* coverage (%) was calculated by dividing the area covered by mussels (black) by total area of the image. For density estimations all visible mussels were counted in the entire original clipped still image before digitizing (Fig. 6, A) and the counts converted to density (individuals/m^2) using BIS sampling area 0.2154 m^2 (coefficient used to recalculate density per m^2 = 5.16). In six cases with >90% coverage, mussels were counted in three subsamples (10 x 10 cm each) and the subsample average was used to estimate *Dreissena* density. Unusable images were excluded from the analysis and therefore for three stations we used only two images (replicates) per station, and only one replicate image for another five stations.

Figure 6. *Dreissena* in original clipped still image before digitizing (A), with *Dreissena* digitized (B), and in black and white image after *Dreissena* digitized (C). In digitized images *Dreissena* appear black and the background appears white. *Dreissena* coverage (%) is calculated by dividing the area covered by mussels (black) by total area of the image.

According to U.S. EPA Standard Operation Procedure (SOP LG410; US EPA, 2019) for quality control purposes at least 10% of randomly selected still images should be recounted by a different analyst. Percent errors in *Dreissena* coverage and counts less than 20% are considered acceptable, and all images with differences >20% should be re-evaluated (SOP LG410; US EPA, 2019). For this study we accepted a more rigorous threshold and considered images acceptable with <10% differences in coverage and density. However, for sites with very low coverage (usually <5%), even small differences while processing images can lead to a high percentage of error, and therefore for such images we used a 20% threshold. Twelve percent of all samples (28 of the 232 total samples) were 're-digitized' for quality control purposes. Only three samples had >20% difference in counts and were re-evaluated. On average, differences in *Dreissena* coverage across all other images was 11%, and differences in density were 8% (excluding samples with no mussels but including stations with very low coverage and density).

RESULTS

Dreissena population assessment using BIS *vs.* Ponar samples

Usable images for recording *Dreissena* presence/absence were collected with the BIS (from the down- and/or side-looking cameras) at a total of 86 of the 92 LTM and CSMI stations (93.5% success rate). Images from 82 stations (89.1% success rate) were usable for coverage estimation, and images from 81 stations (88.0% success rate) were used for both mussel counts and coverage. Images from one of the 17 western basin stations sampled with BIS were not usable for assessment of dreissenid presence/absence due to high turbidity. At another station in the western basin, images were too blurry to estimate coverage or to count mussels, however *Dreissena* were visible and therefore the image was used to determine mussel presence. Similarly, of the 50 central basin stations sampled with BIS, presence/absence of mussels was not assessed at two stations due to high turbidity; at a third central basin station *Dreissena* presence, but not coverage or counts, could be assessed owing to high turbidity. In the eastern basin algae cover prevented successful BIS sampling at two stations, and rough weather prevented sampling at two other stations. Ponar samples were successfully collected at all but two of the 92 LTM and CSMI stations (97.8% success rate).

From a total of 85 stations sampled with both BIS and Ponars, *Dreissena* spp. occurrence recorded with BIS was the highest in the eastern basin (95%) and much lower in the western (44%) and central (32%) basins (Table 6; Fig. 7). Ponar samples revealed the same mussel occurrence (95%) in the eastern basin, 1.5-fold higher occurrence (47%) in the central basin, and 2.1-fold higher occurrence (94%) in the western basin. The discrepancies between BIS and Ponar data in the western basin were most likely due to high turbidity and a large proportion of juvenile mussels (<10 mm), which were very hard to detect on video images. In addition, the proportion of large mussels (>10 mm) was also much smaller in the western (23%) and central (33%) basins than in the eastern basin (61%). When mussels <10 mm were excluded from the analysis, *Dreissena* occurrences estimated using BIS and Ponar were more similar: 32% vs. 36% in the central basin and 44% vs. 63% in the western basin, respectively (Table 6; Fig. 7).

Table 6. Number of stations where *Dreissena* were recorded (presence/absence and percent of occurrence in parenthesis) from the 85 total stations sampled both with BIS and Ponar grabs in different basins of Lake Erie in 2019.

Parameters	Western	Central	Eastern
BIS	7/9 (44%)	15/32 (32%)	21/1 (95%)
Ponar, mussels of all sizes	15/1 (94%)	25/22 (47%)	21/1 (95%)
Ponar, mussels >10 mm	10/6 (63%)	17/30 (36%)	20/2 (91%)

Both coverage and density were the highest in the eastern basin, lower in the western basin, and the lowest in the profundal zone of central basin, which is subject to annual hypoxia (Karatayev et al., 2018). *Dreissena* spatial distribution estimated via BIS and Ponar samples for mussels >10 mm showed similar patterns in the eastern basin, while in the western basin BIS substantially underestimated mussel coverage, especially when small mussels occurred in the population (Fig. 8).

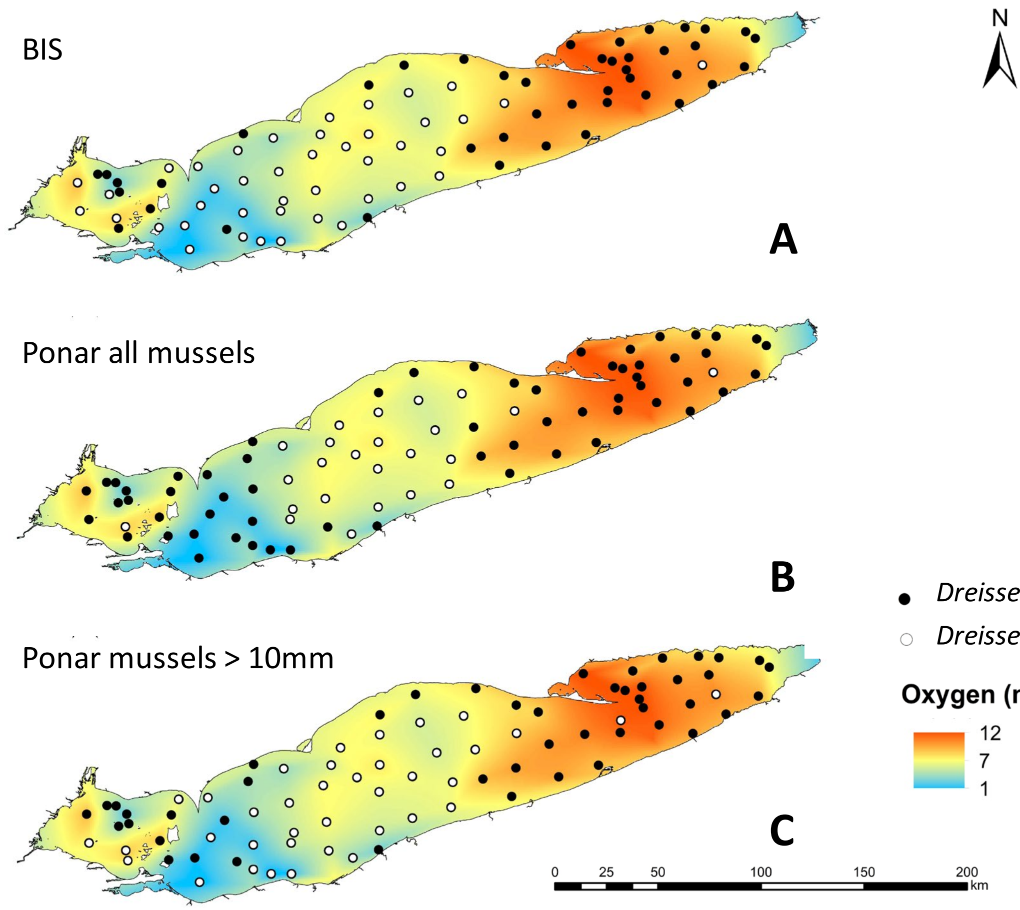

Figure 7. *Dreissena* spp. presence and absence in Lake Erie in 2019 based on BIS (A) and Ponar grabs including all *Dreissena* sizes classes (B), and mussels >10mm (C) superimposed over concentrations of near-bottom oxygen based on Seabird profile data (colors changing from 1 mg/L (blue) to 12 mg/L (red)). Only the 85 matching stations where presence/absence data from both BIS and Ponar were available are shown.

In the eastern basin, average densities estimated using BIS (1015 ± 230/m^2) and Ponar grabs (1032 ± 179/m^2) were highly similar (Z = 0.41, *P* = 0.68, Wilcoxon Matched Pairs test). In the central basin which was dominated by small mussels, basin-wide average density estimated with Ponars (383 ± 196/m^2) was 1.4-fold higher than in BIS images (267 ± 126/m^2), although the difference was not significant (Z = 1.37, *P* = 0.17). The largest difference (Z = 2.92, *P* = 0.0035) between the two methods was found in the most turbid western basin were the Ponar-generated basin-wide average (604 ± 191/m^2) was over 30-fold higher than BIS estimates (18 ± 10/m^2).

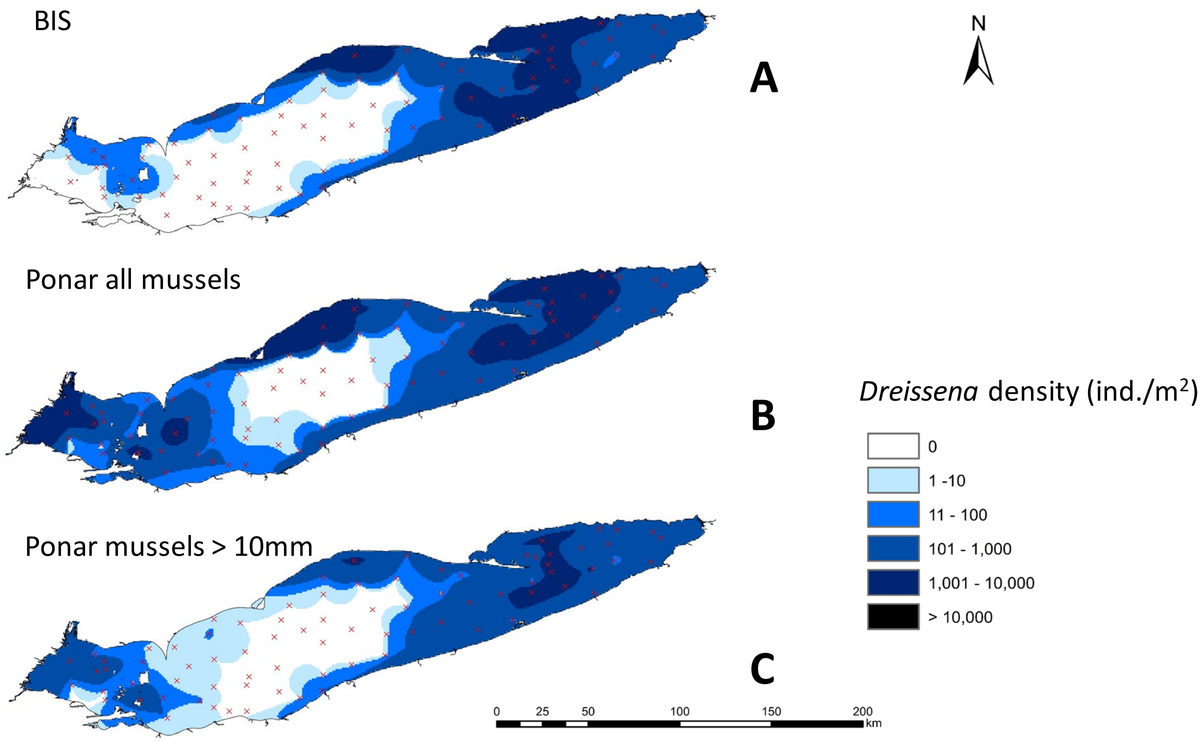

Figure 8. Spatial distribution of *Dreissena* spp. in Lake Erie in 2019 expressed as density (ind./m^2) estimated by using BIS video image analysis (A) and Ponar samples including all *Dreissena* size classes (B), and mussels >10 mm (C). Red crosses indicate sampling stations. Only the 81 matching stations where density data from both BIS and Ponar samples were available are shown.

Our rapid assessment of *Dreissena* densities in Lake Erie revealed a strong decline in Lake Erie mussel populations compared to the previous lakewide survey (2014), which was confirmed by Ponar data. In the eastern basin both methods revealed a 2.3-fold decline in the average density compared to 2014, however the changes were not significant due to high variability in the data (Ponar: $Z = 1.57$, $P = 0.12$, BIS: $Z = 1.27$, $P = 0.20$, Wilcoxon Matched Pairs test, Fig. 9). Central basin *Dreissena* densities experienced almost the same decline (2.3-fold estimated with BIS, $Z = 1.82$, $P = 0.07$ and 1.6-fold with Ponar, $Z = 0.51$, $P = 0.61$). The largest significant changes were found in the western basin where BIS estimations suggested >100-fold decline in *Dreissena* density in 2019 compared to 2014 ($Z = 2.90$, $P = 0.004$), while Ponar data revealed a marginally significant 5-fold decline ($Z = 1.93$, $P = 0.053$).

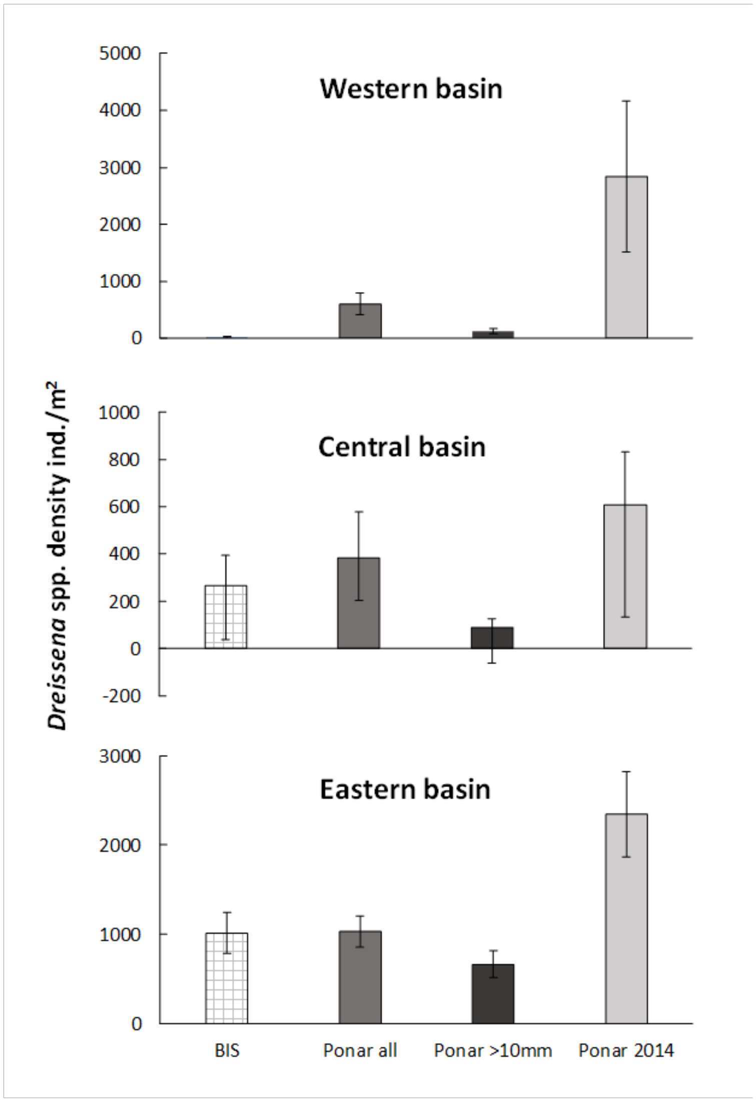

Figure 9. Average densities of *Dreissena* spp. estimated from video images in 2019 (BIS), from Ponars in 2019 [all size classes of *Dreissena* plotted (Ponar all), only *Dreissena* >10 mm plotted (Ponar >10 mm), and from Ponars in 2014 (all size classes plotted, Ponar 2014)].

Dreissena population dynamics

The recent changes in dreissenid populations revealed by both video analysis and traditional grab and sorting methods have advanced our understanding of *Dreissena* spp. population dynamics in Lake Erie (Fig. 10). The largest and most unexpected changes were found in the western basin. The highest average wet biomass (832 ± 132 g/m^2) in the western basin was recorded in 2004, but then declined 18-fold to 48.0 ± 19.6 g/m^2 by 2019 (Fig. 10), the lowest biomass ever recorded in the basin. Due to high variability in the data, the changes in biomass between years were not significant (H = 9.43, P = 0.15, Kruskal-

Wallis test). During the same time period *Dreissena* density decreased less than 3-fold (H = 14.33, P = 0.026) due to a dramatic decline in mussel average weight from 0.50 g in 2004 to 0.08 g by 2019. In 2019 the *Dreissena* population in the western basin was dominated by small juvenile mussels: 77% of all mussels were <10 mm, of which 53% were <5 mm (Fig. 11).

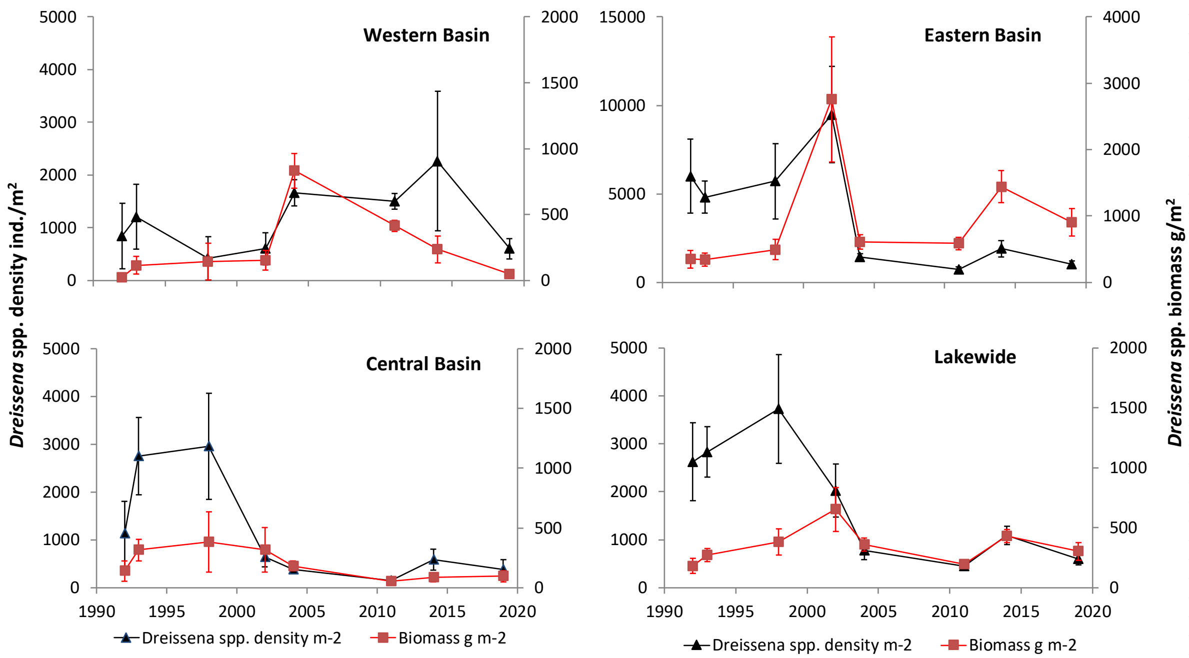

Figure 10. Long-term dynamics of *Dreissena* spp. average (± standard error) density (black, left axis) and total wet biomass (red, right axis) estimated using Ponars. Data from Jarvis et al., 2000; Patterson et al., 2005; Dermott and Dow, 2008; Ciborowski et al., in preparation, and Karatayev et al., 2014, 2018b.

In the central basin both density and especially biomass changed significantly among years (H = 27.68, P <0.001, Kruskal-Wallis test); both were high during the first 10 years after colonization, and then started to decline after 1998. Similar to the western basin, the *Dreissena* population in the central basin is now largely dominated by small mussels, especially at depths >20 m which are subject to seasonal hypoxia (Fig. 7; Karatayev et al., 2018a).

In the eastern basin *Dreissena* population maximum occurred in 2002, followed by declines in both density and biomass (density: H = 37.23, P <0.001; biomass: H = 18.13, P = 0.006, Kruskal-Wallis test, Fig. 10). The decline in population density, however, was more pronounced/more rapid than in biomass, due to an almost 10-fold increase in mussel average weight (from 0.09 g in 1998 to 0.83 g in 2019). In 2019, *Dreissena* basin-wide average weight in the eastern basin was >10-fold higher than in the western, and 3.4-fold higher than in the central basin. Also in 2019, the depth zone <40 m in the eastern basin was the only portion of Lake Erie where the *Dreissena* population was represented by multi-year cohorts (Fig. 11), while at depths >40 m the population was dominated by mussels >16 mm. Hypolimnetic waters of the eastern basin were normoxic.

Ninety-nine percent of all *Dreissena* collected in the eastern basin in 2019 were quagga mussels, while in the central basin quaggas comprised 79% of combined density and 75% of biomass. The largest proportion of zebra mussels, as in previous years, was found in the western basin where they represented 72% of combined dreissenid density and 59% of biomass.

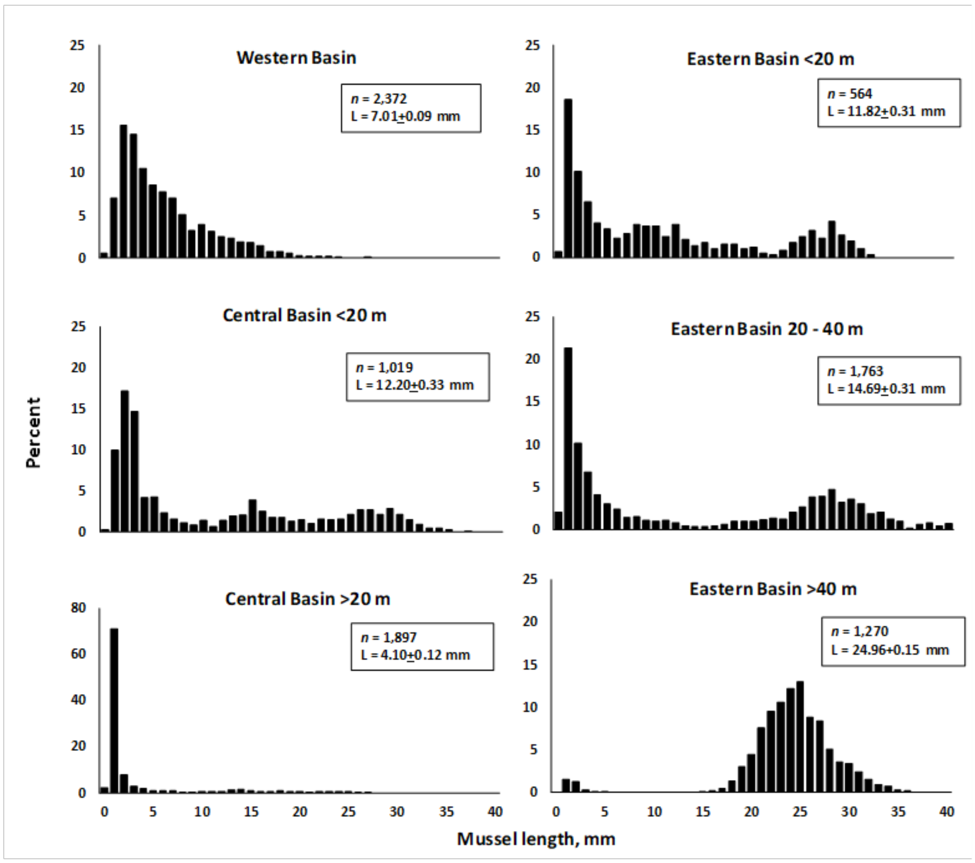

Figure 11. Length-frequency distributions of *Dreissena* spp. in Lake Erie in 2019. Sample size and average length (± standard error) for each basin and depth zone are indicated.

SUMMARY

We have developed a novel assessment method using the Benthic Imaging System (BIS) to estimate *Dreissena* spp. distribution and density in near real-time across large waterbodies like the Great Lakes. Comparison of the results of our rapid assessment with Ponar grab data collected at the same stations showed that the agreement depends on near-bottom turbidity and size structure of dreissenids. Despite undersampling of small mussels, the BIS method provided a rapid and reliable estimation of density of ecologically important large mussels. Underestimated by this method, the newly settled small dreissenids have very high mortality, very low biomass and thus a negligible functional role. Our results showed that by substantially reducing the time to assess dreissenid distribution and population size across large areas, rapid assessment could be a useful and cost-effective addition for monitoring dreissenid populations in the Great Lakes and other freshwater systems where they occur, excluding areas with high turbidity and macrophyte coverage. Rapid assessment in 2019 revealed *Dreissena* population decline in all three Lake Erie basins compared to 2014 data (Fig. 9). The largest decline in *Dreissena* spp. density was recorded in the western basin. Based on BIS estimations, *Dreissena* densities in 2019 were among the lowest across all three Lake Erie basins in over 25 years of recorded observations. Ponar data largely confirmed results of the rapid assessment in the central and eastern basins.

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CHAPTER 3. UNDERWATER VIDEO ANALYSIS OF *DREISSENA* DISTRIBUTION IN LAKE ERIE IN 2019

INTRODUCTION

Underwater video is a valuable tool to examine lake communities and can be used alongside traditional grab sampling to expand the resolution and sampling area covered in benthic surveys. Utilizing underwater video increases precision of *Dreissena* population estimates (Karatayev et al., 2018). Underwater video has previously been used to study benthos in Lake Erie, but these studies were limited in spatial scale to specific nearshore zones or to a single basin of the lake (Custer and Custer, 1997; Lietz et al., 2015). Other similar studies that examine *Dreissena* populations using underwater video have taken place on other large lakes and rivers (Mehler et al., 2018; Ozersky et al., 2009, 2011). We developed standardized methods to estimate *Dreissena* coverage in Great Lakes offshore zones using video imagery (Karatayev et al., 2018) and applied them to Lake Erie. These methods have been used previously in Lakes Michigan, Huron, and Ontario. Here, we evaluated *Dreissena* presence in Lake Erie with a combination of Ponar videos, and 500 m benthic sled video transects. These video methods were compared with traditional Ponar grabs to determine a conversion between percent coverage from video estimates and density or biomass from traditional Ponar grabs.

METHODS

We sampled *Dreissena* using video methods at several stations in each basin of Lake Erie (Fig. 12). We took Ponar videos at 32 stations and sled transects at 21 stations (Fig. 12; Table 7). Stations were limited to the Eastern Basin and the eastern sections of the Central Basin because previous analyses revealed that western parts of Lake Erie have high turbidity that restricts the usage of video methods. Ponar videos were taken with a GoPro Hero 4 Black camera attached to the top of the Ponar (Fig. 13) and videos for sled transects were taken from a GoPro camera mounted to a benthic sled that was towed for 500 m behind the R/V *Lake Guardian*. Three replicates were taken at each station for Ponar videos, and one replicate was taken for sled tows.

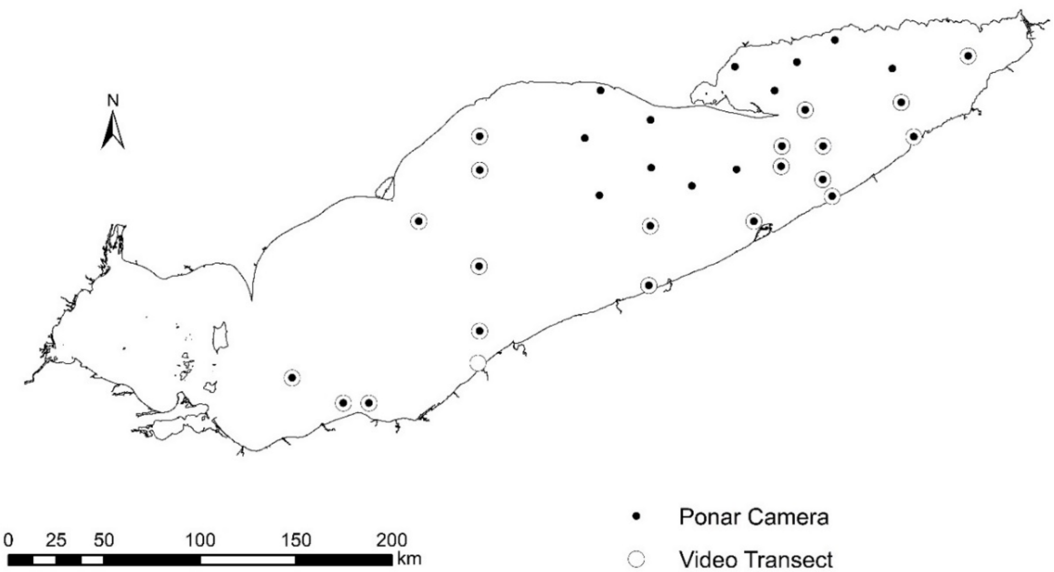


Figure 12. Sampling stations in Lake Erie where video methods (Ponar camera and video transects) were collected.

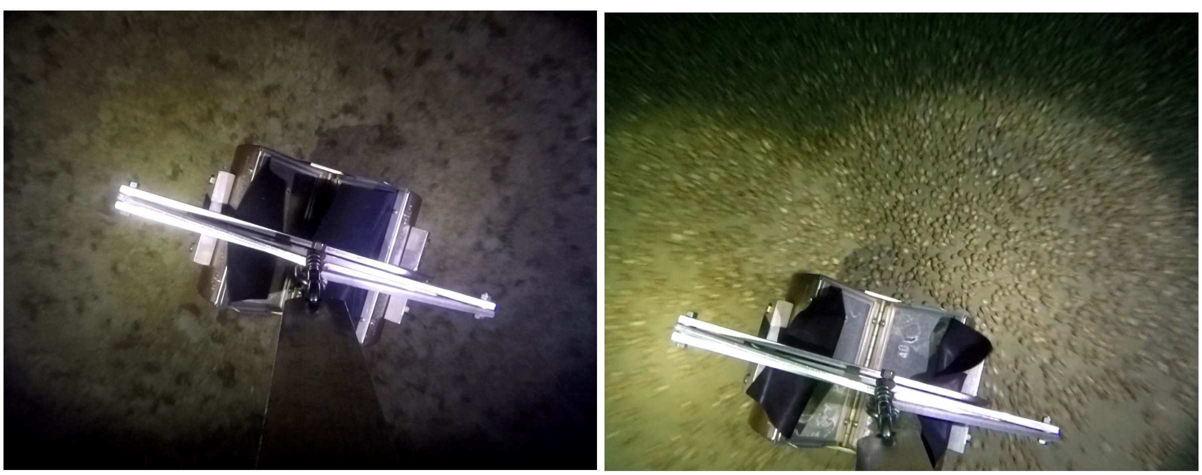


Figure 13. Examples of images from Ponar videos. The left image is taken from station 946 and was classified as unusable due to difficulty in distinguishing *Dreissena* from the sediment. The image on the right from station 940 was classified as useable and *Dreissena* are clearly visible on the sediment.

Prior to analysis, we classified each video as acceptable or unacceptable for estimating *Dreissena* coverage. Unacceptable videos were further classified as controllable (e.g., camera out of focus, dim lighting) or uncontrollable (e.g., turbidity, macrophyte cover). Ponar videos were classified as acceptable for 24 out of 33 videos (73%; Table 7) and 12 out of 21 sled videos (57%) were classified as acceptable.

Videos were unacceptable mostly due to uncontrollable reasons, i.e. high water turbidity, macrophyte coverage, etc. Controllable reasons were due to the sled being off the bottom. Only videos classified as acceptable were used in subsequent analyses.

Table 7. Number of acceptable (percent of total in parenthesis) and unacceptable bottom images collected in Lake Erie in 2019 using GoPro cameras attached to Ponar grab and benthic sled. Unacceptable images were classified as controllable (e.g. equipment malfunction or human error) or uncontrollable (e.g. high turbidity, difficulty in distinguishing *Dreissena* shells from sediment, etc.).

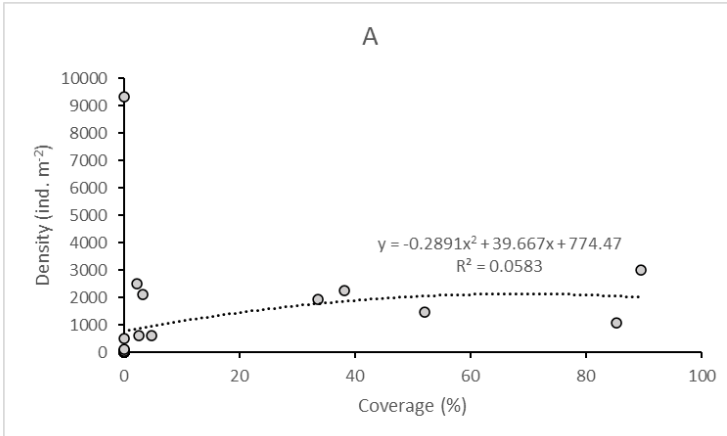
Parameters	Ponar videos	Sled videos
Number of stations (CSMI) videos were collected	33	21
Number of acceptable videos	24 (73%)	12 (57%)
Number of unacceptable videos	9 (27%)	9 (43%)
Controllable	0	3
Uncontrollable	9	6

Videos were converted to still images for processing. For Ponar videos, a still image was taken at the instant just before the Ponar hit the sediment, then an image of known area was cropped from the area with sediment (i.e., next to the Ponar). *Dreissena* coverage was calculated as the percentage of area covered by *Dreissena* in Photoshop CS6. Videos from sled transects were converted to still images and 100 images were randomly chosen to calculate percent coverage in Photoshop CS6. *Dreissena* coverage from Ponar videos was compared with density and biomass calculated from Ponar grabs.

RESULTS AND DISCUSSION

Ponar videos

Ponar videos estimated *Dreissena* biomass from Ponar grabs better than estimated density, as evidenced by a higher model fit (R^2). The relationship between density and percent coverage showed a weak increasing trend that was fitted with a polynomial equation ($R^2 = 0.0583$; Fig. 14A). The relationship between biomass and percent coverage was stronger ($R^2 = 0.6664$) despite limited data. A high number of stations had no *Dreissena* collected in the grab or recorded on video. A slightly decreasing biomass at high percent coverage (Fig. 14) indicates that some smaller mussels that were not visible in video may have been present in locations with moderate percent coverage.



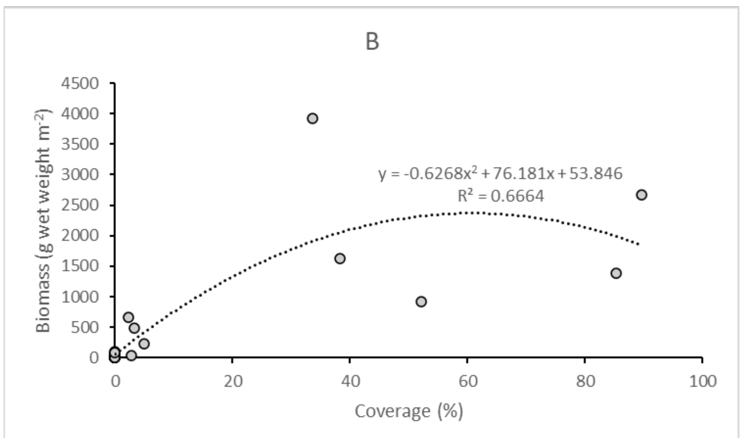


Figure 14. Relationship between *Dreissena* coverage in video, and density (ind./m^2) and biomass (g/m^2) obtained from the same Ponar grabs in Lake Erie in 2019. All replicates of Ponar videos are included in the plot. Note that there are 25 points in each plot, but many are located at zero percent coverage in the absence of mussels and thus overlap.

Sled transects

Sled transects were less successful in Lake Erie than in other lakes where our method has been tested previously (Karatayev et al., 2018). High turbidity and algal coverage precluded our ability to use sled transects in the entire Western Basin and much of the Central Basin. In addition, several stations where sled transects were performed in the Central and Eastern Basins had no *Dreissena* (Table 8). The standard error around percent coverage estimates was generally small (Table 8), suggesting that *Dreissena* coverage was consistent within each 500 m transect. Therefore, results from sled transects in Lake Erie collected only in specific parts of the lake could not be compared to estimates from Ponar videos due to limited non-zero data. In contrast to the other Great Lakes where benthic sled transects have proven useful to estimate offshore *Dreissena* populations (Karatayev et al. 2018), sled transects were of limited utility in Lake Erie. We recommend use of sled transects for *Dreissena* population estimates in areas with higher water clarity.

Table 8. *Dreissena* coverage (average ± standard errors, %) from sled transects in Lake Erie. Averages by basin are averages of transects.

Station	Depth(m)	Basin	*Dreissena* coverage (%)
946	24	Central	0.00
951	21	Central	0.96 ± 0.30
952	23	Central	0.00
954	25	Central	0.00
955	21	Central	0.00
I15	24	Central	0.00
Average of Central Basin			0.16 ± 0.16
K29	37	Eastern	42.80 ± 3.92
L29	45	Eastern	28.95 ± 3.99
Pt. Abino	21	Eastern	3.19 ± 0.74
935	34	Eastern	0.26 ± 0.19
939	58	Eastern	58.55 ± 0.45
940	48	Eastern	48.00 ± 3.36
941	37	Eastern	28.62 ± 3.23
Average of Eastern Basin			30.05 ± 8.32

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APPENDIX. List of all CSMI and LTM stations sampled on Lake Erie in 2019.

All CSMI and LTM stations sampled on Lake Erie in April, July, and August 2019 with information on lake basins, location (decimal coordinates), water depth, coefficient for area conversion, taxa reported, and main substrates. Coefficients used to calculate density per m^2 depended on sampler area and samplers used and were 19.12 for *Lake Guardian* Ponar with sampling area 0.0523 m^2, 43.28 for Great Lakes Center small Ponar with sampling area 0.0231m^2, and 21.42 for NOAA Ponar with sampling area 0.04669 m^2. Taxa reported: All – all benthic taxa; D – *Dreissena* only. Basin: W – Western, C – Central, E – Eastern. HWB – Historic Western Basin Survey, in which samples were collected from the Great Lakes Center small vessel *John J Freidhoff* on April 24, 2019. LTM – GLNPO long-term monitoring stations sampled aboard *Lake Guardian* during the summer survey in August 2019. The following three stations were sampled with the NOAA small boat *4108* on July 11, 2019: 973, D02, and E03 (marked with asterisks). Samples from Stations 948n and J31n (highlighted in grey) were removed from analyses because there were large differences in type and amount of substrate between replicates, indicating that incomplete samples were taken.

Station	Basin	Latitude	Longitude	Depth, m	Ponar area, m^2	Coefficient	Sample type	Survey	Substrate
ER 965	Western	41.4999	-82.4998	13	0.0523	19.12	All	CSMI	Silt
ER 966	Western	41.9830	-82.6232	11	0.0523	19.12	All	CSMI	Silt
ER 967	Western	41.8917	-82.6666	12	0.0523	19.12	All	CSMI	Silt
ER 968	Western	41.7417	-82.7336	11	0.0523	19.12	All	CSMI	Silt, Sand
ER 970	Western	41.8263	-82.9760	11	0.0523	19.12	All	CSMI	Silt
ER 973*	Western	41.7911	-83.3340	6.8	0.0467	21.42	All	CSMI	Silt, Clay
ER B07	Western	41.5418	-82.6937	10	0.0523	19.12	All	CSMI	Silt
ER C05	Western	41.6253	-82.9213	8.8	0.0523	19.12	All	CSMI	Silt
ER C07	Western	41.6300	-82.6820	14	0.0523	19.12	All	CSMI	Silt, Gravel
ER D02*	Western	41.7070	-83.2823	6.5	0.0467	21.42	All	CSMI	Silt
ER E03*	Western	41.8020	-83.1651	9.3	0.0467	21.42	All	CSMI	Silt, Shells
ER 15D	Western	42.0333	-83.1528	4.0	0.0231	43.28	All	HWB	Gravel, Rocks
ER 1M	Western	41.7138	-83.4250	2.4	0.0231	43.28	All	HWB	Shells
ER 2L	Western	41.7972	-83.2305	7.5	0.0231	43.28	All	HWB	Silt
ER 3D	Western	41.9388	-83.2028	7.0	0.0231	43.28	All	HWB	Gravel
ER 5/4R	Western	41.8722	-83.2638	6.5	0.0231	43.28	All	HWB	Shells
ER 58	Western	41.6850	-82.9333	9.9	0.0523	19.12	All	CSMI	Silt, Sand, Shells
ER 59	Western	41.7278	-83.1493	8.0	0.0523	19.12	D	CSMI	Silt
ER 6L	Western	41.8472	-83.1167	8.5	0.0231	43.28	All	HWB	Silt

Station	Basin	Latitude	Longitude	Depth, m	Ponar area, m^2	Coefficient	Sample type	Survey	Substrate
ER 7M	Western	41.7333	-83.2972	5.0	0.0231	43.28	All	HWB	Silt
ER 8D	Western	41.9555	-83.1195	7.3	0.0231	43.28	All	HWB	Clay
ER 8M	Western	41.7888	-83.3555	4.0	0.0231	43.28	All	HWB	Shells
ER F03	Western	41.8960	-83.1645	8.9	0.0523	19.12	All	CSMI	Silt, Shells
ER F05	Western	41.8966	-82.9289	11	0.0523	19.12	All	CSMI	Silt, Clay
ER KM15	Western	41.6411	-82.5286	14	0.0523	19.12	D	CSMI	Silt
ER KM16	Western	41.7601	-82.4346	14	0.0523	19.12	D	CSMI	Sand, Shells
ER W42	Western	41.9446	-82.9910	9.5	0.0523	19.12	All	CSMI	Silt, Clay
ER 944	Central	42.5315	-80.6397	17	0.0523	19.12	All	CSMI	Sand, Stones, Shells
ER 945	Central	42.3673	-80.6376	21	0.0523	19.12	All	CSMI	Silt
ER 946	Central	42.1653	-80.6417	24	0.0523	19.12	All	CSMI	Sand, Shells
ER 948	Central	41.9588	-80.6491	13	0.0523	19.12	None	CSMI	Shells
ER 951	Central	42.4755	-81.4403	21	0.0523	19.12	All	CSMI	Shells, Silt, rocks
ER 952	Central	42.3590	-81.4409	23	0.0523	19.12	All	CSMI	Silt
ER 953	Central	42.1834	-81.4413	24	0.0523	19.12	All	CSMI	Silt
ER 954	Central	42.0257	-81.4445	24	0.0523	19.12	All	CSMI	Silt
ER 955	Central	41.8002	-81.4421	21	0.0523	19.12	All	CSMI	Silt
ER 956	Central	41.6892	-81.4491	12	0.0523	19.12	All	CSMI	Rocks, Gravel, Shells
ER 957	Central	41.6834	-81.7407	13	0.0523	19.12	All	CSMI	Silt
ER 958	Central	41.5250	-81.7072	12	0.0523	19.12	All	CSMI	Gravel, Sand, Shells, Clay
ER 959	Central	42.1867	-82.1832	14	0.0523	19.12	All	CSMI	Sand, Shells
ER 961	Central	41.9075	-82.1814	21	0.0523	19.12	All	CSMI	Silt
ER 962	Central	41.7169	-82.1844	20	0.0523	19.12	All	CSMI	Silt
ER 963	Central	41.5744	-82.1835	16	0.0523	19.12	All	CSMI	Silty sand
ER 964	Central	41.4837	-82.1816	9.9	0.0523	19.12	All	CSMI	Sand, Shells
ER B12	Central	41.5488	-82.0791	17	0.0523	19.12	All	CSMI	Silt
ER B13	Central	41.5481	-81.9604	16	0.0523	19.12	All	CSMI	Silt
ER C10	Central	41.6197	-82.2813	14	0.0523	19.12	All	CSMI	Sand, Gravel
ER C16	Central	41.6415	-81.5986	17	0.0523	19.12	All	CSMI	Gravel, Shells
ER D13	Central	41.7289	-81.9616	22	0.0523	19.12	All	CSMI	Silt

Station	Basin	Latitude	Longitude	Depth, m	Ponar area, m^2	Coefficient	Sample type	Survey	Substrate
ER 30	Central	42.4302	-81.2041	21	0.0523	19.12	D	CSMI	Silty clay
ER 31	Central	42.2534	-81.1066	22	0.0523	19.12	D	CSMI	Silty clay
ER 32	Central	42.0819	-81.0121	23	0.0523	19.12	D	CSMI	Silt, Shells
ER 37	Central	42.1102	-81.5754	25	0.0523	19.12	D	CSMI	Silt
ER 38	Central	42.2825	-81.6713	22	0.0523	19.12	D	CSMI	Silt
ER G09	Central	41.9922	-82.4512	14	0.0523	19.12	All	CSMI	Sand, Shells
ER H11	Central	42.0869	-82.2152	21	0.0523	19.12	All	CSMI	Silt
ER I15	Central	42.1814	-81.7268	24	0.0523	19.12	All	CSMI	Silt
ER I28	Central	42.1816	-80.1561	15	0.0523	19.12	All	CSMI	Sand
ER J22	Central	42.2720	-80.8795	22	0.0523	19.12	All	CSMI	Silt, Shells
ER KM1	Central	41.8601	-82.3536	15	0.0523	19.12	D	CSMI	Silt
ER KM10	Central	42.5935	-81.2313	13	0.0523	19.12	D	CSMI	Gravel
ER KM11	Central	42.1141	-80.3903	19	0.0523	19.12	D	CSMI	Clay, Sand, Silt
ER KM12	Central	42.3041	-80.4468	18	0.0523	19.12	All	CSMI	Clay
ER KM13	Central	42.4915	-80.5103	18	0.0523	19.12	D	CSMI	Sand, Shells
ER KM14	Central	42.3619	-80.2372	31	0.0523	19.12	All	CSMI	Clay
ER KM2	Central	41.9611	-81.9726	24	0.0523	19.12	D	CSMI	Silt
ER KM3	Central	42.1610	-82.0050	21	0.0523	19.12	D	CSMI	Silt, Gravel, Clay
ER KM4	Central	41.8499	-81.7541	24	0.0523	19.12	D	CSMI	Silt
ER KM5	Central	42.0631	-81.7734	24	0.0523	19.12	D	CSMI	Silt
ER KM6	Central	41.8727	-81.2493	21	0.0523	19.12	D	CSMI	Silt
ER KM7	Central	41.9352	-81.0217	20	0.0523	19.12	D	CSMI	Silt
ER KM8	Central	42.1010	-80.8355	23	0.0523	19.12	D	CSMI	Clay, Sand
ER KM9	Central	42.4687	-80.9481	20	0.0523	19.12	D	CSMI	Silt, Shells
ER N22	Central	42.6283	-80.8770	13	0.0523	19.12	All	CSMI	Sand, Gravel, Shells
ER 932	Eastern	42.7919	-79.2095	22	0.0523	19.12	All	CSMI	Clay
ER 933	Eastern	42.8158	-79.5684	17	0.0523	19.12	All	CSMI	Gravel
ER 934	Eastern	42.7080	-79.5075	29	0.0523	19.12	All	CSMI	Silt
ER 935	Eastern	42.5943	-79.4644	33	0.0523	19.12	All	CSMI	Silt
ER 936	Eastern	42.4791	-79.4067	15	0.0523	19.12	All	CSMI	Shells

Station	Basin	Latitude	Longitude	Depth, m	Ponar area, m^2	Coefficient	Sample type	Survey	Substrate
ER 937	Eastern	42.7149	-80.2454	9.0	0.0523	19.12	All	CSMI	Sand
ER 938	Eastern	42.6324	-80.0594	36	0.0523	19.12	All	CSMI	Silt
ER 939	Eastern	42.5665	-79.9161	57	0.0523	19.12	All	CSMI	Silt
ER 940	Eastern	42.4420	-79.8325	49	0.0523	19.12	All	CSMI	Silt
ER 941	Eastern	42.3255	-79.8353	36	0.0523	19.12	All	CSMI	Silt, Shells
ER CCW20	Eastern	42.5842	-79.2168	19	0.0523	19.12	D	CSMI	Silty sand
ER J31	Eastern	42.2683	-79.7903	12	0.0523	19.12	None	CSMI	
ER K29	Eastern	42.3721	-80.0286	37	0.0523	19.12	All	CSMI	Clay, Silt, Sand, Shells
ER L29	Eastern	42.4422	-80.0248	45	0.0523	19.12	All	CSMI	Silt
ER Lowbanks (20m)	Eastern	42.8084	-79.4489	21	0.0523	19.12	D	CSMI	Clay
ER N30	Eastern	42.6380	-79.9017	42	0.0523	19.12	All	CSMI	Silt
ER P31	Eastern	42.8054	-79.7798	17	0.0523	19.12	All	CSMI	Sand, Clay, Shells
ER Peacock Pt (20m)	Eastern	42.7309	-79.9548	21	0.0523	19.12	D	CSMI	Clay
ER Pt Abino (20m)	Eastern	42.7527	-79.1529	21	0.0523	19.12	D	CSMI	Silty sand, Shells
ER WFD20	Eastern	42.3666	-79.6016	19	0.0523	19.12	D	CSMI	Sand
ER09	Eastern	42.5383	-79.6167	50.3	0.0523	19.12	All	LTM	100% Silt
ER10	Eastern	42.6800	-79.6917	33.7	0.0523	19.12	All	LTM	100% Silt
ER15M	Eastern	42.5167	-79.8933	63.5	0.0523	19.12	All	LTM	100% Silt
ER43	Central	41.7883	-81.9450	23	0.0523	19.12	All	LTM	100% Silt
ER61	Western	41.9467	-83.0450	9.6	0.0523	19.12	All	LTM	100% Silt
ER63	Eastern	42.4167	-79.8000	47.8	0.0523	19.12	All	LTM	100% Silt
ER78M	Central	42.1167	-81.2500	23.8	0.0523	19.12	All	LTM	100% Silt
ER91M	Western	41.8408	-82.9167	11.1	0.0523	19.12	All	LTM	100% Silt
ER93b	Eastern	42.6167	-80.0000	42.5	0.0523	19.12	All	LTM	100% Silt
ER95b	Central	42.0000	-80.6664	17.6	0.0523	19.12	All	LTM	70% Sand, 20% Silt, 10% Gravel

* Stations sampled on July 11, 2019 from NOAA small boat *4108* using NOAA Ponar (sampling area 0.04669 m^2).