Sub-Indicator: Zooplankton

Overall Assessment

Status: Good

Trends:

10-Year Trend (2013-2022): No Trend

Long-term Trend (1997-2022): Deteriorating

Rationale: The oligotrophic zooplankton community of Lake Superior did not change from 1997 to 2022. Lake Huron experienced a well-documented decrease in zooplankton biomass in 2003, particularly for cladocerans. Similar but smaller decreases in biomass and community shifts occurred at this time for Lakes Michigan and Ontario. In recent years biomass in Lake Ontario has decreased. Lake Erie zooplankton biomass has been highly variable over the time series with some decreases in bosminids in the central basin.

Lake-by-Lake Assessment

Lake Superior

Status: Good

10-Year Trend (2013-2022): Unchanging

Long-term Trend (1997-2022): Unchanging

Rationale: Lake Superior consistently maintains an oligotrophic zooplankton community dominated by calanoid copepods and maintenance of low but sustained zooplankton biomass near 2-3 g m^{-2}. This has not changed since the beginning of the monitoring period resulting in Unchanging 10-year and long-term trends.

Lake Michigan

Status: Good

10-Year Trend (2013-2022): No Trend

Long-term Trend (1997-2022): Deteriorating

Rationale: The oligotrophic zooplankton community has been dominated by calanoid copepods since the early 2000s, with a marked decrease in cladoceran biomass after 2004. This has accounted for a Deteriorating long-term trend. In recent years, a slight recovery in biomass was observed with high cladocerans in 2021 and 2022. This variability in zooplankton biomass and community composition led to the determination of No Trend in Lake Michigan in the past 10 years.

Lake Huron

Status: Fair

10-Year Trend (2013-2022): Unchanging

Long-term Trend (1997-2022): Deteriorating

Rationale: The decrease in zooplankton biomass in 2003, particularly of cladocerans, to levels below that of Lake

Superior (< 2 g m^{-2}) was sudden and likely represents levels limiting to forage fish. This leads to a status assessment of Fair and a long-term trend of Deteriorating. The decadal status has not changed, although the long-term trend remains of concern.

Lake Erie

Status: Good

10-Year Trend (2013-2022): No Trend

Long-term Trend (1997-2022): No Trend

Rationale: Overall zooplankton biomass has been highly variable from year to year since 1997, which results in no clear decadal or long-term trend. However, declines in bosminids occurred in the central basin after 2012 and in *Daphnia* in the eastern basin in 2020-2022. Zooplankton biomass had increased in the last SOGL report but has since returned to lower levels in 2021-2022 and there is concern for decreasing trends in cladocerans in the central and eastern basins.

Lake Ontario

Status: Fair

10-Year Trend (2013-2022): No Trend

Long-term Trend (1997-2022): Deteriorating

Rationale: Over the entire time series, biomass has decreased, and the community shifted toward calanoid copepods after 2005, with losses of cyclopoid copepods and cladocerans. The recent decrease in biomass may be approaching levels of concern for forage fish.

Status Assessment Definitions

The current available U.S. Environmental Protection Agency (EPA) Great Lakes National Program Office (GLNPO) time series is 1997-2022. New data added in this report is for 2020-2022.

Good: Zooplankton biomass and community structure consistent with target total phosphorus (TP) concentrations of specific deep lakes (higher than 2 g m^{-2} in Lakes Superior, Huron and Michigan, 3 g m^{-2} in Lake Ontario). For shallow Lake Erie, 2 g m^{-2} in Eastern and Central Lake Erie, and 1 g m^{-2} in Western Lake Erie. Zooplankton communities in lakes Superior, Huron, and Michigan are dominated by calanoid copepods including *Limnocalanus macrurus*. Lake Ontario initially had more cyclopoid copepods but after 2003 shifted toward the calanoid dominated communities of other deep lakes. The zooplankton community of Lake Erie has been diverse with calanoid copepods (but few *L. macrurus*), cyclopoid copepods, and cladocerans but cladocerans have declined over time in the central and eastern basins.

Fair: Evidence of change in biomass or community structure away from the desired lake-specific goals.

Poor: Offshore zooplankton biomass below 1 g m^{-2} in Lakes Superior, Huron and Michigan and 2 g m^{-2} in Lake Ontario. For Lake Erie, below 1 g m^{-2} in Eastern and Central Basin and 0.5 g m^{-2} in the Western Basin. Such low values may limit forage fish populations.

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

Trend Assessment Definitions

Improving: Recovery to sustaining levels of biomass and return to baseline native community composition.

Unchanging: No consistent or sustained changes in biomass or composition, generally a good thing unless in restoration process.

No Trend: Data for a 10-year or longer trend is available but the trend is not consistently Improving or Deteriorating due to high variability in the data.

Deteriorating: Zooplankton biomass declining well below goals, low prevalence of large *Daphnia* species (and perhaps small overall average size) due to high fish predation, high prevalence of non-native species such as exotic predatory cladocerans.

Undetermined: Data are not available to report on a trend.

Endpoints and/or Targets

Due to the bottom-up connection of nutrients (Total Phosphorus - TP) with algal concentration (Chl *a*) and zooplankton carrying capacity, targets for areal zooplankton biomass (measured in dry weight) should reflect the International Joint Commission (IJC) goals for spring total phosphorus concentrations (Chapra and Dolan 2012). Thus, lakes with lower target TP concentrations (e.g. Lake Superior and Huron at phosphorus concentrations of 5 μg l^{-1} and Lake Michigan at 7 μg l^{-1}) will have a lower target zooplankton biomass (2 g m^{-2}) than lakes with higher target TP concentrations (e.g. Lake Ontario at 10 μg P l^{-1}) which will have a target offshore zooplankton biomass of 3 g m^{-2}. Although Lake Erie has a similar TP target as Lake Ontario, it is a much shallower lake. Therefore, goals set for whole water column zooplankton biomass are lower with 2 g m^{-2} for the Eastern (40 m) and Central Basin (20 m) and 1 g m^{-2} for the Western Basin (10 m).

Sub-Indicator Purpose

The offshore zooplankton biomass sub-indicator assesses the standing stock and community composition of zooplankton in the Great Lakes over time and space.

Changes in the offshore zooplankton biomass sub-indicator reflect influences from both bottom-up (primary production) and top-down (vertebrate or invertebrate predation) mechanisms as well as energy transfer across trophic levels. The purpose of this sub-indicator is to contribute to the measurement of the stepwise trophic efficiency of the food web at transferring algal production to fish. Zooplankton biomass has often been used to explain deviations in the relationship between nutrients (total phosphorus, TP) and phytoplankton biomass (Chl *a*) (Taylor and Carter 1997). Phytoplankton biomass in the Great Lakes is often not well correlated with zooplankton biomass so each trophic level provides unique information (Kovalenko et al. 2023).

Ecosystem Objective

Maintain and support a healthy and diverse fishery; maintain trophic states consistent with the lake-specific goals – oligotrophic Lakes Superior, Huron, Michigan, and Ontario, and mesotrophic Lake Erie. Zooplankton represent an important trophic link from primary production to fish and thus abundant zooplankton tend to improve water quality and produce more fish.

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

Methods

The primary offshore zooplankton index is average lakewide or basinwide areal biomass (g dry weight m^{-2}). This value can be expressed as summer mean biomass (July-August) or as growing season mean biomass (e.g. April 1-October 31) if more frequent sampling is available. Standard U.S. EPA Great Lakes National Program Office (GLNPO) collection protocols call for vertical net tows from 2 m above the bottom or the top 100 m, whichever is less, with a metered 0.5-m diameter mouth net and 153-µm mesh (U.S. EPA GLNPO LG 402). Zooplankton dry weight biomass is estimated using length measurements in standard sets of length-dry weight equations available for each taxa (U.S. EPA GLNPO LG 403). Since zooplankton sampling is conducted both day and night, mysid biomass is not included here. Nighttime *Mysis* abundance is reported as a new sub-indicator in the 2025 SOGL report.

Several Canadian/US provincial/state and federal agencies routinely collect offshore zooplankton samples in each Great Lake. U.S. EPA GLNPO collects offshore samples for all five Great Lakes in April and August. GLNPO samples at eight to twenty offshore stations in each lake (in both the US and Canada) using the same method and has been the preferred data source for this sub-indicator. Data are now available for the period 1997-2022. Note that little data was collected in 2020 due to COVID-19. Assistance from Fisheries and Oceans Canada (DFO) and other groups was essential for collecting samples during the 2020-2022 time period.

Discussion

Summer biomass of crustacean zooplankton communities in the offshore waters of Lake Superior has remained at a relatively low but stable level near 2-3 g m^{-2} since at least 1997 (Figure 1). The plankton community is dominated by large calanoid copepods (*Leptodiaptomus sicilis* and *Limnocalanus macrurus*) that are characteristic of oligotrophic, coldwater ecosystems (Gannon and Stemberger 1978).

Changes observed in the zooplankton communities of Lakes Huron and Michigan, and to a lesser extent Lake Ontario (Figure 1), are consistent with expected responses to the reductions in nutrient levels seen in all three lakes. These changes could represent a consequence of nutrient reduction activities, perhaps compounded by effects of dreissenid mussels. The reductions in cladocerans in Lakes Huron and Michigan could represent a decreasing food base for forage fish. However, exact mechanisms of these declines, and the relative strength of bottom-up versus top-down forcing, have yet to be determined.

Over time, zooplankton indicators of Lakes Huron and Michigan have converged towards Lake Superior in terms of biomass levels and community composition (Barbiero et al. 2012 and 2019). The community shift towards dominance by calanoid copepods (Figure 3) is consistent with increased oligotrophication (Gannon and Stemberger ,1978). In 2003, zooplankton biomass in Lake Huron fell below that of ultra-oligotrophic Lake Superior (Barbiero et al. 2011). Bunnell et al. (2014) highlighted this decline as a potential explanation for the concurrent collapse of alewife and reduced growth of salmonids (Riley et al. 2008). Here we show that there has been little additional change since 2003 in Lake Huron.

Lake Ontario has not experienced recent declines in primary production, suggesting that top-down control may better explain the observed zooplankton community shifts in this lake. There has also been a change away from a

long-term community of cyclopoid copepods and *Daphnia retrocurva* to a community composed of calanoid copepods (Figure 3) and *Daphnia mendotae*, which may be related to low alewife abundance and a rise in invertebrate predation by the predatory cladoceran *Bythotrephes* (Barbiero et al. 2014, Rudstam et al. 2015). Since 2019 zooplankton biomass has been at Fair status levels.

The zooplankton community of Lake Erie is taxonomically diverse and rich in native and non-native cladoceran species (Figure 2). The low abundance of deep dwelling calanoid *Limnocalanus macrurus*, and the overall maintenance of cladocerans relative to calanoids in Lake Erie, can be attributed to the shallow bathymetry and hence lower volume of cool hypolimnetic habitat as well as the lake's mesotrophic state. An example of long-term historical change, *L. macrurus* was common in the central and eastern basins in the 1920s but has been rare since the 1950s likely due to a combination of declining hypolimnetic oxygen levels and the introduction of rainbow smelt (Gannon and Beeton, 1971). Zooplankton biomass has been highly variable among years in all three basins. Declines of bosminids (included in non-Daphnid cladocerans category) in the central basin after 2012 and Daphnia in the eastern basin in 2021-2022 are of concern and are being closely monitored.

Linkages

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

- Other Habitat and Species sub-indicators (phytoplankton, benthic community, *Mysis*, and prey fish diversity). Zooplankton consume phytoplankton, and thus respond to changes in algal biomass. Zooplankton also respond to changes in their predators that include both fish and invertebrates such as *Mysis*. Both zooplankton and benthic invertebrate community structure influences the prey fish community biomass and composition.
- Nutrients in Lakes (open water) – phosphorus levels regulate primary productivity by phytoplankton and thus impact food availability for zooplankton.
- Increased water clarity shifts primary production to deeper depths in the form of deep chlorophyll layers (DCL, Scofield et al. 2020), which affects food availability for zooplankton. Water clarity also affects forage fish predation success.
- Interannual changes in water temperatures and ice cover could lead to impacts on the distribution of cold-water fauna such as large bodied calanoid copepods that have become increasingly prevalent in the upper Great Lakes. Water levels and changes in precipitation are less likely to affect zooplankton.

Assessing Data Quality

Data Characteristics	Agree	Neutral or Unknown	Disagree	Not Applicable
Data are documented, validated, or quality-assured by a recognized agency or organization	X			
Data are from a known, reliable and respected generator of data and are traceable to original sources	X			

Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X			
Data obtained from sources within the U.S. are comparable to those from Canada	X			
Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X			
Data used in assessment are openly available and accessible	Yes	https://cdx.epa.gov/cdx		

Notes on Accessing Data

To use the EPA GLENDA database at the cdx website (https://cdx.epa.gov/cdx/login), you first need to register an account with a login and password and then request access to the GLENDA database. The zooplankton data is available as a RTD (Ready-to-Download) file that includes site specific zooplankton biomass data by taxa groups for spring and summer surveys from 1997-2022. A ReadMe table includes sampling metadata and defines data fields for this dataset.

Data Limitations

Both U.S. and Canadian agencies conduct zooplankton monitoring programs. Note that sampling and analysis methodologies and biomass calculations differ, highlighting the importance in consolidating efforts across agencies to increase the ability for data sharing in the future.

Many historic time series are based only on epilimnetic sampling that miss deeper dwelling zooplankton, particularly for increasingly oligotrophic offshore settings and in lakes with higher water clarity that have zooplankton residing in deep water during the day and migrating to surface water during the night. Those data are not being utilized in this assessment; only deeper net tow data were used (100 m or 2-m off the bottom, whichever is shallower), which limits the time series to years with deep tow data.

Several taxa-based ratios (e.g. calanoids to cyclopoids+cladocerans) have been proposed but are not always consistently presented (i.e. by density or biomass). Several of the proposed indices have not been fully tested for Great Lakes or in long term datasets across many lakes. We provide an example of the index % calanoids by biomass for four of the five Great Lakes (Figure 3), which may capture both changes in lake productivity and the proportion of the zooplankton biomass below the thermocline (Figary et al. in press).

Additional Information

Note that we use areal biomass (g m^{-2}) rather than volumetric (g m^{-3}) units to better evaluate the overall standing biomass of these lakes for connecting to fish production potential (Bunnell et al. 2014). A change to using areal units as indicators was done in 2015. Whole water column (in this case maximum of 100 m) tows in deep lakes include large strata of hypolimnion that have few zooplankton. Volumetric biomass estimates from 100 m net tows are thus “diluted” relative to shallower lakes that have less hypolimnion. Areal biomass represents the zooplankton biomass found within a one meter square water column. Note that for Lakes Superior, Michigan, and Ontario, most

offshore GLNPO sites are > 100 m but many of the sites for Lake Huron are < 100 m. In Lake Erie, depths range from 10 m in the Western to 20 m in the Central to 50 m in the Eastern basins.

More information could be included in this sub-indicator in the future. Mean body size and species composition of zooplankton are also sensitive indicators of predatory pressure by planktivorous fish and large invertebrates (*Mysis* and predatory cladocerans). Nearshore measures for the Zooplankton sub-indicator have also been proposed. Several long-term nearshore biomonitoring programs that focus on zooplankton exist (e.g. Lakes Erie and Ontario) and time series have detected changes that can complement offshore trends in biomass and community composition. For example, the Lake Ontario Biomonitoring Effort (NY DEC Regional Offices, USGS, USFWS and Cornell) collects nearshore (10 m depth) samples biweekly throughout the growing season at several sites along the south shore of Lake Ontario (Holeck et al. 2020). Nearshore zooplankton data for Lake Ontario have been presented in Figary et al. (2023) and Bowen et al. (2022). NOAA GLERL has nearshore zooplankton data for lakes Michigan and Huron. Lake Superior nearshore zooplankton data is represented in Schapov and Ozersky(2023).

An important threat to the zooplankton communities of the Great Lakes is posed by invasive species. The continued proliferation of dreissenid populations can be expected to impact zooplankton communities through the alteration of the structure and abundance of the phytoplankton community that many zooplankton depend on for food. Predation from the non-native cladocerans *Bythotrephes longimanus* and *Cercopagis pengoi* may also have an impact on zooplankton abundance and community composition. These invasive predatory cladocerans have been shown to have a major impact on zooplankton community structure in the Great Lakes (Lehman 1991; Barbiero and Tuchman 2004; Warner et al. 2006). Five new non-native zooplankton species were recently detected in Western Lake Erie: the rotifer *Brachionus leydigii*, the cyclopoid copepods *Thermocyclops crassus*, *Mesocyclops pehpeiensis*, and *Cyclops divergens*, and the cladoceran *Diaphanosoma fluviatile*. All of these species were detected at very low abundances in at least one year between 2013-2022, but they have not rapidly expanded and thus their potential impacts are not likely to be significant.

Some of the other measures useful for the interpretation of the zooplankton data include: total phosphorus, chlorophyll *a*, temperature, oxygen (seasonal depletion in upper hypolimnion, including anoxia in central basin of Lake Erie), primary production, and phytoplankton composition and biomass.

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Data Source:

U.S. EPA Great Lakes National Program Office

Anne Scofield, Great Lakes National Program Office (U.S. EPA), Chicago, IL

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List of Figures

Figure 1. Proportion and areal biomass (g m^{-2}) calculated from U.S. EPA's GLNPO summer survey D100 tows (towed from 100 m depth or 2 m above bottom for shallower sites to the surface) 153-µm tows for lakes Ontario, Michigan, Huron, and Superior. Horizontal lines represent basin-specific biomass thresholds for Good and Fair ratings. Data Sources: U.S. EPA Great Lakes National Program Office, Cornell University

Figure 2. Proportion and areal biomass (g m^{-2}) calculated from U.S. EPA's GLNPO summer survey D100 tows (towed from 100 m depth or 2 m above bottom for shallower sites to the surface) 153-µm tows for the Western, Central, and Eastern basins of Lake Erie. Horizontal lines represent basin-specific biomass thresholds for Good and Fair ratings. Data Sources: U.S. EPA Great Lakes National Program Office, Cornell University

Figure 3. Percent calanoid (by biomass) indicator for the four deeper Great Lakes over time series. Data Sources: U.S. EPA Great Lakes National Program Office, Cornell University

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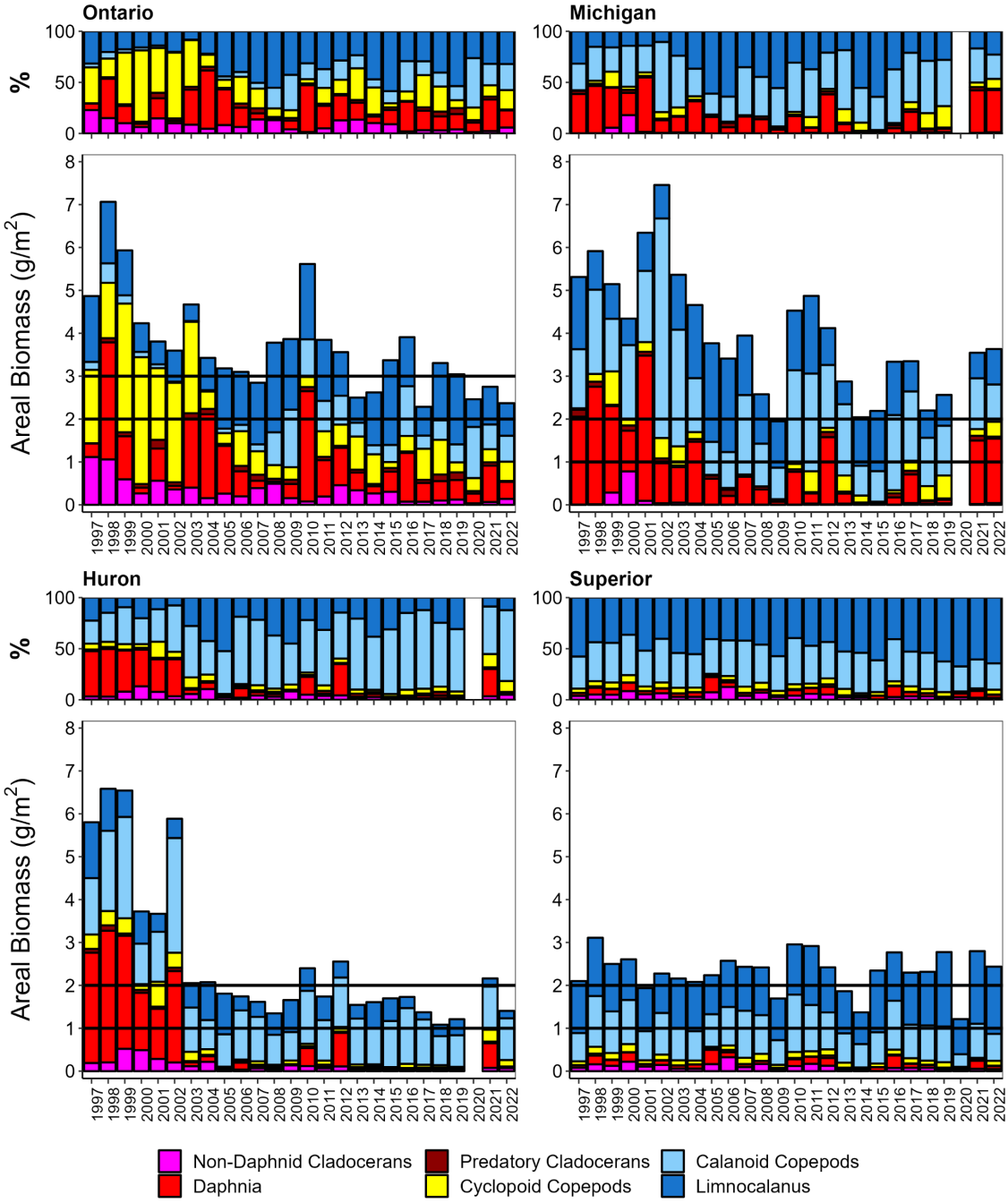

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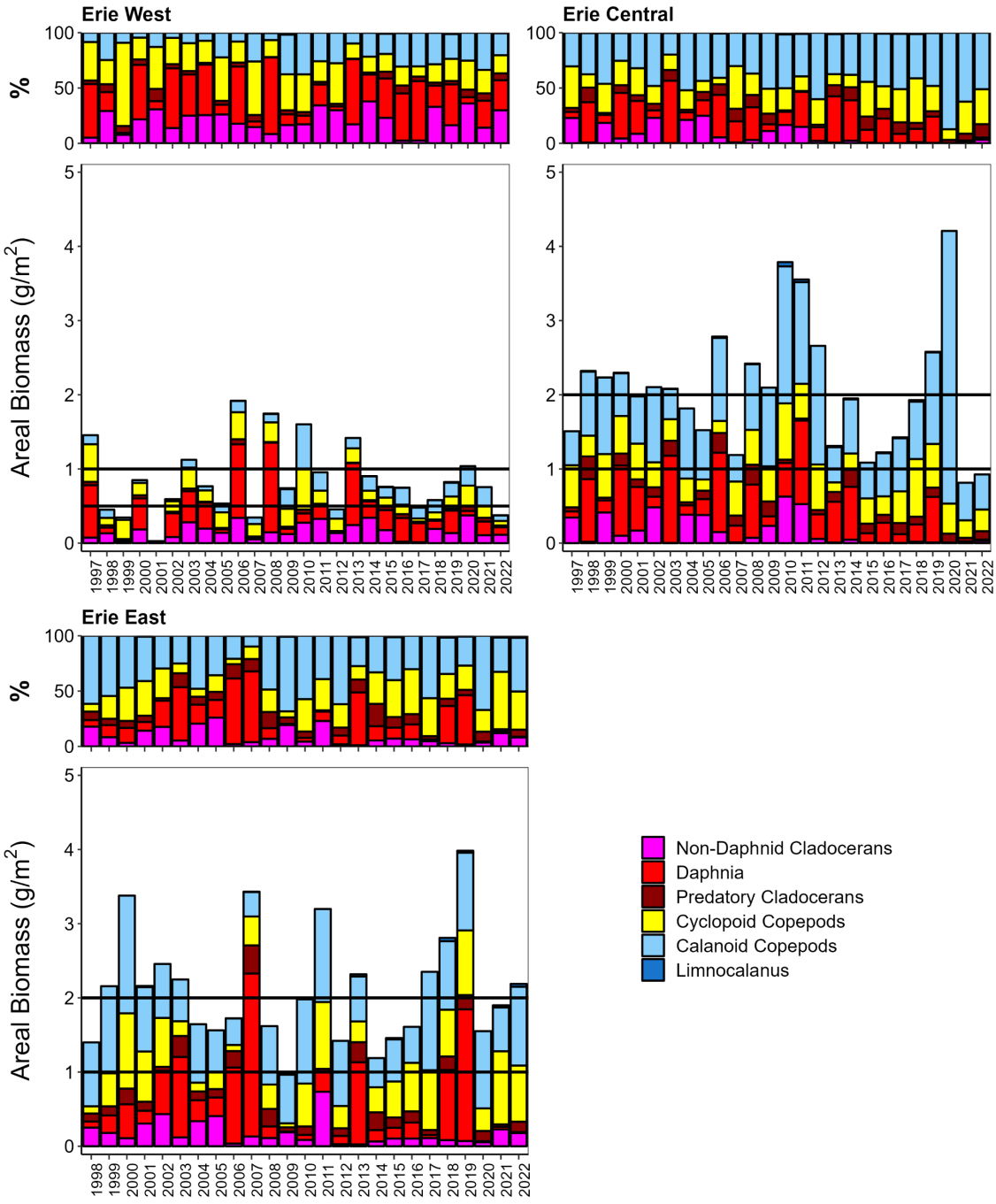

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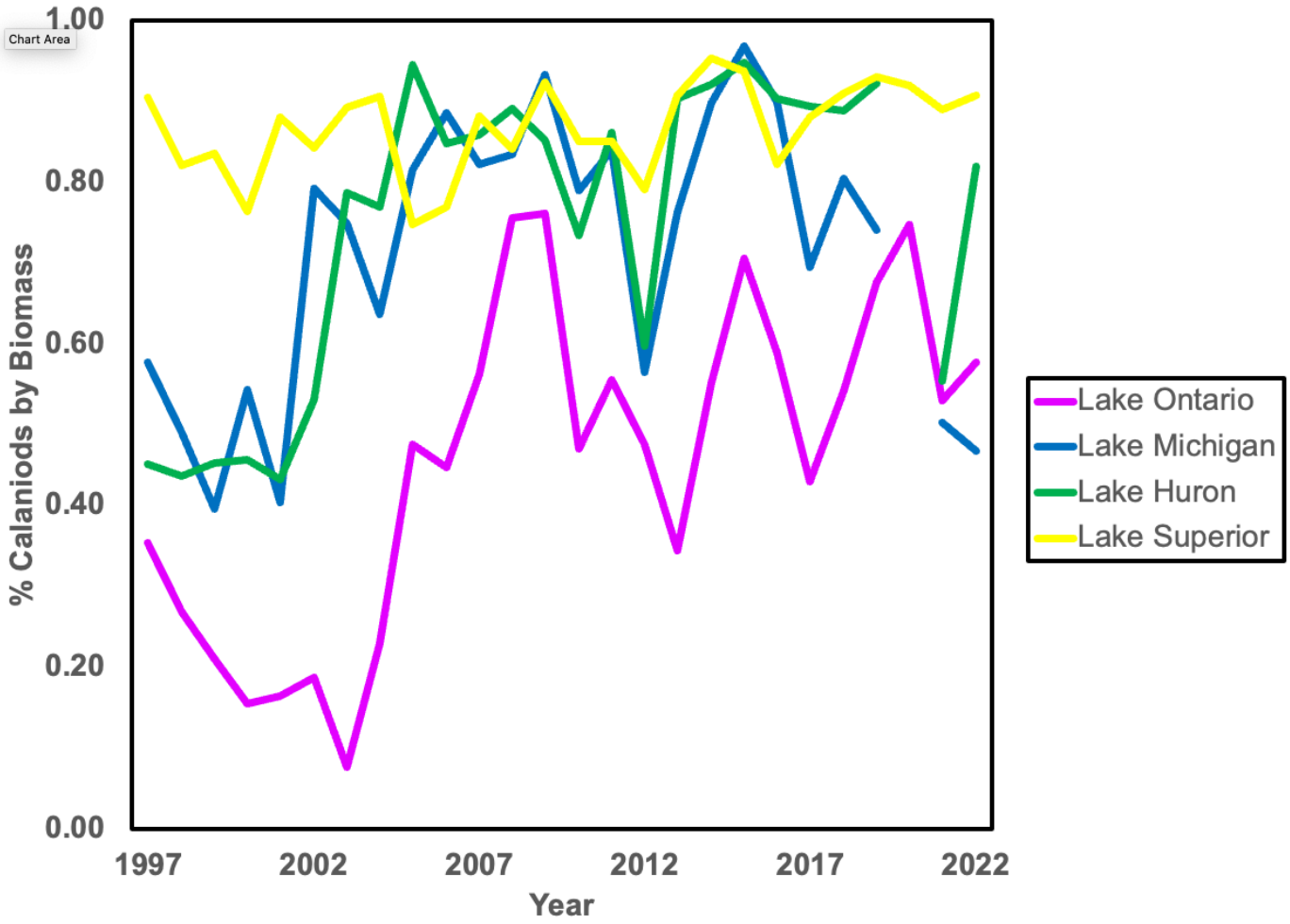

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