Sub-Indicator: Benthos Open Water

Overall Assessment

Status: Good

Trends:

10-Year Trend (2013-2022): Unchanging

Long-term Trend (1998-2022): Unchanging

Rationale: Based on the Oligochaete Trophic Index (OTI) scores, the status and trends in the trophic condition of the lakes are generally considered to be Good and Unchanging for long-term (1998 - 2022), 10-year (2013-2022), and short-term (2021-2022) time periods. Offshore sites in the Great Lakes are generally oligotrophic, but Lake Erie and some nearshore (<30m) stations in lakes Ontario, Huron, and Michigan are assessed as Poor and the long-term trends for those particular areas are indicative of increased eutrophication. Overall, an increasing OTI score reflects an increase in trophic condition (more eutrophic).

Lake-by-Lake Assessment

Lake Superior

Status: Good

10-Year Trend (2013-2022): Unchanging

Long-term Trend (1998-2022): Unchanging

Rationale: All nearshore and offshore stations in Lake Superior were classified as oligotrophic, based on OTI scores, both long-term (1998-2022) and in recent years (2021-2022). No significant long-term or 10-year trends were observed in the trophic condition of the lake. The endpoint for this sub-indicator is to maintain oligotrophic conditions in the open waters of Lake Superior.

Lake Michigan

Status: Good

10-Year Trend (2013-2022): Unchanging

Long-term Trend (1998-2022): Unchanging

Rationale: Since 1998, the majority (12 out of total 16) of stations in Lake Michigan had OTI scores below 0.6, indicating an oligotrophic condition. Of the nine nearshore stations, one was mesotrophic (0.6 < OTI < 1.0), and three were eutrophic (OTI scores > 1.0). Significant long-term trends of increasing eutrophication were evident at seven nearshore stations, and trends of increasing oligotrophication were found at one offshore station and one station in Green Bay. Overall, no significant long-term or 10-year trends were observed in the trophic condition of the lake as a whole. The endpoint for this sub-indicator is to maintain an oligotrophic state in the open waters of Lake Michigan.

Lake Huron

Status: Good

10-Year Trend (2013-2022): Unchanging

Long-term Trend (1998-2022): Unchanging

Rationale: All stations in Lake Huron are oligotrophic except for three nearshore stations (two mesotrophic and one eutrophic). The trophic condition of the lake, as measured by OTI scores, has not changed significantly since 1998. The endpoint for this sub-indicator is to maintain an oligotrophic state in the open waters of Lake Huron.

Lake Erie

Status: Poor

10-Year Trend (2013-2022): Unchanging

Long-term Trend (1998-2022): Unchanging

Rationale: Almost all stations in Lake Erie are eutrophic, and two have a long-term trend of increasing eutrophication. However, two stations have a long-term trend of increasing oligotrophication. Overall, no significant long-term or 10-year trends in trophic condition were observed. The endpoint for this sub-indicator is to maintain mesotrophic conditions in the open waters of the western and central basins of Lake Erie, and oligotrophic conditions in the eastern basin of Lake Erie.

Lake Ontario

Status: Fair

10-Year Trend (2013-2022): Unchanging

Long-term Trend (1998-2022): Unchanging

Rationale: OTI scores indicate that all deep-water stations (>80 m) in both the western and eastern basins of Lake Ontario are oligotrophic, whereas two nearshore stations are eutrophic, one is mesotrophic, and one is oligotrophic in 2021-2022. The nearshore stations that were mesotrophic and oligotrophic during 2021 and 2022 had previously been eutrophic in 2017-2019. However, the two eutrophic nearshore stations showed trends of increasing oligotrophication. Overall, no significant decreasing or increasing trends were found in the trophic condition of the lake either since 1998 or in the last 10 years.

Status Assessment Definitions

Good: OTI score of less than 0.6 (oligotrophic conditions)

Fair: OTI score of 0.6 to 1.0 (mesotrophic conditions)

Poor: OTI score of greater than 1.0 (eutrophic conditions)

Undetermined: Data are not available or are insufficient to assess condition of the ecosystem components.

Trend Assessment Definitions

The desired trend is toward an oligochaete open water community indicative of oligotrophic conditions throughout the lakes, with the exception of the nearshore waters of all lakes and open waters of the western and central basins of Lake Erie, where mesotrophic conditions are desired.

Improving: a decrease in the OTI indicating declining eutrophication (i.e., increasing oligotrophication)

Unchanging: OTI score is not changing

No Trend: Data are available for a 10 year or longer period, but the trend is not statistically Improving or Deteriorating due to high variability in the data. No Trend is different from Unchanging (which would be used when the OTI score is not changing and has low variability (i.e., stable)) and Undetermined (which should be reserved for cases where data availability is limited).

Deteriorating: an increase in the OTI indicating increasing eutrophication (i.e., declining oligotrophication)

Undetermined: metrics do not indicate a clear overall trend, or data are not available to report on a trend

Endpoints and/or Targets

Maintain an oligotrophic state consistent with healthy aquatic ecosystems in the open waters of Lakes Superior, Michigan, Huron, and Ontario; maintain mesotrophic conditions in the nearshore waters of all lakes and open waters of the western and central basins of Lake Erie, and oligotrophic conditions in the eastern basin of Lake Erie.

Sub-Indicator Purpose

The purpose of this sub-indicator is to assess trends in trophic conditions in the Great Lakes using oligochaete diversity, abundances, and the individual species responses to organic enrichment. We also report general trends in the full benthic community; although these supplementary data are not used directly in the indicator assessment, they provide useful context.

Ecosystem Objective

The Ecosystem Objective is that the benthic community in the Great Lakes should be comparable to unimpaired waters with similar depth and substrate.

This sub-indicator most closely aligns with General Objectives #5 and #6 of the 2012 Great Lakes Water Quality Agreement, which states that the Waters of the Great Lakes should “support healthy and productive wetlands and other habitats to sustain resilient populations of native species” and “be free from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that promote growth of algae and cyanobacteria that interfere with aquatic ecosystem health, or human use of the ecosystem”.

This sub-indicator evaluates trophic conditions in the Great Lakes using oligochaete diversity, abundances, and the individual species responses to organic enrichment.

Methods

This sub-indicator (OTI) evaluates trophic conditions in the Great Lakes using oligochaete diversity, abundances, and the individual species responses to organic enrichment. In addition to the assessment of lake trophic status using OTI, we are providing summary data on status and trends in the whole benthic community and its role in food webs for additional context.

Triplicate samples for benthic invertebrates were collected from each long-term station using a Ponar grab (sampling area 0.0523 m^2), washed through a 500 µm mesh sieve and preserved in 5-10% formalin. Organisms were picked

out of samples using a dissecting microscope. Oligochaetes and chironomids were mounted on slides and identified under a compound microscope; other organisms were identified under a dissecting microscope. Chironomids were mostly identified to genus; other invertebrates were identified to species, when possible. Adult oligochaetes were identified to species; immatures were taken to the lowest taxonomic level, usually family; fragments were included in biomass but excluded from density estimates. To calculate the wet weight, we blotted dry and then weighed all individuals of each species (or size category, e.g., as for Oligochaeta and *Dreissena*), recorded the total number and weight for the group. All *Dreissena* in each sample were identified to species, counted, measured, and weighted by 5 mm size groups. The density (ind.m^{-2}) and biomass (g m^{-2}) of benthic invertebrates were calculated using counts and wet weights (molluscs with shells) in each sample.

Calculation of the OTI

To evaluate trends in the trophic conditions of the Great Lakes based on status of benthic community, an OTI is used. The OTI was initially described by Mozley and Howmiller (1977) with subsequent modifications by Howmiller and Scott (1977), Milbrink (1983), and Lauritsen et al. (1985). This sub-indicator primarily follows Milbrink's formula (Burlakova et al. 2018a) with several modifications. Here we use the old division of Oligochaeta by Enchytraeidae, Lumbriculidae, Naididae and Tubificidae, comparable with historical data, despite the fact that only three orders are currently recognized (Enchytraeida, Lumbriculida and Tubificida) and former families of Naididae and Tubificidae in the order Tubificida are now combined in one family Naididae (Erseus et al., 2008). Therefore for practical reasons and clarity Tubificidae was retained for the analyses. Oligochaetes (tubificids and lumbriculids) are classified into four ecological classes relative to their tolerance to organic pollution, from 0 indicating intolerant of enrichment to 3 indicating tolerant of enrichment. The index ranges from 0 to 3; scores less than 0.6 indicate oligotrophic conditions; scores above 1 indicate eutrophic conditions; and scores between 0.6 and 1.0 indicate mesotrophic conditions. The index is calculated as:

$$c * [(1/2\sum n_0 + \sum n_1 + 2\sum n_2 + 3\sum n_3) / (\sum n_0 + \sum n_1 + \sum n_2 + \sum n_3)$$

where n_0, n_1, n_2, and n_3 indicate the abundances of organisms in each of the four trophic categories (see Table 1) and c is a density coefficient that scales the index to absolute densities (m^{-2}) of tubificids and lumbriculids. The c coefficient is as follows (Milbrink 1983):

c=1 if n > 3,600

c=0.75 if 1,200 < n <3,600

c=0.5 if 400 < n < 1,200

c=0.25 if 130 < n < 400

c=0 if n < 130

There are several parts of the OTI calculation that were interpreted as follows (Riseng et al. 2014):

- only lumbriculids and tubificids were used to calculate the index;
- all immature lumbriculids were classified as Stylodrilus heringianus;
- the c coefficient was estimated from abundances (n) of mature and immature lumbriculids and tubificids.

Milbrink (1983) assigned the tubificid *Tubifex tubifex* dual classifications depending on the dominance of *S. heringianus* or *Limnodrilus hoffmeisteri*. The dual classification was formalized as follows: if the ratio of abundances of n_0 oligochaetes to n_3 oligochaetes (*L. hoffmeisteri*) < 1 then *T. tubifex* is classified as a 3; if the ratio is >1 then *T. tubifex* is classified as a 0; however, if the ratio is close to one (0.75 to 1.25) then *T. tubifex* is a 3 if $c \geq 0.5$ and a 0 if

$c < 0.5$; if *L. hoffmeisteri* density is zero and n_0 is relatively high and/or total density is low, then *T. tubifex* is 0, otherwise 3. If the total density of oligochaetes is zero, then the OTI is zero.

Trophic classifications were obtained from literature for the Great Lakes and are shown in Table 1.

For each lake or sub-basin, a graph showing the OTI values on the y-axis and years on the x-axis is presented to illustrate the changes in species metrics over time (Figure 1). A map is used to show the major, within lake, spatial-temporal differences (Figures 2 and 3).

Data are sourced from the long-term benthic monitoring program of U.S. EPA Great Lakes National Program Office (GLNPO) which samples 57 stations annually within the five Great Lakes during summer (August). While this monitoring program started in 1997, data from 1997 are omitted from the status and trends assessments in this report due to unreconcilable discrepancies. The GLNPO benthic station ON64 was discontinued in 2016; prior to 2016 a total of 58 long-term monitoring stations were sampled and included in the OTI calculations. Less frequent but more spatially intensive sampling of all Great Lakes is now undertaken during Cooperative Science Monitoring Initiative (CSMI) field years to enhance lake-wide estimates of changes in benthic community diversity and abundance.

Discussion

State of the Great Lakes Reporting uses the modified oligochaete-based trophic condition index (OTI, Milbrink 1983; Howmiller and Scott 1977) to assess trophic status of each station. Benthic invertebrate data for OTI calculation are collected annually at 57 permanent GLNPO sampling stations (Lakes Superior and Huron: 11 stations each, Michigan: 16, Erie: 10, and Ontario: 9 stations) located mostly offshore (Figure 2). The OTI is calculated based on known organic enrichment tolerances and abundances of aquatic annelid worms (Oligochaeta) (see the Methods section for more information). As organic pollution increases, oligochaete species with different physiological tolerances to water and sediment pollution replace each other and the community composition shifts. Overall, an increasing OTI means increasing eutrophication or increasing trophic conditions. The OTI scores range from 0 – 3: scores less than 0.6 (the lower blue line in Figure 1) indicate oligotrophic conditions; scores above 1 (the top red line in Figure 1) indicate eutrophic conditions; and scores between 0.6 and 1 suggest mesotrophic conditions. Scores approaching 3 indicate high densities of oligochaetes dominated by the pollution tolerant tubificids.

Because we expect nearshore and offshore stations to support different benthic communities, we make the distinction between offshore and nearshore zones when using the OTI to assess overall lake-wide trends in trophic conditions. The original GLNPO sampling program design established two components (offshore and nearshore) with different objectives: the offshore component is intended to assess the benthic invertebrate community as an indicator of basin-wide cumulative stressors, while the nearshore component serves as an indicator of more localized environmental stressors (Barbiero et al., 2018). For example, some of the benthic stations were chosen near tributary mouths that deliver organic matter to the lake. In general, Oligochaeta distributions exhibit depth-specific patterns, with species that are tolerant of organic enrichment found only at depths <70m. As a result, many nearshore stations will be classified as eutrophic. Because the offshore component of the monitoring program is designed to be used as an indicator of basin-wide cumulative stressors, the offshore data most directly address the goal of this indicator.

A consistent difference in trophic conditions among and within the Great Lakes was found during the study period (1998– 2022) (Figure 1). Trophic condition was significantly inversely related to station depth ($r = -0.75$, $P < 0.001$), with Lake Erie being the most eutrophic lake, followed in order of decreasing trophic condition by lakes Ontario, Michigan, Huron, and Superior. To assess the temporal trends in OTI scores at each station, we used linear regression, and trends were considered significant if $P < 0.05$. No significant lake- or basin-wide long-term trends of increasing

trophic condition were found since 1998, but localized positive or negative trends in OTI scores over time were found at some stations in Lake Erie, Michigan, Huron, and Ontario (Figure 3).

All 11 stations in Lake Superior were oligotrophic based on OTI scores since 1998, and there were no significant long-term or 10-year trends in OTI scores either lake-wide scale or at specific stations (Figure 3), consistent with the 2022 report. Densities of major taxonomic groups, including *Diporeia*, an indicator of oligotrophic conditions and an important lipid-rich fish prey item (e.g., Kainz et al., 2010), were stable in Lake Superior from 1998 (Figure 4). The Lake Superior total benthos biomass is the lowest of all Great Lakes, but *Diporeia* comprised over 50% of the biomass (Figure 5).

Almost all stations in northern and central Lake Michigan, as well as deep stations in the southern part of the lake (13 of 16 total stations) are oligotrophic (Figure 2). Of the 9 nearshore stations in Lake Michigan two southeastern stations (MI48 near the Kalamazoo River outlet and MI46 near the Grand River outlet) and one northern Michigan station (MI52) were eutrophic and one station (MI49 in Green Bay) was mesotrophic. Six nearshore stations and one offshore station (MI51, 106 m) had significant long-term trends of increasing eutrophication ($P < 0.01$) in 2021-2022, compared to five nearshore stations and one offshore station in the 2022 report. At the same time, one deep station (MI47, 186m, $P < 0.03$), along with one station in Green Bay (MI49, 44 m, $P < 0.0001$), showed signs of increasing oligotrophication (Figure 3). Overall, no significant lake- or basin-wide long-term trends of increasing trophic condition were found in the lake since 1998. Lake Michigan exhibits the highest lake-wide density and biomass of *Dreissena* of all invaded Great Lakes (Figures 5, 6). The majority of Lake Michigan's non-dreissenid biomass is comprised of Oligochaeta (Figure 5). Nearshore *Diporeia* in Lake Michigan underwent large declines in early 2000s, followed by declines in offshore populations in the mid-2000s, but have remained relatively stable at depths >90 m since 2005. Despite the declines in *Diporeia*, high total benthic biomass (including *Dreissena*) in Lake Michigan can likely support abundant benthic fish populations and native fish that feed on benthos and/or bottom fish. The percent of Oligochaeta comprising the non-dreissenid community increased with the decline in *Diporeia* and Sphaeriidae that began in early 2000s (Figure 4).

Most of the stations in northern and central Lake Huron (8 of 11 total stations) are oligotrophic (Figure 2). Of the five nearshore stations, two were classified as mesotrophic and one as eutrophic (Figure 2). Two of these mesotrophic stations (HU06, the southernmost station, and HU96, near the outlet of Saugeen River in Ontario, Canada) were classified as eutrophic during the previous reporting period. The only eutrophic station is located in Saginaw Bay (Figure 2). Overall, no significant lake- or basin-wide long-term trends of increasing trophic condition were found in the lake since 1998. The Lake Huron benthic community, including *Diporeia*, has undergone similar changes as in Lake Michigan, but the lake-wide density and biomass of *Dreissena* is lower than in lakes Michigan and Ontario (Figures 5, 6). Currently, the majority of Lake Huron non-dreissenid biomass is comprised of Oligochaeta (Figure 5). The percent of Oligochaeta in non-dreissenid community increased with the decline in *Diporeia* and Sphaeriidae that began in late 1990s (Figure 4).

In Lake Erie, all stations are shallower than 70m deep. Eight stations were classified as eutrophic, and two stations were classified as mesotrophic. Two stations changed their status compared to the previous reporting period, including station ER78, which was eutrophic in the 2022 report but was classified as mesotrophic in 2021-2022, and station ER63, which was mesotrophic in the 2022 report but was classified as eutrophic in 2021-2022. No significant trends of increasing eutrophication were found lake-wide in the trophic condition during either the long-term or in the last 10 years. Two stations showed significant long-term trends of decreased OTI scores (ER63, $P < 0.005$, and ER91, $P < 0.015$), compared to one station in the 2022 report. Due to large declines in *Dreissena* in Lake Erie in the last decade caused by hypoxic events in the central and western basins, the lake-wide dreissenid density and biomass in these two basins are now the lowest of all invaded lakes, but the biomass in the eastern basin is still high (Karatayev et al., 2018, 2022b) (Figures 5, 6). Biomass of non-dreissenid benthos is the highest among all other

lakes and is largely comprised by Oligochaeta in the eastern and central basins, and *Hexagenia* in the western basin. The largest density of Oligochaeta in the lake was found in 2000s. *Diporeia* has not been found in Lake Erie samples since the beginning of GLNPO monitoring in 1997, but abundant benthic communities can support large fish populations. Overall, due to shallow depths and high productivity, Lake Erie has higher benthic biomass and species richness than the other Great Lakes (Burlakova et al., 2018b).

All deep-water stations in Lake Ontario have remained oligotrophic throughout the 1998-2022 reporting period, and no significant trends in the trophic condition were found lake-wide both long-term and in the last 10 years. However, in the current reporting period only two nearshore stations (ON69 and ON67) were eutrophic (Figure 2). These stations are located in the western basin and displayed a trend toward increasing eutrophication since 1998 (likely being affected in the southern shore by the outlet of the Niagara River) (Figure 3). Compared to the previous report in 2021-2022, two stations changed status from eutrophic to mesotrophic and oligotrophic. Deep stations, for the most part, remain oligotrophic and Unchanging in both the long-term and within the last 10 years. Lake Ontario has the second largest biomass and density of *Dreissena* among the Great Lakes and dreissenid populations are stable (Figures 5, 6). The replacement of *Diporeia* with quagga mussels and Oligochaeta began in Lake Ontario in the 1990s, which was earlier than in the other deep lakes, and very few *Diporeia* have been recorded in the samples since the late 2000s. As in the other lakes, both density and biomass of non-dreissenid benthos are now dominated by Oligochaeta.

Overall, benthic communities in lakes Ontario, Michigan and Huron have shifted from dominance by *Diporeia* to dreissenids and oligochaetes during the time series. Dreissenid populations continue to increase in deep regions of Lake Michigan, Huron, and Ontario and decline in shallow areas of deep lakes as well as in Lake Erie, but non-dreissenid populations have exhibited relative stability over the past decade. Dreissenids were the largest contributor of biomass (>99%) in all lakes except Superior. Following the patterns of declining benthic diversity and density with depth, Lake Erie benthos is the most abundant and diverse, and supports the most productive Great Lakes fishery. In lakes where *Diporeia* no longer constitutes a significant part of benthic community (all lakes except Lake Superior), current benthic populations (including dreissenids) can still sustain substantial amounts of benthivorous fish, transferring the energy from the lower to the upper trophic levels (Madenjian et al., 2010).

Linkages

Linkages to other sub-indicators in the indicator suite include:

- Dreissenid Mussels – the relative abundance of non-native suspension feeding benthic species such as zebra and quagga mussels can dramatically change the structure of aquatic communities (both benthic and pelagic), affect ecosystem functioning, and alter lake trophic state. In addition to direct local effects (e.g. creating additional habitat and enhancing food supply for some benthic species), dreissenid mussels also affect other sub-indicators such as Nutrients in Lakes, Chlorophyll, Phytoplankton, Zooplankton, and *Diporeia*, and they alter the amount of available food for some profundal taxa (Karatayev and Burlakova, 2022a, b). In addition, dreissenids together with other benthic taxa abundant in mussel aggregations serve as food for fish, including round goby (Walsh et al., 2007; Perello et al., 2015), that in turn are preyed upon by many other fish species (e.g., lake sturgeon, walleye, salmon, smallmouth and largemouth bass, lake trout, whitefish and yellow perch) (Steinhart et al., 2004; Pennuto et al., 2021). There are strong interactions between these sub-indicators that are not well understood and require further investigation.
- Nutrients in Lakes (open water) – as a natural and essential part of aquatic ecosystems, nutrients play an important role in supporting the production of aquatic plants and algae, which provide food and habitat

for planktonic and benthic organisms at the base of the food chain. The addition of nutrients affects the structure, abundance, and population dynamics of the benthic community, changing the proportion of tolerant and intolerant species, but the magnitude of changes varies depending on the depth and lake trophic status. Since the OTI was designed to reflect community changes following organic enrichment, it is expected to co-vary with an increase in nutrients. Indeed, the OTI positively correlates with the amount of Total Phosphorus and Total Soluble Phosphorus measured in near-bottom waters (Burlakova et al. 2018a). On the other hand, dreissenids can alter the amount and turnover of nutrients in the water and sediments (Li et al. 2021).

- *Diporeia* (open water) – *Diporeia* is a benthic macroinvertebrate in the cold, deep-water habitats of all the Great Lakes (except Lake Erie, where it is extirpated). It is an indicator of oligotrophic conditions, and an important fish food item. Historically *Diporeia* had been a dominant benthic macroinvertebrate in profundal regions of all five of the Great Lakes (Cook and Johnson, 1974). Proliferation of dreissenid mussels coincided with significant declines in *Diporeia* in Lakes Ontario, Michigan, and Huron, but the nature of these interactions is still not well-understood. While the abundance of *Diporeia* is not included and not necessarily responsive to the OTI, a significant increase in organic enrichment may negatively affect *Diporeia*.
- Changes in Physical Conditions – increasing water temperatures may affect survivorship and increase the developmental rate, the timing of development, spawning, and food availability for benthic taxa. As a result, there may be potential shifts in distribution and abundance of oligochaetes, affecting the performance of the OTI index, driven directly by water temperature. Both abiotic changes and biological responses in the lakes are complex, and changes in water chemistry, hydrology, etc. may also be important for the growth and survival of benthic organisms. Warmer water temperatures may stimulate biological activity, reduce the solubility of oxygen in water, and lead to longer and more intense periods of stratification that, coupled with intensive land use and widespread use of fertilizers in agricultural areas, will likely increase the extent, severity, and duration of bouts of hypoxia in Great Lakes (reviewed in Tellier et al., 2022).

This sub-indicator also links directly to the other sub-indicators in the Habitat and Species indicator.

Assessing Data Quality and Data Availability

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

Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X			
Data used in assessment are openly available and accessible	Yes	Data can be found here: https://cdx.epa.gov/		

Clarifying Notes:

*The annual benthic monitoring program design of U.S. EPA GLNPO samples 9-16 stations per lake, larger spatial coverage provided by CSMI surveys.

Notes on Accessing Data

Those wishing to access the raw benthos data used in this report will need to make an account on USEPA's CDX site linked in the table above and will need to request access to the Great Lakes Environmental Database (GLENDA) data portal.

Data Limitations

The OTI was developed to characterize situations of organic enrichment due to anthropogenic eutrophication, which was an important issue addressed by the Great Lakes Water Quality Act in 1972. Currently, the Great Lakes open waters are undergoing a reverse trend of gradual oligotrophication due to the combined effect of nutrient mitigation and dreissenids (Evans et al., 2011). Therefore, excessive eutrophication remains an issue only in some nearshore areas and shallow bays (e.g., western Lake Erie, Saginaw Bay, Green Bay), but is no longer a concern at lake-wide scales or in profundal areas, limiting the utility of the OTI for this sub-indicator. In addition, the current index does not allow for assessment of the status and trends in the whole benthic community, which is a gap given the whole benthic community's role in food webs. Therefore, this sub-indicator would be improved by using an index or indices that account for the whole benthic community.

Two important factors should be considered while using the OTI to evaluate lake trophic conditions. First, due to species-specific patterns of Oligochaeta distribution with depth, most of the species tolerant of organic enrichment are found at depths <70 m (Burlakova et al., 2018b). Secondly, some of the benthic stations were deliberately positioned next to mouths of large tributaries that deliver large amounts of organic matter to the lake (Barbiero et al., 2018). As a result, many nearshore stations will be classified as eutrophic. The ratio of nearshore (≤70 m) to offshore stations varies by lake (100% in Lake Erie, 56% in Michigan, 45% in Huron, 44% in Ontario, and 18% in Superior) and may therefore additionally affect the overall OTI score and our estimates of trophic condition of the lake.

Additional Information

Benthic invertebrate biomonitoring has long been a tool of choice in assessing anthropogenic impacts on aquatic systems due to species' relative longevity, limited mobility, and wide range in tolerance to environmental stressors. Abundant, pollution-tolerant benthic species indicate degraded habitats. Increasing species diversity and decreasing abundance of pollution-tolerant species indicate return to healthy habitats. In addition, benthic secondary production plays a central role in supporting higher trophic level production, comprising over half of total consumption of fishes common to north-temperate lakes of North America (Vander Zanden and Vadeboncoeur, 2002). The benthic

community serves as a good indicator of overall ecosystem health as it integrates water, sediment and habitat qualities. Changes in the benthic community closely reflect shifts in the overall productivity of the system.

The oligochaete sub-indicator used for the benthos component of the State of the Great Lakes report assesses trophic status of the lakes and may suggest pressures due to organic enrichment. Most of the stations that showed increasing eutrophication are located near large river mouths, suggesting that pollution abatement efforts in the upland watersheds could help to improve water quality and sediment conditions at these stations. Other pressures not accounted for in the OTI include invasive species, changes in physical conditions, water level changes, and toxins or other contaminants. The tendency of OTI to decrease with depth (due to the lack of pollution-tolerant species residing deeper than 70 m) may affect lake-wide index values, depending on the ratio of deep to shallow stations sampled in each lake. Non-native species that strongly affect freshwater ecosystems (e.g., *Dreissena* spp.) can alter the composition and abundance of benthic communities, affecting behavior of benthic indices, and can modify the response of communities to trophic state.

There is an emerging realization of the importance of benthic processes and pathways within a whole-lake context (Vander Zanden and Vadeboncoeur, 2002). A recent analysis of long-term dynamics of major trophic levels in the Laurentian Great Lakes revealed a far greater prevalence of bottom-up regulation since 1998, as a result of long-term declines in total phosphorus (TP) inputs and the more recent proliferation of nonindigenous dreissenid mussels (Bunnell et al. 2013). Filter feeding Ponto-Caspian bivalves *Dreissena polymorpha* and *D. rostriformis bugensis* are powerful ecosystem engineers that affect both abiotic (e.g., enhance water clarity and alter nutrient cycling) and biotic (e.g., reduce abundance of phytoplankton and microzooplankton, enhance benthic algae and macrophytes, induce changes in benthic community) components of the ecosystem (Karatayev et al. 1997, 2002; Higgins and Vander Zanden 2010; Karatayev and Burlakova, 2022a, b). Dreissenid tissues and shells now contain nearly as much phosphorus as the entire water columns of the impacted Great Lakes, and mussels have become a major agent of phosphorus cycling, offsetting or overshadowing the effects of external loading (Li et al. 2021). Filter-feeding activity, sediment deposition and habitat provided by dreissenids directly affect benthic macroinvertebrate community abundance and composition by promoting epifaunal predators, scavengers, and collectors while replacing native filter feeders (e.g., Karatayev et al. 1997, 2002; Ward and Ricciardi 2007; Higgins and Vander Zanden 2010; Bayba et al., 2022). After the *Dreissena* invasion, the abundance of some non-dreissenid taxa (e.g., *Diporeia*, Sphaeriidae) declined in profundal habitats (Nalepa et al. 2007, 2009; reviewed in Karatayev and Burlakova, 2022a, b) where quagga mussels compete for space and food resources with most of native invertebrates. This may be a result of system-wide (e.g. food interception effect, resulting in a strong decline of spring phytoplankton blooms) vs. local *Dreissena* (e.g. enrichment of sediments with biodeposits) effects. The resulting effect of *Dreissena* on the oligochaete community (e.g., increasing amount of both tolerant and intolerant Oligochaeta in the presence of *Dreissena*, Burlakova et al., 2018b; Bayba et al., 2022; Eifert et al., 2023) may induce changes in the OTI that will not reflect the changes in the trophic status of the ecosystem. Therefore, more data on the effect of dreissenids on species composition and abundance of benthic invertebrates in profundal vs. nearshore zone are needed to fully understand dreissenid impacts on benthic communities.

The number of permanent stations visited by U.S. EPA GLNPO allows for a cost-effective benthic monitoring program each year. Less frequent (once every 5 years) but more spatially explicit sampling of all Great Lakes occurs during the Cooperative Science and Monitoring Initiative intensive field years to assess changes in benthic community diversity and abundance. These lake-wide samplings of historical stations and other stations of concern allow the diversity, density, and biomass of the benthic community to be monitored in each lake and enable the estimation of lake-wide population changes of invasive and native indicator species (e.g., dreissenids, *Hexagenia*, *Diporeia*; Mehler et al., 2020; Karatayev et al., 2022a, b; Burlakova et al., 2022).

Values of the Benthos sub-indicator representative of the nearshore are very important, as nearshore benthos are more diverse and are also affected more quickly and more directly (than offshore benthos) by inputs from adjacent watersheds, including runoff of nutrients. However, different indicators and indices would need to be developed for the assessment of status and trends in the nearshore benthic community, since many of the nearshore substrates lack the Oligochaete species used in the calculation of the current benthic index (OTI) for State of the Great Lakes reporting. In addition, the current index does not allow for assessment of status and trends in the whole benthic community and its role in food webs.

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Source: Riseng et al. 2014.

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Figure 1. Scatterplot of the index scores for Milbrink's (1983) modified Oligochaete Trophic Index, applied to data from GLNPO's 1998 through 2022 summer surveys. Scores ranging from 0 to less than 0.6 indicate oligotrophic conditions (blue line); scores from 0.6 to 1.0 indicate mesotrophic conditions (red line); and scores greater than 1.0 indicate eutrophic conditions. Data points represent the average of triplicate samples taken at each sampling station; immature specimens were included in the analysis for calculation of overall density used to establish the coefficient *c* but only mature specimens were used to calculate the number belonging to each ecological group of oligochaetes (see the description of index calculation in the Methods section).

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Source: 1998-2022 U.S. EPA GLNPO benthic data.

Figure 4. Trends in benthos areal density (bottom panels) and percent areal density (top panels) of major taxonomic groups in Great Lakes (1998–2022). These values exclude *Dreissena* spp., which was monitored only after 2003, and Bivalves include only Sphaeriidae. Error bars represent one standard error.

Source: 1998-2022 U.S. EPA GLNPO benthic data. U.S. EPA Great Lakes National Program Office. (2023). EPA_GLBMP_Benthic Macroinvert Data 1998-2022_20230922_V1 [Microsoft Excel file]. Retrieved from https://cdx.epa.gov/

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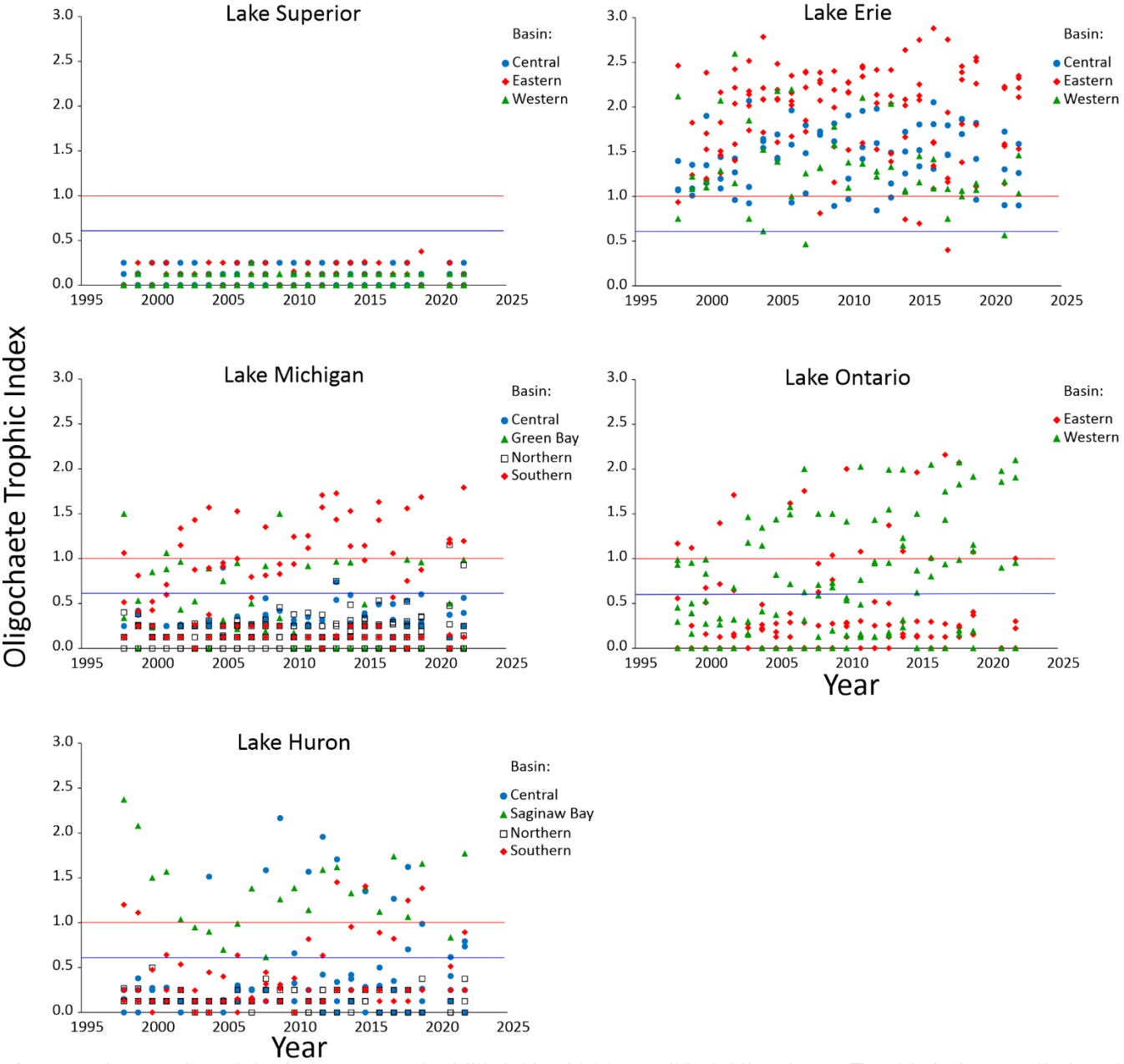
Source: Riseng et al. 2014.

SPECCODE	GENUS	SPECIES	Trophic Class	Source	Comment
RHYCOCC	*Rhyacodrillus*	*coccineus*	0	Howmiller and Scott 1977	Same classification as Krieger 1984 & Lauritsen et al. 1985
TASAMER	*Tasserkidrilus*	*americanus*	0	Howmiller and Scott 1977	formerly *T. kessleri* in both Lauritsen et al. 1985 and Krieger 1984
LIMPROF	*Limnodrilus*	*profundicola*	0	Howmiller and Scott 1977	Same classification as Krieger 1984 & Lauritsen et al. 1985
RHYMONT	*Rhyacodrilus*	*montana*	0	Krieger 1984	Same classification as Lauritsen et al. 1985
RHYSP	*Rhyacodrilus*	*spp.*	0	Krieger 1984	Same classification as Lauritsen et al. 1985
SPINIKO	*Spirosperma*	*nikolskyi*	0	Krieger 1984	Same classification as Lauritsen et al. 1985
STYHERI	*Stylodrilus*	*heringianus*	0	Howmiller and Scott 1977	General agreement from all sources for this taxon
TASSUPE	*Tasserkidrilus*	*superiorensis*	0	Krieger 1984	Same classification as Lauritsen et al. 1985
AULAMER	*Aulodrilus*	*americanus*	1	Howmiller and Scott 1977	Classification based on Aulodrilus sp.
AULLIMN	*Aulodrilus*	*limnobius*	1	Milbrink 1983	
AULPIGU	*Aulodrilus*	*pigueti*	1	Milbrink 1983	
ILYTEMP	*Ilyodrilus*	*templetoni*	1	Krieger 1984	Same classification as Milbrink 1983 & Lauritsen et al. 1985
ISOFREY	*Isochaetides*	*freyi*	1	Krieger 1984	Same classification as Lauritsen et al. 1985
SPIFERO	*Spirosperma*	*ferox*	1	Howmiller and Scott 1977	Same classification as Krieger 1984 & Lauritsen et al. 1985
AULPLUR	*Aulodrilus*	*pluriseta*	2	Milbrink 1983	
LIMANGU	*Limnodrilus*	*angustipenis*	2	Howmiller and Scott 1977	
LIMCERV	*Limnodrilus*	*cervix*	2	Howmiller and Scott 1977	same as Milbrink 1983
LIMCECL	*Limnodrilus*	*cervix/ claparedeianus*	2	Howmiller and Scott 1977	same as Milbrink 1983
LIMCLAP	*Limnodrilus*	*claparedeianus*	2	Howmiller and Scott 1977	same as Milbrink 1983

LIMMAUM	*Limnodrilus*	*maumeensis*	2	Howmiller and Scott 1977	
LIMUDEK	*Limnodrilus*	*udekemianus*	2	Howmiller and Scott 1977	same as Milbrink 1983
POTBEDO	*Potamothrix*	*bedoti*	2	Milbrink 1983	
POTMOLD	*Potamothrix*	*moldaviensis*	2	Milbrink 1983	Same classification as Lauritsen et al. 1985
POTVEJD	*Potamothrix*	*vejdovskyi*	2	Milbrink 1983	Same classification as Lauritsen et al. 1985
QUIMULT	*Quistadrilus*	*multisetosus*	2	Howmiller and Scott 1977	
LIMHOFF	*Limnodrilus*	*hoffmeisteri*	3	Milbrink 1983	Differs from classification in Lauritsen et al. 1985
TUBTUBI	*Tubifex*	*tubifex*	0 or 3	Milbrink 1983	Depends on densities of LIMHOFF and STYHERI and total oligochaete density



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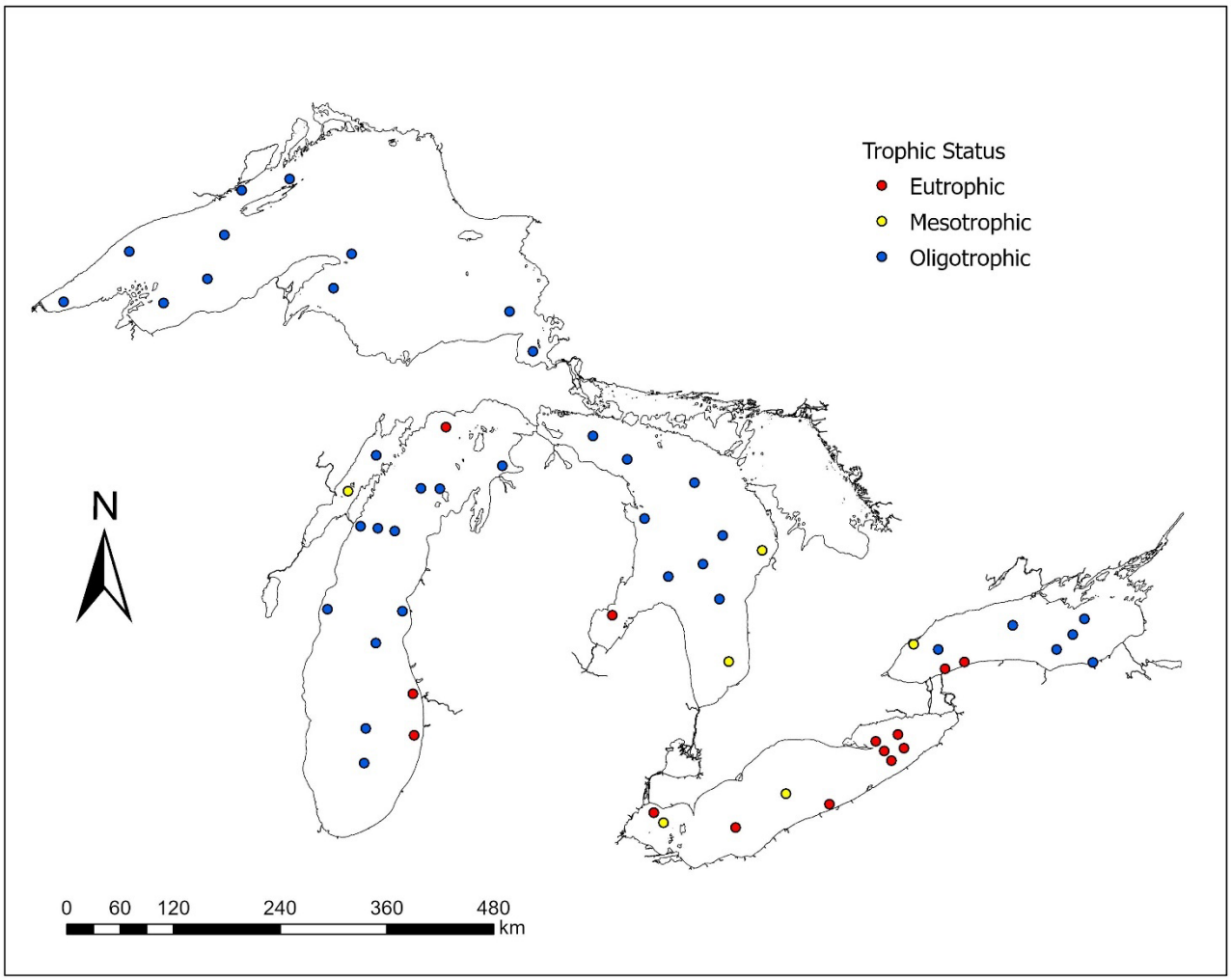

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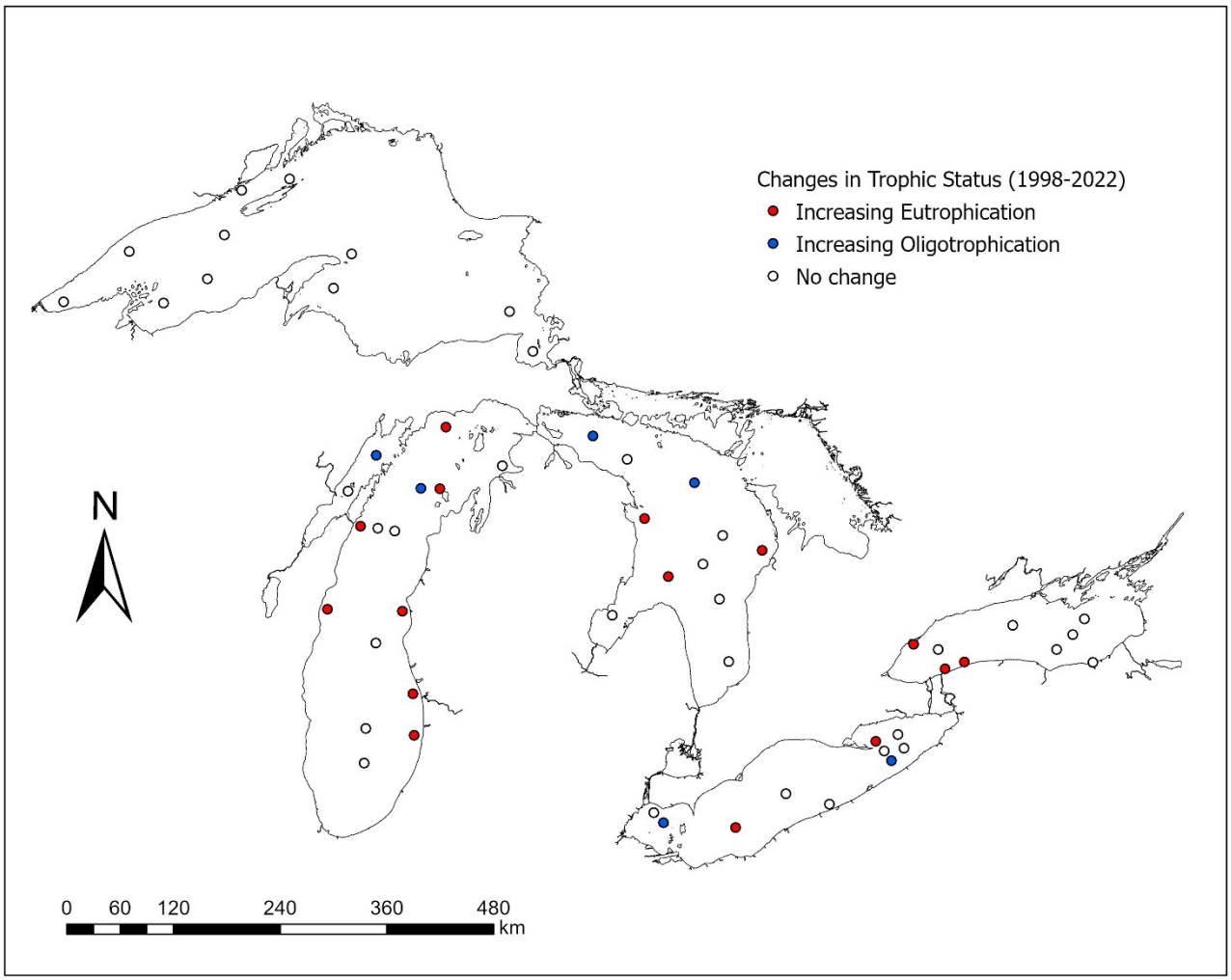

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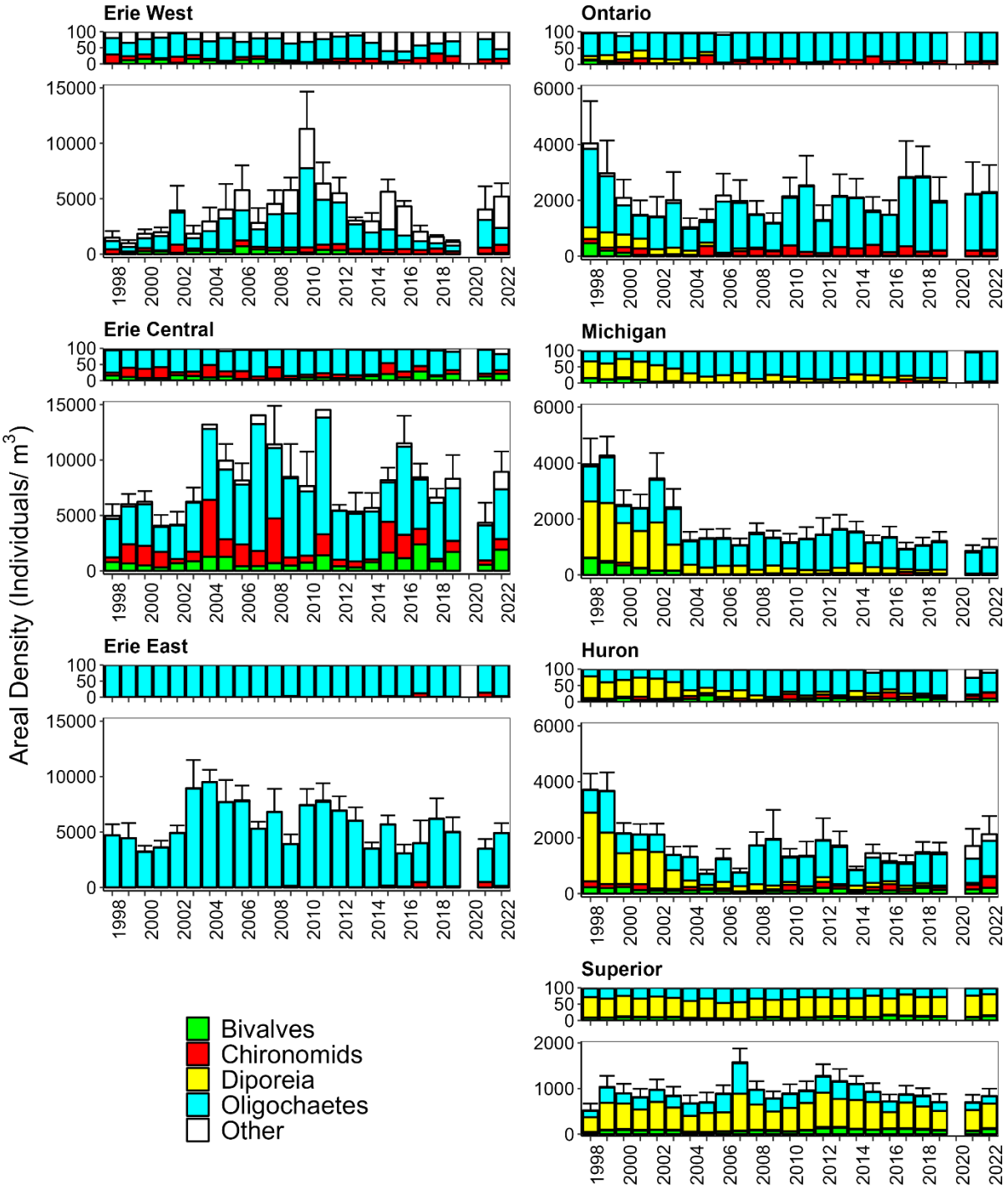

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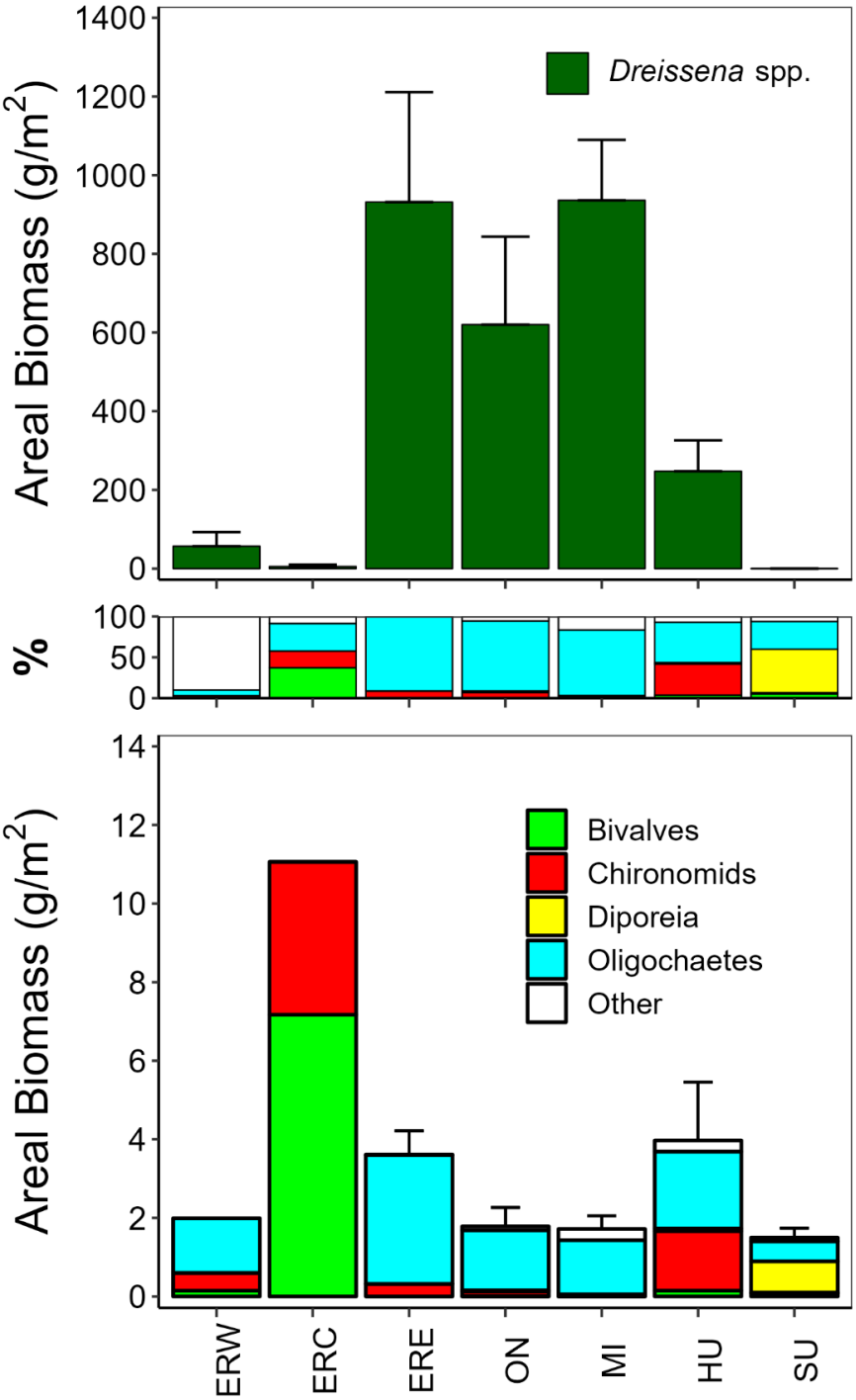

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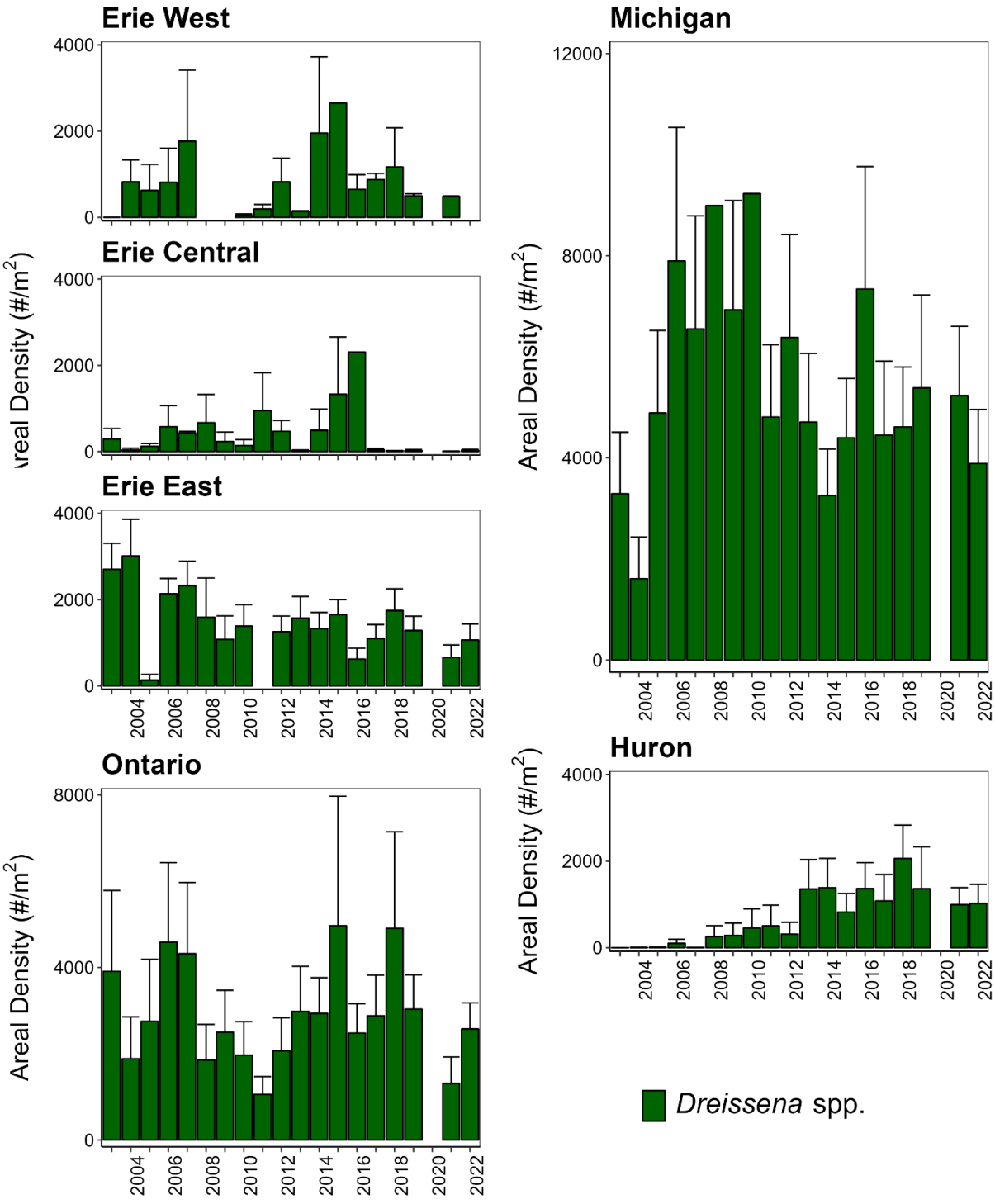

Figure 6. Changes in density (2003–2022) of dreissenid mussels in Lakes Erie, Michigan, Ontario, and Huron. Dreissenid mussel populations are not established in Lake Superior. Error bars represent one standard error.

Source: 2003-2022 U.S. EPA GLNPO benthic data.

U.S. EPA Great Lakes National Program Office. (2023). EPA_GLBMP_Benthic Macroinvert Data 1998-2022_20230922_V1 [Microsoft Excel file]. Retrieved from https://cdx.epa.gov/