# Sub-Indicator: Phytoplankton

## Overall Assessment

**Status:** Fair

**Trends:**

**10-Year Trend:** Deteriorating

**Long-term Trend (1950-2021):** Deteriorating

**Rationale:** Phytoplankton are a critical food resource for zooplankton and small fish. Invasive mussels have caused algal reductions in Lake Michigan and Lake Huron, negatively impacting food webs of those lakes. Re-eutrophication has occurred in Lake Erie. Changes in Lake Superior and Lake Ontario are more subtle. Despite problematic aspects of Great Lakes phytoplankton, in most places the biomass of phytoplankton represents oligotrophic conditions, so an overall rating of fair is given. Stressors including rising surface water temperatures, invasive mussels, and nutrient pollution are driving continued changes in phytoplankton communities. In some cases, significant reorganization of the phytoplankton community is occurring, but drivers and eventual consequences are not yet fully understood.

## Lake-by-Lake Assessment

### Lake Superior

**Status:** *Good*

**10-Year Trend:** *Deteriorating*

**Long-term Trend** (1950-2021): *Unchanging*

**Rationale:** The lake has maintained a phytoplankton assemblage reflecting oligotrophic conditions, though nearshore occurrences of algal blooms are being recognized. Invasive species are not notably affecting phytoplankton, but there is evidence from paleolimnological data of gradual assemblage reorganization due to rising surface water temperatures.

### Lake Michigan

**Status:** *Fair*

**10-Year Trend:** *Unchanging*

**Long-term Trend** (1950-2021): *Deteriorating*

**Rationale:** A reduction in phytoplankton and consequent diminution in seasonality has occurred. Lower levels of primary production could be reducing resources for higher trophic levels. Although the lake has a phytoplankton assemblage reflecting oligotrophic conditions, the designation of “Fair” is appropriate based on these observations.

### Lake Huron

**Status:** *Fair*

**10-Year Trend:** *Unchanging*

**Long-term Trend** (1950-2021): *Deteriorating*

**Rationale:** The lake has a phytoplankton assemblage reflecting oligotrophic conditions, which may appear to be "good" however, the change is likely due to the recent invasion by mussels that have reduced pelagic primary producers (negatively affecting invertebrate grazers).

### Lake Erie

**Status:** *Poor*

**10-Year Trend:** *Deteriorating*

**Long-term Trend** (1950-2021): *Deteriorating*

**Rationale:** Re-eutrophication and proliferation of undesirable cyanobacteria is an increasing problem, particularly in the western basin. The central and eastern basins also exhibit cyanophyte increases in the last two decades, though not yet to concerning levels.

### Lake Ontario

**Status:** *Good*

**10-Year Trend:** *Unchanging*

**Long-term Trend** (1950-2021): *Improving*

**Rationale:** The lake has a phytoplankton assemblage reflecting mesotrophic to oligotrophic conditions. There is some evidence of assemblage changes due to invasive dreissenids and variable surface water temperatures, but at this time we maintain a "good" assessment until these recent changes can be better described relative to future water quality and health risk. Sporadic harmful blooms have been noted in the St. Lawrence River, though more data are needed to determine whether this is an increasing trend. The long-term trend of "improving" reflects much older improvements in nutrient loads and phytoplankton levels following initiation of the Clean Water Act.

## Status Assessment Definitions

An appropriate condition is defined relative to known or inferred baseline conditions for a lake, including natural levels of nutrients and algae. For the purpose of this sub-indicator, the following conditions are the benchmark for a "Good" status assessment: Oligotrophic conditions in Lakes Superior, Huron and Michigan; Oligotrophic to Mesotrophic conditions for Lakes Ontario and Erie.
Oligotrophic and mesotrophic status are generally assumed to represent chlorophyll concentrations of <10 µg/L and 3.4 - 5.0 ug/L (USEPA 2000), but in practice, assigning status is more nuanced than simply comparing phytoplankton assemblages to the general boundaries of trophic state. See the Endpoints and Discussion sections for further explanation of the status assignments made in this report.

**Good:** the phytoplankton assemblage reflects the appropriate trophic structure for the lake.

(Good = Oligotrophic for Lakes Superior, Huron and Michigan; Oligotrophic to Mesotrophic conditions for Lakes Ontario and Erie.)

**Fair:** the phytoplankton assemblage is moderately/periodically reflecting the appropriate trophic structure for the lake.

**Poor:** the phytoplankton assemblage does not reflect the appropriate trophic structure for the lake.

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

## Trend Assessment Definitions

**Improving:** changes in phytoplankton biovolume, density and species composition in support of a healthy food web.

**Unchanging:** phytoplankton characteristics as they relate to food web and water quality are not showing an overall change in trend.

**Deteriorating:** changes in phytoplankton biovolume, density and species composition resulting in an unhealthy food web.

**Undetermined:** data are insufficient to make an assessment.

**No Trend:** data are available for a 10-year or longer period but the data are reflecting conflicting trends or the trend is not statistically improving or deteriorating due to high variability in the data.

## Endpoints and/or Targets

For the purposes of SOGL phytoplankton as an indicator largely refers to inferred trophic status or algal abundance. Lake-specific trophic status that reflects baseline conditions has been determined from paleolimnological analyses (oligotrophic conditions for Lakes Superior, Huron and Michigan; oligo-mesotrophic conditions for Lakes Erie and Ontario) so there is potential to set remedial targets. However, re-attaining historical phytoplankton assemblages (or "desirable" species) is not realistic because of the fundamental reorganization of the algal communities that are likely not recoverable under current physical, chemical, and biological regimes. More general terms like "oligotrophic" are suitable, though geographic context (i.e., lake) is often important to identify more specific issues that are driven by stressors beyond nutrient pollution. It is not realistic to derive endpoints for stressor impacts related to invasive species impacts and changes in thermal conditions. Instead, scientific inquiry is required to interpret the unique, lake-specific trends related to these variables, and base current conditions on whether trajectories are desirable. For instance, the oligotrophication and reorganization of phytoplankton in Lake Huron may be interpreted as lower nutrient stress, but instead is a negative food web impact resulting from the invasion of profundal dreissenids and likely warming surface water temperatures.

## Sub-Indicator Purpose

The purpose of this sub-indicator is to directly assess phytoplankton species composition, biomass, and primary productivity in the Great Lakes, and to indirectly assess the impact of stressors on Great Lakes water quality, lower food webs, and potential threats to human and environmental health. This includes inferring impacts from pollution, invasive non-native species, rising surface water temperatures, and harmful algal blooms.

## Ecosystem Objective

1. This sub-indicator best supports work towards General Objective #5 of the 2012 Great Lakes Water Quality Agreement (The Government of the United States of America and the Government of Canada

2012) 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." Also, as an indicator at the bottom of the food chain phytoplankton can detect subtler ecosystem changes, so Article 2(1)(b) of the GLWQA ("develop programs, practices and technology necessary for a better understanding of the Great Lakes Basin Ecosystem") applies.

2. Maintain trophic states with phytoplankton biomass and composition consistent with a healthy aquatic ecosystem in open waters of the Great Lakes. Desired objectives are phytoplankton biomass and community structure indicative of oligotrophic conditions (i.e. a state of low biological productivity, as is generally found in the cold open waters of large lakes) for Lakes Superior, Huron and Michigan; and of mesotrophic (or oligotrophic) conditions for Lakes Erie and Ontario.
3. Qualitatively and quantitatively detect and predict changes in phytoplankton biomass and composition and apply those changes to stressor impacts or recovery. Desired outcomes are maintenance of good condition over several years or a detectable transition to healthy conditions.

## Methods

The measures used to compile indicator results will include the following.

- Biovolume and density of phytoplankton and taxonomic composition for spring and late summer in the offshore, isothermal waters (e.g., Reavie et al. 2014a). Taxonomic identification is to the best detail possible (e.g., species) to identify atypical or non-native taxa. Modern volumetric abundances of taxa (e.g., cyanobacterial or diatom blooms) are compared to previous conditions (from monitoring or paleoecological assessments) to make interpretations on ecological health and trajectory relative to known historical condition within a lake. Sampling and analysis are standardized across all lakes.
- All available historical data on phytoplankton that are sufficiently comparable to allow for long-term reconstructions of trends and trajectories of primary producers. Such data are available from past monitoring (e.g. Munawar & Munawar 1978) and paleolimnological (e.g. Reavie et al. 2017, 2021) assessments and may include bulk biomass measurements (e.g. chlorophyll *a*), biovolume (e.g. $\mu m^3/mL$) and assemblage composition. Paleolimnological data allow for historical inferences as far back as the 19$^{th}$ century, and such data were used to support the newer "long-term trend" requirement in this report.

## Discussion

Phytoplankton composition is an important indicator of water quality and biological condition. Several qualitative indicators also exist: the abundance of cyanobacteria is a clear indicator for nutrient stress; reductions in algal abundance signal dreissenid-driven oligotrophication; and phytoplankton assemblage changes reflect changes in pelagic ecology due to water temperature variation, grazer composition and other factors. Phytoplankton play a critical role in food web processes. Production (energy) sinks from the surface euphotic zone to nourish the benthos. It may flow efficiently, with high productivity across the size-spectrum, or it may accumulate, negatively affecting water quality while little energy reaches top predators; i.e., the current situation in summer in the western basin of Lake Erie.

Phytoplankton are photosynthesizing organisms that inhabit the sunlit layer of aquatic systems. They are microscopic algae that typically form a major component of a lake's primary producers, thereby sustaining the aquatic food web. The amount and taxonomic structure of phytoplankton populations can be related to

anthropogenic stressors, thereby permitting inferences to be made about lake condition and change (Stoermer 1978). Recently, the most important, comprehensive data sources for phytoplankton-based assessments have been time series data on phytoplankton community size and composition (e.g., Reavie et al. 2014a; Figures 1-5), satellite-based measurements of chlorophyll (e.g., Barbiero et al. 2012, Binding et al. 2021, Lekki et al. 2019) and recent paleolimnological studies of fossil phytoplankton (e.g., Shaw Chraïbi et al. 2014, Sgro et al. 2018, Reavie et al. 2021). Additional phytoplankton data have been collected by The US Coast Guard (e.g., Oyserman et al. 2012; winter collections from icebreakers) and Canadian agencies, such as that for Lake Erie winter conditions (Twiss et al. 2012; ECCC 2015).

Status of the Great Lakes ecosystem as a whole is characterized as *fair* although condition and trends vary among lakes. Invasive mussels have caused reductions in phytoplankton (algae) in Lake Michigan and Lake Huron, negatively impacting food webs of those lakes. Re-eutrophication has occurred in Lake Erie in the last 1.5 decades, mainly indicated by cyanobacterial blooms that are occurring with greater frequency in the western basin of Lake Erie and large spring diatom blooms in the central basin that support hypolimnetic hypoxia (Reavie et al. 2016). Slower, long-term changes are occurring in Lake Superior and Lake Ontario, but these changes are not yet well understood. However, with the exception of Lake Erie, trophic status across the basin would generally be considered good. For the most part, trends herein reflect compiled datasets from 2001 through 2021. “Long-term” inferences are supported by older collections and paleolimnology.

Assigning firm condition assessments was also complicated in individual lakes. Consider Lake Michigan and Lake Huron, for instance: if trophic status was the only factor considered their low phytoplankton abundance would superficially reflect *good* conditions. However, the periodic, mussel-driven depletion of phytoplankton in these lakes represents food web stress (Fahnenstiel et al. 2010; Barbiero et al. 2011). Further, paleolimnological trends indicate a longer-term shift to small-celled diatoms in these lakes (Reavie et al. 2017), a likely temperature-related food web disruption though the impacts of this shift on ecosystem health is not yet understood. From an ecological perspective that simultaneously considers multiple parameters *fair* remains an appropriate assessment. It is also worth noting that longer-term data from paleolimnological assessments of phytoplankton pigments (presented in the previous SOGL report) indicate that some of the Great Lakes system has improved on a 50-year scale.

Previous reporting noted the changes that occurred in the phytoplankton community associated with eutrophication and the dreissenid invasion. In general, these changes are continuing, or the lakes remain in the previously reported “changed” state. In association with the dreissenid advance, the spring phytoplankton bloom in Lake Huron, which practically disappeared in 2003 (Barbiero et al. 2011) remains absent (Figure 2). Declines in the spring bloom were also seen in Lake Michigan (Reavie et al. 2014a; Figure 3). Such trends of oligotrophication can be viewed positively, but it likely also represents an overall reduction in the carrying capacity of the two lakes, as evidenced by coinciding losses of invertebrates and reductions in fish energy content (Pothoven and Fahnenstiel 2014).

It is unlikely that the deep waters of Lake Superior will be anything but oligotrophic, so in that context it will remain in *good* condition. However, the lake’s phytoplankton assemblage continues to change over decadal timescales (Figure 1), likely associated with atmospheric warming that is changing the physical properties of the lake (Shaw Chraïbi et al. 2014). Such a shift has now been recognized across all of the Great Lakes and their sub-basins (Reavie et al. 2017), so such longer-term changes in primary producers should continue to be observed to determine future impacts on food webs. Recent observations of nearshore blooms (Sterner et al. 2020, Alexson et al. 2018) and increases in chlorophyll *a* in surface sediments (Reavie et al. 2021) suggest there may be increasing threats from algal blooms that are not apparent in pelagic collections.

In the western basin of Lake Erie, blooms of the nuisance algae *Microcystis* (among other cyanobacteria) have become prominent in late summer most years (Michalak et al. 2013; see summer cyanophyte changes in Figure 4).

The spring algal bloom in the central basin, largely attributed to filamentous, centric diatoms (Reavie et al. 2016, Twiss et al. 2012, Figure 4) is likely contributing substantial organic biomass to the hypolimnion and exacerbating hypoxia. Not every year has a major diatom bloom, possibly a result of extreme winter conditions that may not have been conducive to a robust winter-spring diatom bloom, but the most recent data had the highest spring diatom biomass on record.

Over the last decade in Lake Ontario spring chlorophyll levels have remained stable, but there is evidence of a slight summer chlorophyll increase (Reavie et al. 2021 and USEPA, unpub. data) since declines seen in the 1980s (Johengen et al. 1994). This corresponds with recent changes in Lake Erie, albeit at a smaller scale for Lake Ontario. While current trophic condition in Lake Ontario is stable (Figure 5) and remains better than that during the mid- to late-20$^{th}$ century, future conditions in Lake Ontario should be observed carefully to ensure re-eutrophication does not occur, as may be suggested by very recent sedimentary concentrations of chlorophyll *a* (Reavie et al. 2021), and as has been the case in Lake Erie. The St. Lawrence River, adjacent to Lake Ontario, has had periodic harmful algal blooms of cyanobacteria (Hudon et al. 2014), a phenomenon that should be observed closely to determine whether it represents an increasing threat.

## Linkages

Linkages to other indicators in the indicator suite include:

- Nutrients and Dreissenid Mussels – it is well known that the phytoplankton population and its productivity changes with anthropogenic pollution. The ecosystem changes are reflected by the change of phytoplankton composition and productivity. For example, Lake Superior represents an oligotrophic ecosystem and is widely considered to be in the best condition of the Great Lakes. Similarly, Lake Erie's phytoplankton composition, which was once eutrophic, dramatically changed to seasonally meso-oligotrophic status due to phosphorous abatement and the invasion of zebra mussels, a trophic trend that has since reversed to indicate re-eutrophication. A great deal of recent data are available for phytoplankton biomass, composition and primary productivity which will reflect the overall ecosystem health including grazing pressures of non-native filter-feeders and bottom-up influences from nutrients.
- This sub-indicator also links directly to the other sub-indicators in the Habitat and Species indicator, such as invertebrate grazers that rely on phytoplankton as a primary food resource. The cycling of phosphorus is being driven by catchment inputs and sedimentary processes, impacting the food web and having implications on many forms of aquatic life, especially benthos, zooplankton, and phytoplankton. Effects on fish communities are less direct but must also be considered.
- Rising surface water temperatures are driving changes in Great Lakes phytoplankton. This is not surprising given the known long-term changes in the surface temperatures of all of the lakes. Warming surface waters alter lake physical structure, especially the length of the ice-free period and the size and integrity of the summer epilimnion. The phytoplankton are the first biological component of the Great Lakes that have been noticeably affected by recent atmospheric warming (Reavie et al. 2017) but we have yet to determine the future implications of these changes. Recent temperature-related reorganization of Great Lakes phytoplankton communities should be further studied to identify possible outcomes for higher organisms that rely on stable food resources.

## 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 | Data can be found here: https://cdx.epa.gov/. | | |

## Notes on Accessing Data

Data access requires a free account. The author may also be contacted for data deliveries if desired data are not available on the EPA website.

## Data Limitations

Phytoplankton taxonomy (microscopic identification and enumeration) is a highly specialized and time-consuming activity that requires intensive training and experience. However, if properly done the phytoplankton analysis generates scientific, precise, and reliable species data that helps to identify current community composition and when compared to historic data, it can be used to determine community shifts or the sensitivity of phytoplankton to anthropogenic stressors. Expanding phytoplankton sampling would be beneficial as the majority of interpretations are based on two synoptic surveys each year. For instance, we are missing winter, mid-summer, and late fall conditions, all of which are likely to be important to fully understand year-round food web characteristics. The study of lower trophic levels and their use as indicators has been largely ignored in Great Lakes coastal environments, though localized assessments in Canada (e.g. Currie et al. 2015) and the US (e.g. Luo et al. 2017) exist. To understand the role of phytoplankton in such a rapidly changing ecosystem further evaluation of the microbial loop may be beneficial, including the base of the food chain ranging from bacteria, viruses, fungi (e.g., chytrids), heterotrophic nanoflagellates, autotrophic picoplankton, and ciliates up to phytoplankton (nanoplankton and microplankton-netplankton). This could be further supplemented with eDNA and fluorometric pigment

analysis (currently being explored by the USEPA during sampling cruises) that could identify, for instance, changing proportions of cyanophytes. Also, now that temperature-related changes have been bserved in the phytoplankton, the mechanisms of these changes need to be clarified to make predictions of future conditions. Furthermore, extension of long-term characterization of primary producers (monitoring, paleoecology) to coastal environments (nearshore, embayments, wetlands) would help to identify links between anthropogenic activities in catchments and lake condition. The prevailing observation of algal blooms in shallower, nearshore environments, such as Lake Huron that has dramatically dichotomous deep (oligotrophication) and embayment (algal bloom) conditions, suggests a great deal of further study is needed to characterize phytoplankton as an indicator of ecosystem health.

While there is a well-established long-term monitoring program for the deep waters of the lakes, data are lacking for the rivers, connecting channels and their associated lacustrine systems: St. Lawrence River, St. Marys River, Lake George, and Lake Nicolet upstream of Lake Huron; Lake St. Clair, the Detroit River, and the St. Clair River upstream of Lake Erie; The Niagara River upstream of Lake Ontario. Intermittent reporting on paleolimnological or short-term monitoring provide some insight into the condition of the connecting channels. Baustian et al. (2020) determined via paleolimnology at two locations in Lake St. Clair that phytoplankton history was profoundly affected by decades of agricultural inputs and the more recent mussel invasion. As of 1993 the phytoplankton community of Lake George was considered to be in decline (Reavie et al. 2005). Rozon et al. (2018) determined that no impairments were apparent based on plankton collections in the Niagara River. In most cases, however, river collections of phytoplankton have been sporadic or not performed for decades. Given the population centers associated with these connecting waters a more thorough phytoplankton monitoring program may be a beneficial contribution to the overall SOGL reporting.

## Additional Information

Objective, quantitative mechanisms for evaluating ecosystem health from phytoplankton are gradually being developed. For instance, nutrient optima and tolerances for indicator species are now available for the Great Lakes (Reavie et al. 2014b), thereby allowing quantitative reconstructions of water quality variables from assemblage data.

The U.S. EPA has an active program for phytoplankton collection and analysis in the pelagic regions of all Great Lakes in spring and summer and other, more localized programs are ongoing (e.g. Fahnenstiel et al. 2010). Satellite imagery has also enabled the detection of chlorophyll trends in the surface waters of the Great Lakes (e.g., Kerfoot et al., 2010), and these data can provide a broad overview of algal abundance. A greater synthesis of long-term satellite data across the Great Lakes basin is needed to supplement concurrent phytoplankton collections and paleolimnological results.

To enhance this sub-indicator temporal gaps should be filled by year-round collections similar to those collected by the Lake Guardian, the U.S. Environmental Protection Agency's research vessel. Some lake-specific collections are occurring at times not previously sampled (e.g., Twiss et al. 2012 for Lake Erie), and in specific nearshore areas going back to the 1960s (i.e., water intakes; Ontario by the Ministry of Environment, Conservation and Parks) (Winter et al. 2015) but remote, automated sampling stations could play an important role in more comprehensive year-round sampling.

## Report Authors

**Author**

Euan D. Reavie, University of Minnesota Duluth, Natural Resources Research Institute, Duluth, MN, ereavie@d.umn.edu

## Report Contributors

## References

Alexson, E.E., Reavie, E.D., Axler, R.P., Yemets, S.V., Krasutsky, P.A., Edlund, M.B., Pillsbury, R.W. and Desotelle, D. (2018). Paleolimnology of a freshwater estuary to inform Area of Concern nutrient delisting efforts. Journal of Paleolimnology 59: 373-395.

Barbiero, R.P., Lesht, B.M., and Warren, G.J. (2011). Evidence for bottom-up control of recent shifts in the pelagic food web of Lake Huron. Journal of Great Lakes Research 37: 78-85.

Barbiero, R.P., Lesht, B.M., & Warren, G.J. (2012). Convergence of trophic state and the lower food web in Lakes Huron, Michigan and Superior. Journal of Great Lakes Research 38: 368-380.

Baustian, M.M., Brooks, Y.M., Baskaran, M., Leavitt, P.R., Liu, B., Ostrom, N., Stevenson, R.J., & Rose, J.B. (2020). Paleo-environmental evidence of ecosystem change in Lake St. Clair region of Laurentian Great Lakes basin: contrasting responses to land-use change and invasive mussels. Journal of Paleolimnology 63: 177-193.

Binding, C.E., Pizzolato, L., Zeng, C. (2021). EOLakeWatch; delivering a comprehensive suite of remote sensing algal bloom indices for enhanced monitoring of Canadian eutrophic lakes. Ecological Indicators 121: 106999.

Currie, W.J.S., Bowen, K.L., Niblock, H.A., Koops, M.A. (2015). Compilation and evaluation of historical data and samples to support assessment of phytoplankton and zooplankton populations in Great Lakes Areas of Concern. Great Lakes Laboratory for Fisheries and Aquatic Sciences, Central and Arctic Region, Fisheries and Oceans Canada.

Environment and Climate Change Canada (2015). Great Lakes Surveillance Program. https://open.canada.ca/data/en/dataset/cfdafa0c-a644-47cc-ad54-460304facf2e (Accessed 13 January 2021).

Fahnenstiel, G., Pothoven, S., Vanderploeg, H., Klarer, D., Nalepa, T., & Scavia, D. (2010). Recent changes in primary production and phytoplankton in the offshore region of southeastern Lake Michigan. Journal of Great Lakes Research 36: 20-29.

Hudon, C., De Sève, M. and Cattaneo, A. (2014). Increasing occurrence of the benthic filamentous cyanobacterium Lyngbya wollei: a symptom of freshwater ecosystem degradation. Freshwater Science 33: 606-618.

Johengen, T.H., Johannsson, O.E., Pernie, G.L., and Millard, E.S. (1994). Temporal and seasonal trends in nutrient dynamics and biomass measures in Lakes Michigan and Ontario in response to phosphorus control. Canadian Journal of Fisheries and Aquatic Sciences 51: 2470–2578.

Kerfoot, W.C., Yousef, F., Green, S.A., Budd, J.W., Schwab, D.J., Vanderploeg, H.A. (2010). Approaching storm: Disappearing winter bloom in Lake Michigan. Journal of Great Lakes Research 36: 30-41.

Lekki, J., Ruberg, S., Binding, C., Anderson, R., Vander Woude, A. (2019). Airborne hyperspectral and satellite imaging of harmful algal blooms in the Great Lakes Region: Successes in sensing algal blooms. Journal of Great Lakes Research 45: 405-412.

Luo, L., Wang, J., Hunter, T., Wang, D., & Vanderploeg, H.A. (2017). Modeling spring-summer phytoplankton bloom in Lake Michigan with and without riverine nutrient loading. Ocean Dynamics 67: 1481-1494.

Michalak, A.M., Anderson, E.J., Beletsky, D., Boland, S., Bosch, N.S., Bridgeman, T.B., et al. (2013). Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Proceedings of the National Academy of Sciences 110: 6448-6452.

Munawar, M., Munawar, I.F., 1978. Phytoplankton of Lake Superior. (1973). Journal of Great Lakes Research 4: 415-442.

Oyserman, B.O., Woityra, W.C., Bullerjahn, G.S., Beall, B.F., McKay, R.M.L. (2012). Collecting winter data on US Coast Guard icebreakers. Eos, Transactions American Geophysical Union 93: 105-106.

Pothoven, S.A., Fahnenstiel, G.L. (2014). Declines in the energy content of yearling non-native alewife associated with lower food web changes in Lake Michigan. Fisheries Management and Ecology, 21: 439-447.

Reavie, E.D., Barbiero, R.P., Allinger, L.E., Warren, G.J. (2014a). Phytoplankton trends in the Laurentian Great Lakes: 2001-2011. Journal of Great Lakes Research 40: 618-639.

Reavie, E.D., Heathcote, A.J., Chraïbi, V.L.S. (2014b). Laurentian Great Lakes phytoplankton and their water quality characteristics, including a diatom-based model for paleoreconstruction of phosphorus. PLoS ONE, 9: e104705.

Reavie, E.D., Cai, M., Werne, J.P., Meyer-Jacob, C., Smol, J.P. (2021). Long-term productivity trends in the Laurentian Great Lakes: a comparison of geochemical methods. Journal of Paleolimnology 65: 299-314.

Reavie, E.D., Cai, M., Twiss, M.R., Carrick, H.J., Davis, T.W., Johengen, T.H., Gossiaux, D., Smith, D.E., Palladino, D., Burtner, A., Sgro, G.V. (2016). Winter-spring diatom production in Lake Erie is an important driver of summer hypoxia. Journal of Great Lakes Research 42: 608-618.

Reavie, E.D., Sgro, G.V., Estepp, L.R., Bramburger, A.J., Pillsbury, R.W., Shaw Chraïbi, V.L., Cai, M., Stow, C.A., Dove, A. (2017). Climate warming and changes in *Cyclotella sensu lato* in the Laurentian Great Lakes. Limnology and Oceanography 62: 768-783.

Reavie, E.D., Robbins, J.A., Stoermer, E.F., Douglas, M.S., Emmert, G.E., Morehead, N.R. & Mudroch, A. (2005). Paleolimnology of a fluvial lake downstream of Lake Superior and the industrialized region of Sault Saint Marie. Canadian Journal of Fisheries and Aquatic Sciences 62: 2586-2608.

Rozon, R.M., Bowen, K.L., Niblock, H.A., Fitzpatrick, M.A. & Currie, W.J. (2018). It goes with the flow: Size mediated plankton attenuation through the Niagara River connecting channel. Journal of Great Lakes Research 44: 1327-1338.

Sgro, G.V., Reavie, E.D. (2018). Lake Erie's ecological history reconstructed from the sedimentary record. Journal of Great Lakes Research 44: 54-69.

Shaw Chraïbi, V.L., Kireta, A.R., Reavie, E.D., Brown, T.N., Cai, M. (2014). A paleolimnological assessment of human impacts on Lake Superior. Journal of Great Lakes Research 40: 886–897.

Sterner, R.W., Reinl, K.L., Lafrancois, B.M., Brovold, S. and Miller, T.R. (2020). A first assessment of cyanobacterial blooms in oligotrophic Lake Superior. Limnology and Oceanography, 65: 2984-2998.

Stoermer, E.F. (1978). Phytoplankton assemblages as indicators of water quality in the Laurentian Great Lakes. Transactions of the American Microscopical Society 97: 2-16.

The Government of the United States of America and the Government of Canada (2012). Protocol amending the agreement between the United States of America and Canada on Great Lakes water quality, 1978, as amended on October 16, 1983 and on November 18, 1987.

Twiss, M.R., McKay, R.M.L., Bourbonniere, R.A., Bullerjahn, G.S., Carrick, H.J., Smith, R.E.H., Winter, J.G., D'souza, N.A., Furey, P.C., Lashaway, A.R., Saxton, M.A., Wilhelm, S.W. (2012). Diatoms abound in ice-covered Lake Erie: An investigation of offshore winter limnology in Lake Erie over the period 2007 to 2010. Journal of Great Lakes Research, 3: 18-30.

USEPA 2000. Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs. EPA822-B00-001. U.S. Environmental Protection Agency, Office of Water,

Washington, D.C. RWinter, J.G., Palmer, M.E., Howell, E.T. and Young, J.D. (2015). Long term changes in nutrients, chloride, and phytoplankton density in the nearshore waters of Lake Erie. Journal of Great Lakes Research, 41: 145-155.

## List of Figures

**Figure 1**. Bar plots of phytoplankton biovolume and community composition in Lake Superior from 2001 through 2021. Bars represent averages across all integrated pelagic samples, with error bars calculated from sample totals. Numbers below biovolume bars indicate the number of samples summarized for that bar. Lower plots in each pair represent proportions relative to the average total biomass in each sub-basin. Bars are divided according to algal groups. A significant increasing (+) trend in total biovolume (Kendall's rank correlation test, $P < 0.05$) for the 20-year period is indicated in the upper left corner of each plot. Revised and updated from Reavie et al (2014a).

**Figure 2**. Bar plots of phytoplankton biovolume and community composition in Lake Huron from 2001 through 2021. Bars represent averages across all integrated pelagic samples, with error bars calculated from sample totals. Numbers below biovolume bars indicate the number of samples summarized for that bar. Lower plots in each pair represent proportions relative to the average total biomass in each sub-basin. Bars are divided according to algal groups. Major noteworthy trends include: early-2000s declines in phytoplankton abundance. A significant decreasing (-) trend in total biovolume (Kendall's rank correlation test, $P < 0.05$) for the 20-year period is indicated in the upper left corner of each plot. Revised and updated from Reavie et al (2014a).

**Figure 3**. Histograms of phytoplankton biovolume and community composition in Lake Michigan from 2001 through 2021. Bars represent averages across all integrated pelagic samples, with error bars calculated from sample totals. Numbers below biovolume bars indicate the number of samples summarized for that bar. Lower plots in each pair represent proportions relative to the average total biomass in each sub-basin. Bars are divided according to algal groups. Major noteworthy trends include: early-2000s declines in phytoplankton abundance. A significant decreasing (-) trend in total biovolume (Kendall's rank correlation test, $P < 0.05$) for the 20-year period is indicated in the upper left corner of each plot. Revised and updated from Reavie et al (2014a).

**Figure 4**. Histograms of phytoplankton biovolume and community composition in Lake Erie from 2001 through 2021. Bars represent averages across all integrated pelagic samples, with error bars calculated from sample totals. Numbers below biovolume bars indicate the number of samples summarized for that bar. Lower plots in each pair represent proportions relative to the average total biomass in each sub-basin. Bars are divided according to algal groups. Major noteworthy trends include increases in spring and summer phytoplankton in central and western Lake Erie (mainly attributed to increases in spring diatoms and summer cyanobacteria). A significant increasing (+) or decreasing (-) trend in total biovolume (Kendall's rank correlation test, $P < 0.05$) for the 20-year period is indicated in the upper left corner of each plot. Revised and updated from Reavie et al (2014a).

**Figure 5**. Histograms of phytoplankton biovolume and community composition in Lake Ontario from 2001 through 2021. Bars represent averages across all integrated pelagic samples, with error bars calculated from sample totals. Numbers below biovolume bars indicate the number of samples summarized for that bar. Lower plots in each pair represent proportions relative to the average total biomass in each sub-basin. Bars are divided according to algal groups. Revised and updated from Reavie et al (2014a).

**Last Updated**

*State of the Great Lakes 2022 Report*

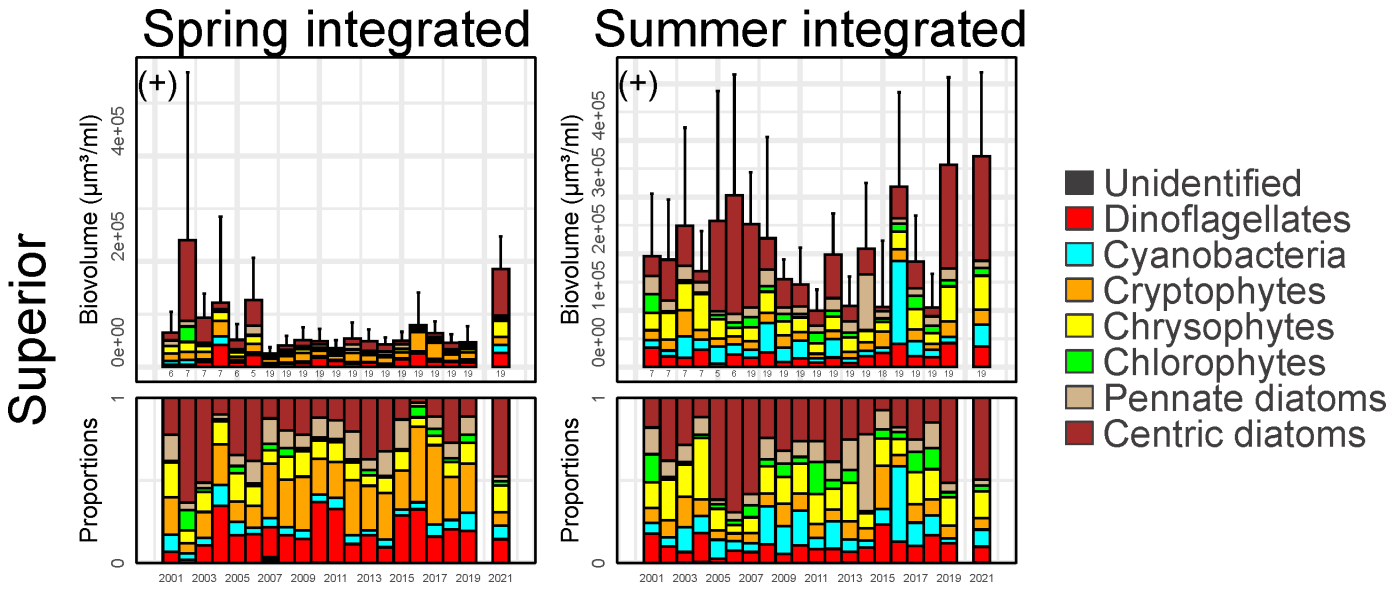


**Figure 1**. Bar plots of phytoplankton biovolume and community composition in Lake Superior from 2001 through 2021. Bars represent averages across all integrated pelagic samples, with error bars calculated from sample totals. Numbers below biovolume bars indicate the number of samples summarized for that bar. Lower plots in each pair represent proportions relative to the average total biomass in each sub-basin. Bars are divided according to algal groups. A significant increasing (+) trend in total biovolume (Kendall's rank correlation test, $P < 0.05$) for the 20-year period is indicated in the upper left corner of each plot. Revised and updated from Reavie et al (2014a).

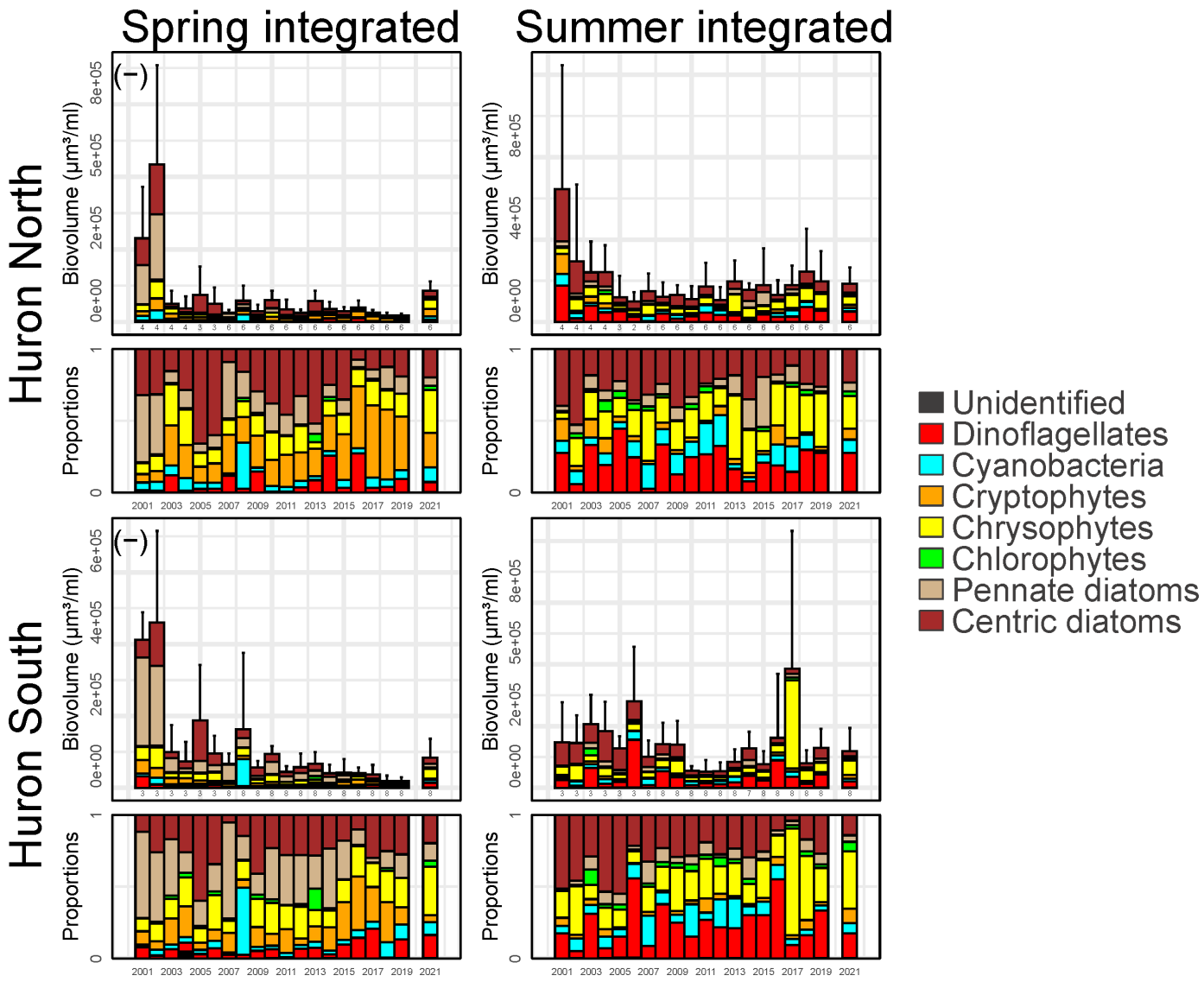


**Figure 2**. Bar plots of phytoplankton biovolume and community composition in Lake Huron from 2001 through 2021. Bars represent averages across all integrated pelagic samples, with error bars calculated from sample totals. Numbers below biovolume bars indicate the number of samples summarized for that bar. Lower plots in each pair represent proportions relative to the average total biomass in each sub-basin. Bars are divided according to algal groups. Major noteworthy trends include: early-2000s declines in phytoplankton abundance. A significant decreasing (-) trend in total biovolume (Kendall's rank correlation test, $P < 0.05$) for the 20-year period is indicated in the upper left corner of each plot. Revised and updated from Reavie et al (2014a).

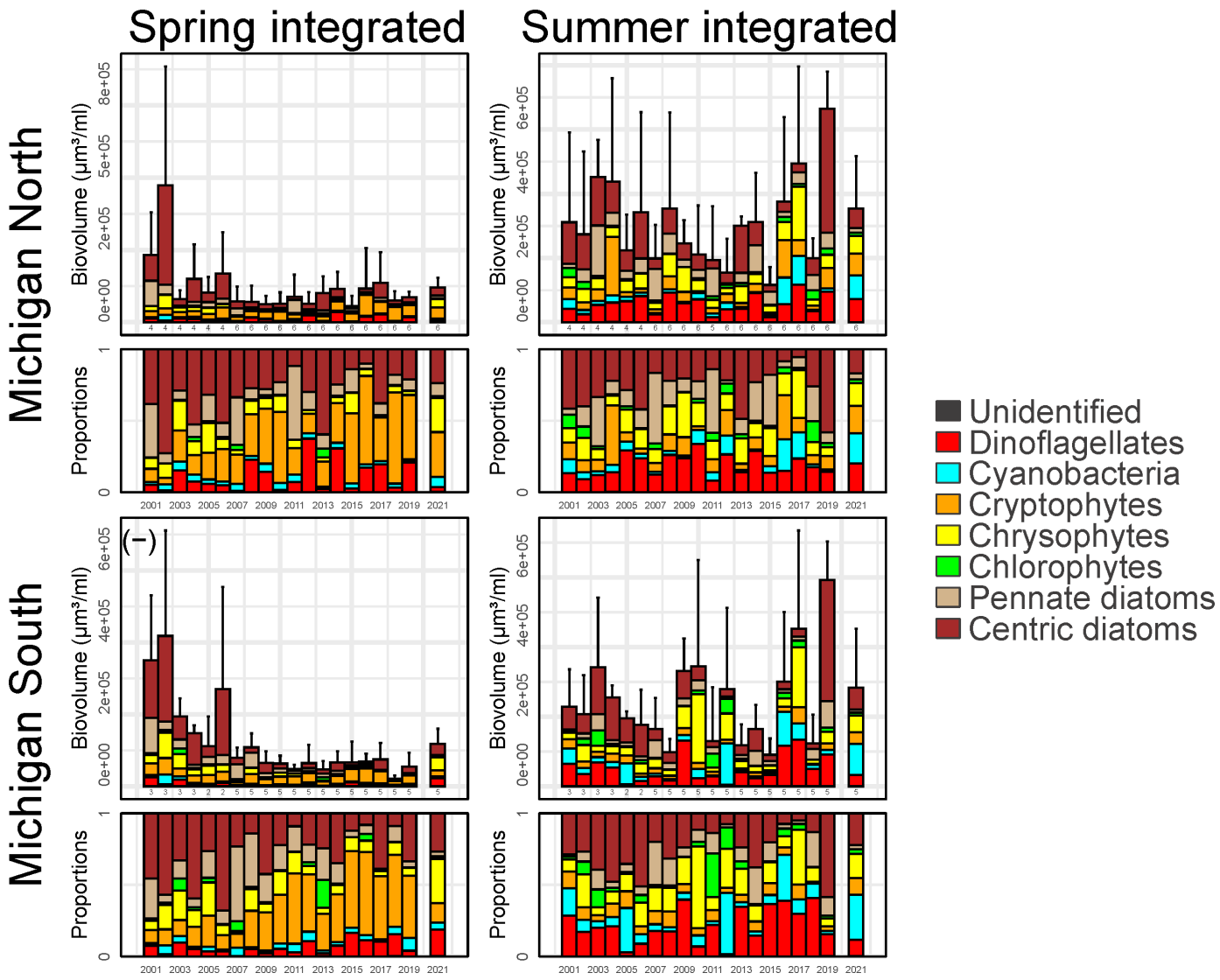


**Figure 3**. Histograms of phytoplankton biovolume and community composition in Lake Michigan from 2001 through 2021. Bars represent averages across all integrated pelagic samples, with error bars calculated from sample totals. Numbers below biovolume bars indicate the number of samples summarized for that bar. Lower plots in each pair represent proportions relative to the average total biomass in each sub-basin. Bars are divided according to algal groups. Major noteworthy trends include: early-2000s declines in phytoplankton abundance. A significant decreasing (-) trend in total biovolume (Kendall's rank correlation test, $P < 0.05$) for the 20-year period is indicated in the upper left corner of each plot. Revised and updated from Reavie et al (2014a).

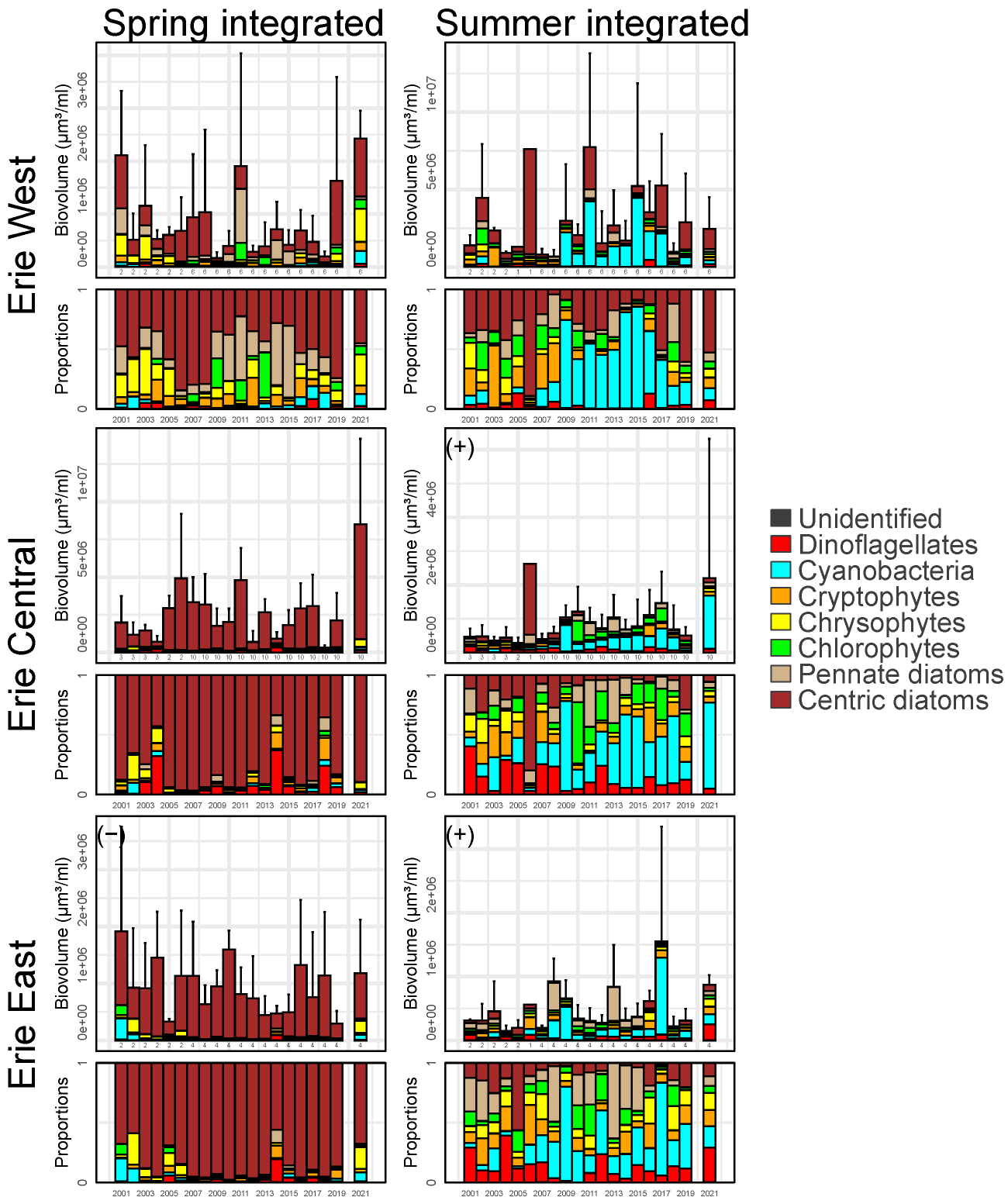


**Figure 4**. Histograms of phytoplankton biovolume and community composition in Lake Erie from 2001 through 2021. Bars represent averages across all integrated pelagic samples, with error bars calculated from sample totals. Numbers below biovolume bars indicate the number of samples summarized for that bar. Lower plots in each pair

represent proportions relative to the average total biomass in each sub-basin. Bars are divided according to algal groups. Major noteworthy trends include increases in spring and summer phytoplankton in central and western Lake Erie (mainly attributed to increases in spring diatoms and summer cyanobacteria). A significant increasing (+) or decreasing (-) trend in total biovolume (Kendall's rank correlation test, $P < 0.05$) for the 20-year period is indicated in the upper left corner of each plot. Revised and updated from Reavie et al (2014a).

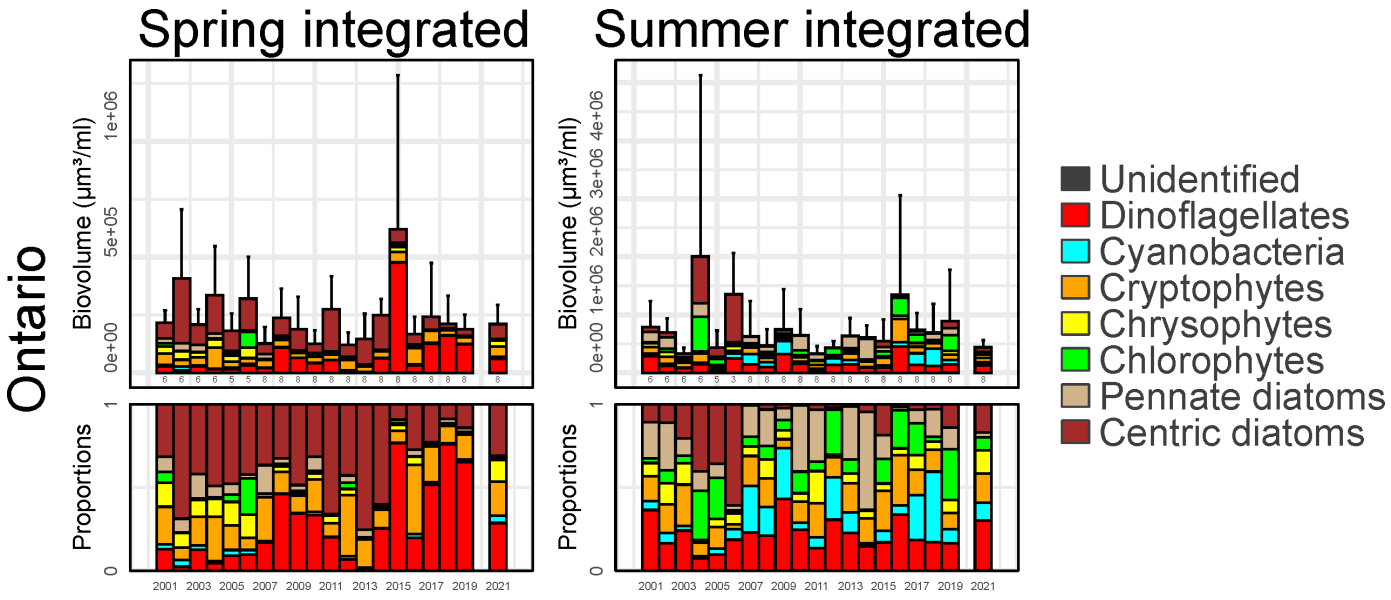


**Figure 5**. Histograms of phytoplankton biovolume and community composition in Lake Ontario from 2001 through 2021. Bars represent averages across all integrated pelagic samples, with error bars calculated from sample totals. Numbers below biovolume bars indicate the number of samples summarized for that bar. Lower plots in each pair represent proportions relative to the average total biomass in each sub-basin. Bars are divided according to algal groups. Revised and updated from Reavie et al (2014a).