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# Results From The Great Lakes National Program Office's Biological Open Water Surveillance Program Of The Laurentian Great Lakes for 1998

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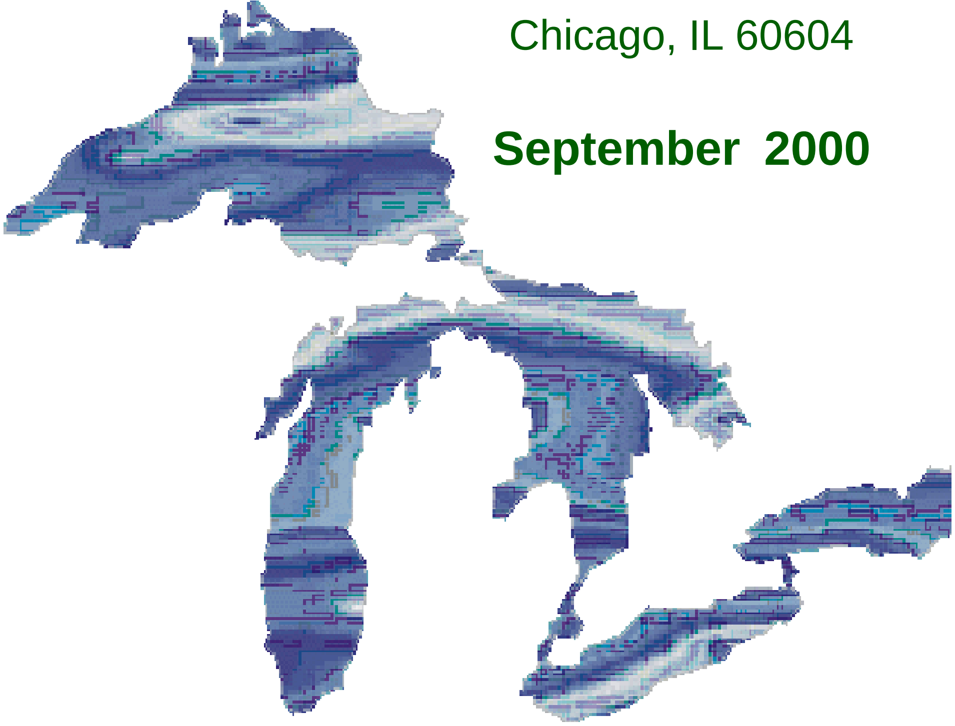

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# INTRODUCTION

The Laurentian Great Lakes constitute the largest continuous body of fresh water on earth, and with a volume of 24,620 $km^2$ (Wetzel, 1983), contain nearly 20% of the world's unfrozen fresh water. These lakes represent an enormous cultural and economic resource for both the United States and Canada. Increasing population and industrial growth in recent history, however, has produced a trend of increasing eutrophication and raised concerns about declining water quality in the lakes. As a result of these concerns, in 1972 the United States and Canada signed the Great Lakes Water Quality Agreement as an expression of each country's commitment to restore and maintain the chemical, physical and biological integrity of the Great Lakes Basin Ecosystem.

The Great Lakes National Program Office (GLNPO) of the United States Environmental Protection Agency (USEPA) has primary responsibility within the US for conducting surveillance monitoring of the offshore waters of the Great Lakes. This monitoring is intended to fulfill the provisions of the Great Lakes Water Quality Agreement (International Joint Commission, 1978) calling for periodic monitoring of the lakes to: 1) assess compliance with jurisdictional control requirements; 2) provide information on non-achievement of agreed upon water quality objectives; 3) evaluate water quality trends over time; and 4) identify emerging problems in the Great Lakes Basin Ecosystem. The monitoring effort is focused on whole lake responses to changes in loadings of anthropogenic substances, so sampling is largely restricted to the relatively homogeneous offshore waters of each lake. Because of the daunting logistical exigencies of sampling such a large area, temporal resolution is currently limited to two well-defined periods during the year: the spring isothermal period and the stable, stratified summer period.

GLNPO's monitoring of the Great Lakes began in 1983, with coverage at that time including Lakes Michigan, Huron and Erie. Initially Lakes Ontario and

Superior were excluded from monitoring because the former was already monitored annually by Canada, and the latter was not felt to be susceptible to eutrophication. In 1986 sampling was extended to include Lake Ontario, and in 1992 sampling of Lake Superior was added. In addition to a wide range of physical and chemical parameters, the lakes have been sampled for phytoplankton and zooplankton, including crustaceans and rotifers, since the inception of the program. In 1997, a benthic invertebrate biomonitoring program was added to complement the existing open water surveillance sampling. This sampling program is unique in that all five lakes are sampled by one agency, and samples are analyzed by one primary lab. Consequently, analytical methods, and most importantly taxonomy, remain consistent both over time and across all five lakes.

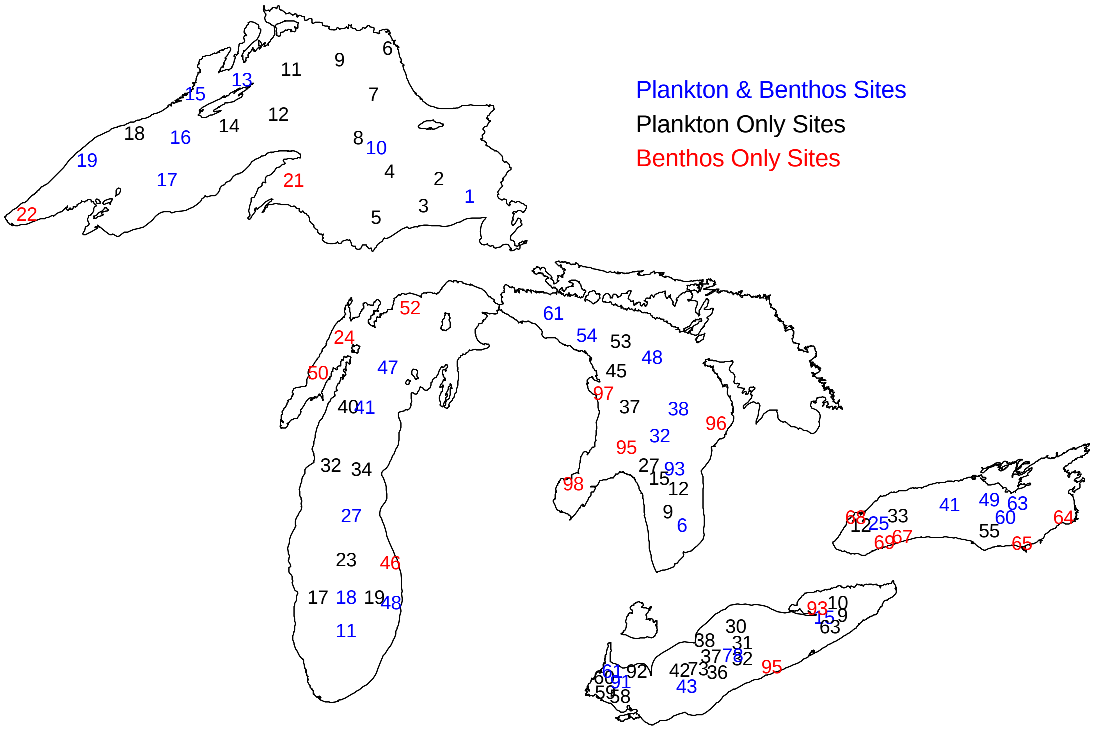
In this report we will present, for the first time, results of GLNPO's biological surveillance sampling program from all five Laurentian Great Lakes. Our goal here is to provide a brief general description of the offshore planktonic and the benthic communities of all five Great Lakes from GLNPO's 1998 surveys.

# METHODS

## Field Methods

In 1998, samples were taken from all five lakes aboard the R/V Lake Guardian during both a spring and a summer survey. The spring survey ran from 29 March to 14 May, while the summer sampling was conducted between 2 August and 5 September. Between 13 and 22 stations were sampled on each lake for plankton, benthos, or both (Figure 1). Two or three stations per lake are designated master stations, at which additional samples are taken in the upper fifty meters of the water column.

Figure 1. Stations sampled during GLNPO 1998 surveys.



At each station, water column profiles for temperature, conductivity, turbidity, pH, and *in vivo* chlorophyll *a* fluorescence were taken using a Seabird STE-911 CTD multi-sensor unit. Integrated samples for soluble nutrients, *in vitro* chlorophyll *a*, and phytoplankton enumeration were created from a composite of water samples taken at discrete depths (spring: surface, 5M, 10M, and 20M; summer: surface, 5M, 10M, and upper metalimnion) with Niskin bottles mounted on a SeaBird Carousel Water Sampler. Samples for total soluble phosphorus (TSP) were filtered in the field through 0.45 µm Sartorius filters and preserved with $H_2SO_4$ for later analysis in the lab. Samples for soluble silica (Si) were stored at 4° C. Samples for phytoplankton analysis were preserved in the field with Lugol's solution, and with formalin upon return to the laboratory.

Two net tows were performed at each site for zooplankton sample collection, using a 0.5 m diameter conical net (D:L = 1:3). The first tow was taken from 20 meters below the water surface or 1 meter above the bottom, whichever was less, using a 64 µm mesh net, and the second tow from 2 meters above the bottom or 100 m, whichever was less, using a 153 µm mesh net. If the station depth was less than 20 m, both tows were taken from one meter above the bottom. Triplicate tows of each depth were taken at the master stations. After collection, zooplankton were immediately narcotized with soda water, and were preserved with sucrose formalin solution (Haney and Hall, 1973) approximately twenty minutes later.

During the summer survey, quantitative samples for benthic invertebrate analysis were collected from selected sites using a Ponar grab sampler. Samples were taken in triplicate, and material sieved through a 500 µm mesh net. Samples were preserved with buffered formaldehyde with Rose Bengal to a final concentration of 5-10 % formaldehyde. In addition, a fourth Ponar sample was collected at each site for grain size determination and chemical analysis for particulate carbon, nitrogen and phosphorus.

Laboratory methods

## *Laboratory Methods*

After acid persulfate digestion, TSP and PP were measured on a Lachat QuikChem AE autoanalyzer by the ascorbic acid method (APHA, 1985). Si was determined by the molybdate method on a Lachat QuikChem AE autoanalyzer (APHA, 1985). POC was determined by the combustion-infrared method on a Carlo Erba carbon analyzer (APHA, 1985). Chlorophyll *a*, uncorrected for pheophytin, was determined on a Turner Designs 10-AU fluorometer following the method of Welschmeyer (1994). Phytoplankton were identified and abundances were estimated using the Utermöhl technique (Lund et al. 1958) at a magnification of 500x, with diatoms other than *Rhizosolenia* identified as either centrics or pennates. Diatoms were identified, and relative abundances determined, from permanent slide mounts at 1250x. Relative proportions of each taxon of centrics and pennates were then multiplied by the appropriate Utermöhl counts. At least 10 individuals of each taxon were measured per sample, and cell volumes computed using appropriate geometrical formulae. Primary taxonomic keys used were Prescott (1962), Kramer and Lange-Bertalot (1986, 1991, 1997), Patrick and Reimer (1966, 1975) and Germain (1981).

Samples for zooplankton analysis were split in the lab using a Folsom plankton splitter, and four stratified aliquots examined per sample using a stereoscopic (crustaceans) or compound (rotifers) microscope. Adult calanoids were identified according to Balcer et al. (1984). Adult cyclopoids and harpacticoids were identified according to Hudson et al. (1998). Immature calanoids and cyclopoids are identified to the lowest taxonomic level possible, usually suborder or genus. Nauplii were counted with rotifers. The following cladocerans were identified according to Balcer *et al* (1984): *Leptodora kindti*, *Polyphemus pediculus*, *Holopedium gibberum*, and *Diaphanosoma birgei*. Brooks (1957) and Evans (1985) were used for all Daphnidae. The remaining cladocerans (Chydoridae, Bosminidae, and

Macrothricidae) were identified according to Edmundson (1959). Members of Cercopagidae (i.e. *Bythotrephes cedarstroemii*, *Cercopagis pengoi*) were identified according to Rivier (1998). Length measurements were made on the first twenty individuals of each species encountered per sample (crustaceans) or per lake (rotifers). Crustacean biovolumes were computed using length-weight relationships found in the literature, while rotifer biomass was calculated according to A. Ruttner-Kolisko (in Bottrell et al., 1976).

Organisms were picked out of benthos samples under low magnification using a dissecting microscope. Oligochaetes and chironomids were mounted on slides and identified under a compound scope at 63x; other organisms were identified under a dissecting scope. Taxonomy followed Kathman and Brinkhurst, 1998 (oligochaetes); Holsinger, 1972 (amphipods); Wiederholm, 1983 (chironomids) and Merritt and Cummins, 1996 (all else).

# RESULTS

## *Physical Chemical*

Temperatures across the lakes during the spring survey were between 2-4° C, with the exception of the shallow western basin of Lake Erie, where temperatures reached 7.6° C (Figure 2).

Concentrations of most chemical constituents showed a general trend of increase from upstream to downstream, i.e. along the sequence Superior, Michigan, Huron, Erie and Ontario. Lake Michigan was often an exception to this sequence, however, exhibiting relatively elevated levels of alkalinity, chloride, pH and conductivity. In the case of both

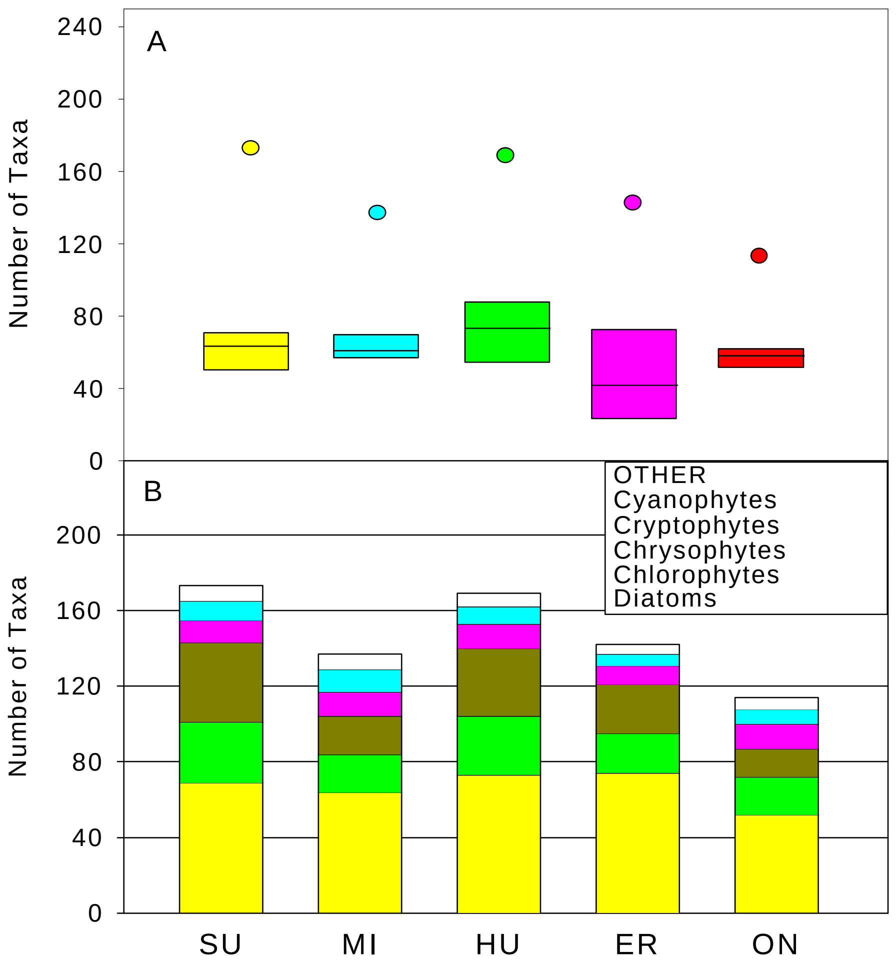


Figure 4. A.) Phytoplankton species richness, spring cruise, 1998. Boxes represent minimum, mean, and maximum numbers of taxa per station at each lake; circles represent total numbers of taxa found in each lake; B.) Contribution of major taxonomic groups to species richness.

chlorophyll and dissolved phosphorus, Lake Erie exhibited the highest average concentrations. Dissolved silica showed a reverse trend, generally decreasing from upstream to downstream. Nitrate showed very little variation across the lakes.

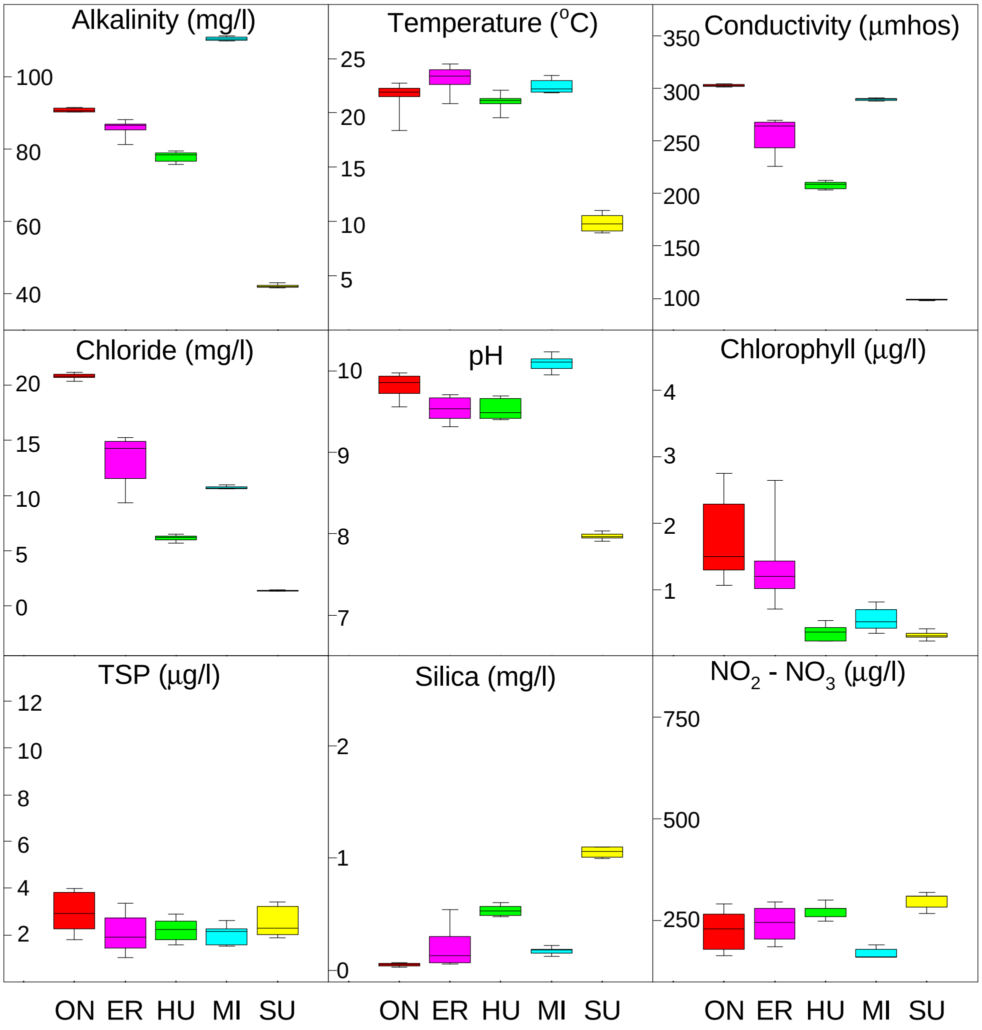


Figure 3. Box plots of physical and chemical data for the Great Lakes, summer 1998. Boxes represent 25th, 50th and 75th percentiles; whiskers indicate 10th and 90th percentiles.

During the summer survey, stable stratification had developed at nearly all open water sites in all lakes except for Lake Erie, where stratification was only evident in the deeper eastern basin. The depth of the epilimnion (delimited by a greater than 1° C difference per meter) ranged from 5.5 m in western Ontario to 23.5 m in northern Lake Superior, averaging between 14 and 17 for the upper lakes and 19 and 11 for Lakes Erie and Ontario, respectively. Epilimnetic temperatures at most sites were generally between 21 and 24° C, with the exception of Lake Superior, where temperatures were only about 10° C.

pH values across the lakes were higher than in spring, and differences between the lakes were somewhat more pronounced with Superior substantially lower than the other lakes, and Michigan and Ontario somewhat higher (Figure 3). Values for chloride, alkalinity and conductivity were essentially identical to spring. Both total soluble phosphorus and chlorophyll were higher in the lower lakes compared to the upper lakes, with Lake Ontario on average exhibiting the highest values for both parameters. Available nitrogen fluctuated within a very narrow range for all lakes, while dissolved silica was highest in Lake Superior and Lake Huron.

## Phytoplankton

### Spring

During spring, a total of 261 phytoplankton taxa were identified in the 72 samples examined. All lakes supported over one hundred taxa, with Lakes Superior and Huron having the greatest number of species (Figure 4a). Average numbers of taxa per site for the lakes ranged from 42 in Lake Erie to 73 in Lake Huron. Diatoms, overwhelmingly the most diverse group across all lakes, contributed between 40 and 50% of the species found in each lake (Figure 4b). Chlorophytes and chrysophytes each contributed between about 20 and 40 species per lake, while between 10 and 12 species of Cryptophyte were found in each lake. Other groups, while occasionally

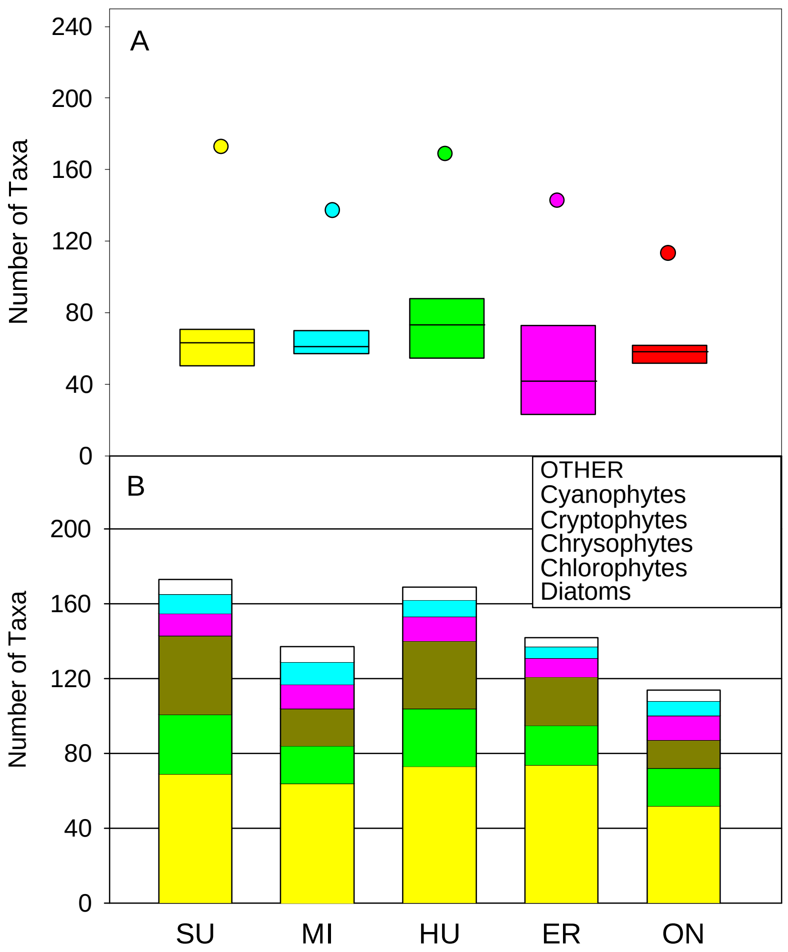
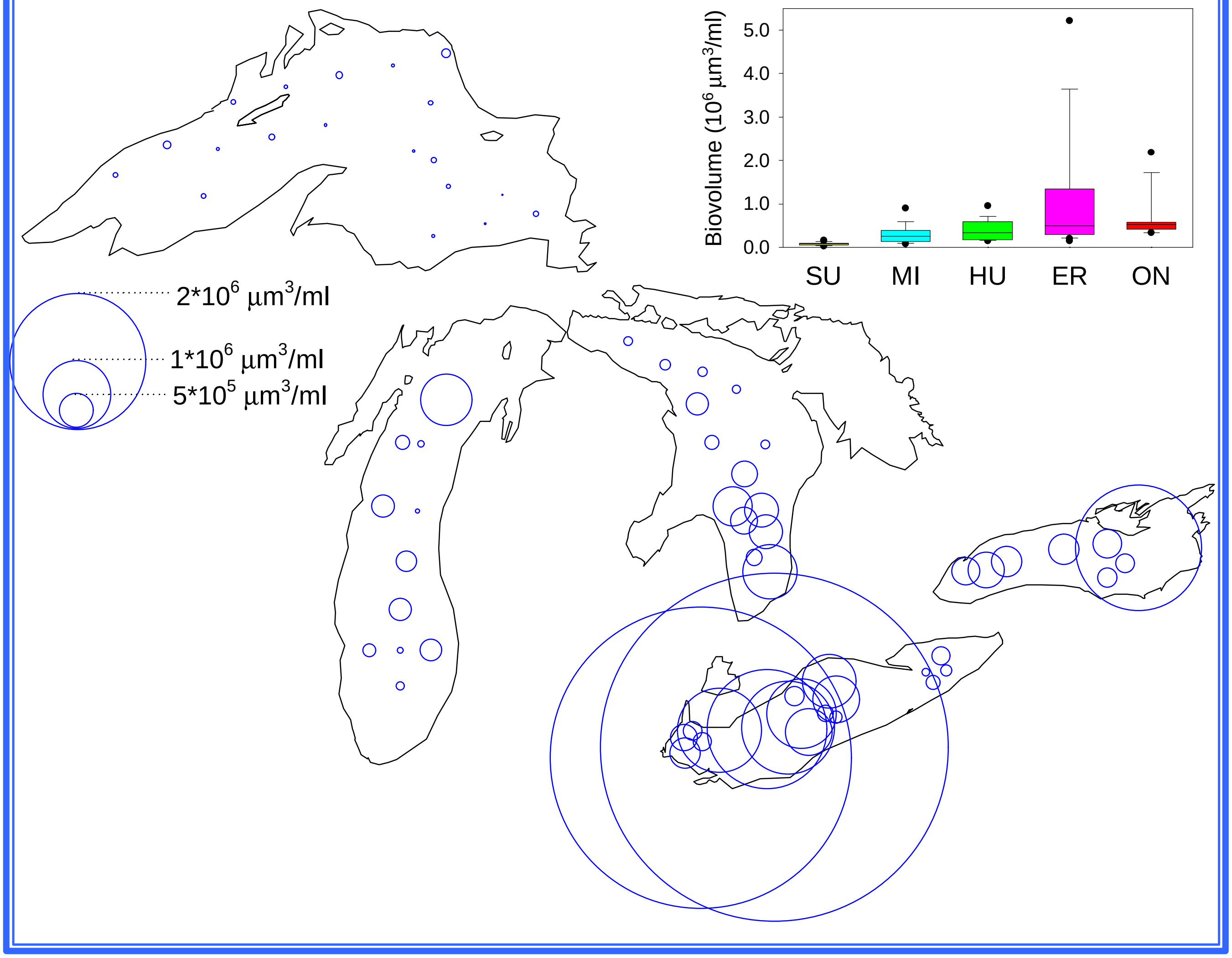


Figure 4. A.) Phytoplankton species richness, spring cruise, 1998. Boxes represent minimum, mean, and maximum numbers of taxa per station at each lake; circles represent total numbers of taxa found in each lake; B.) Contribution of major taxonomic groups to species richness.

responsible for high numbers of individuals, were considerably less diverse.

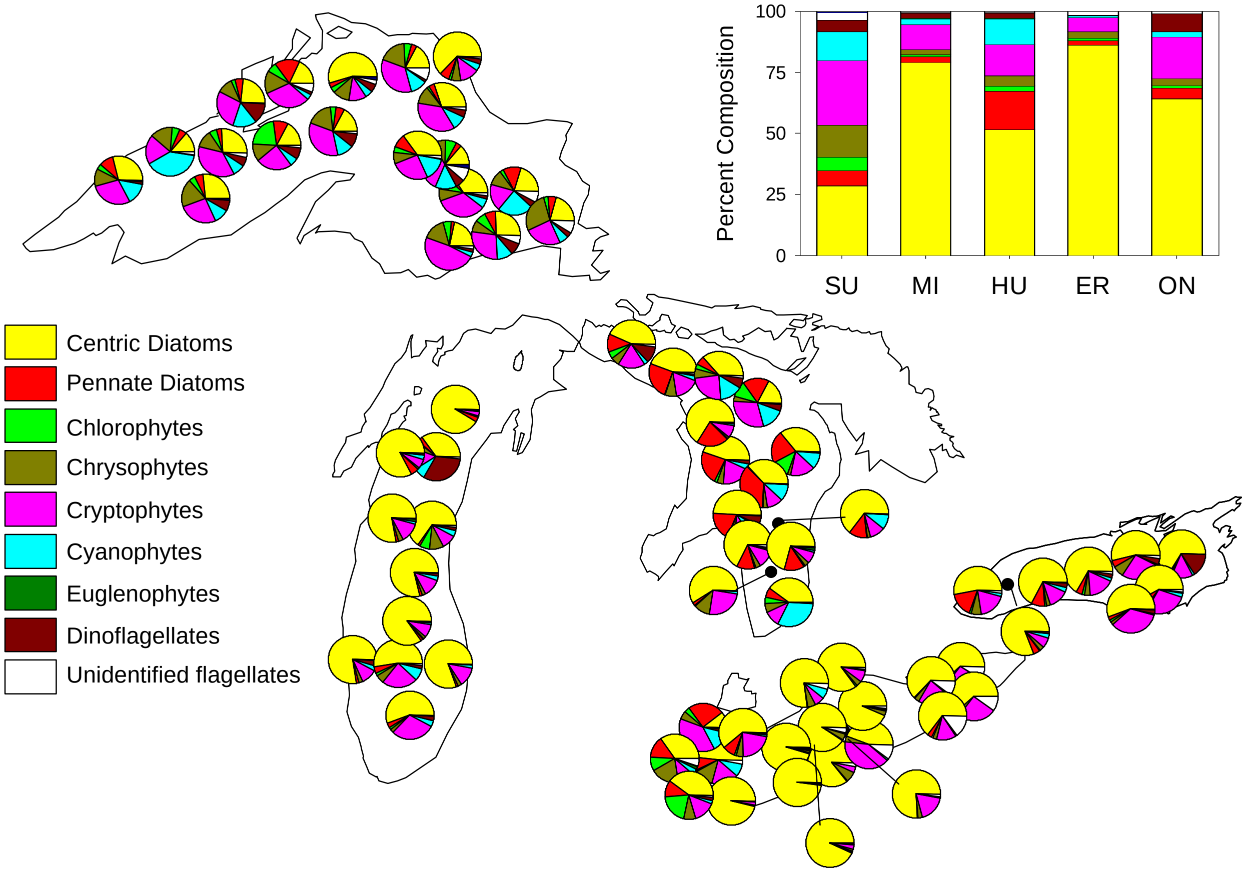
Total phytoplankton biovolumes across the lakes ranged from $2.6\cdot 10^{4}\ \mu m^{3}\ ml^{-1}$ at a site in Lake Superior to $6.0\cdot 10^{6}\ \mu m^{3}\ ml^{-1}$ at a site in Lake Erie (Figure 5), with the most spatial heterogeneity apparent in Lake Erie. Median biovolumes for each lake, however, ranged only between $2.6\cdot 10^{5}\ \mu m^{3}\ ml^{-1}$ in Lake Michigan to $5.2\cdot 10^{5}\ \mu m^{3}\ ml^{-1}$ in lakes Erie and Ontario, with the exception of Lake Superior (Median = $8.5\cdot 10^{4}\ \mu m^{3}\ ml^{-1}$).

Figure 5. Biovolume of the total phytoplankton community in the Great Lakes, spring 1998. Inset shows box plots of phytoplankton biovolumes for each lake.



Diatoms were the dominant phytoplankters at most sites, making up between 70 and 80% of phytoplankton biovolume, on a lake-wide basis, in all lakes except Superior (Figure 6; Table 1). Cryptophytes were second in importance, contributing between 6% (Lake Erie) and 27% (Lake Superior) of phytoplankton biovolume. Cyanophytes contributed a relatively minor amount of biovolume to most sites, although substantial populations were found at some sites in Lake Superior and in southern Lake Huron. Biovolumes of chlorophytes were uniformly low throughout the lakes in spring.

Figure 6. Relative biovolumes of major phytoplankton groups in the Great Lakes, spring cruise, 1998. Inset shows whole-lake averages.



## *Summer*

A total of 285 phytoplankton taxa were identified from epilimnetic samples taken during the summer survey, a number similar to that found in the spring. Numbers of taxa found at each lake, and numbers of taxa found at sites within lakes, were also similar to those in spring, although Lake Erie had slightly greater species richness in summer compared to spring (Figure 7a). The contribution of different phytoplankton divisions to species diversity was similar to that of spring, although diatoms contributed somewhat fewer species and chlorophytes and chrysophytes slightly more (Figure 7b). Again, the contribution of cryptophytes and cyanophytes to species richness was 10% or less.

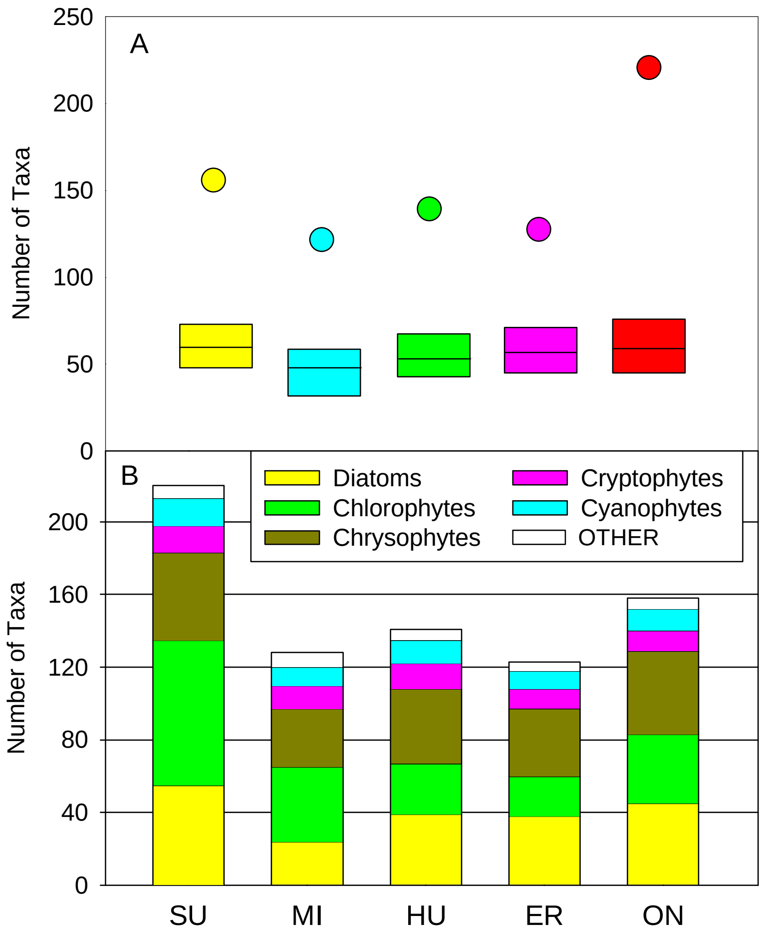
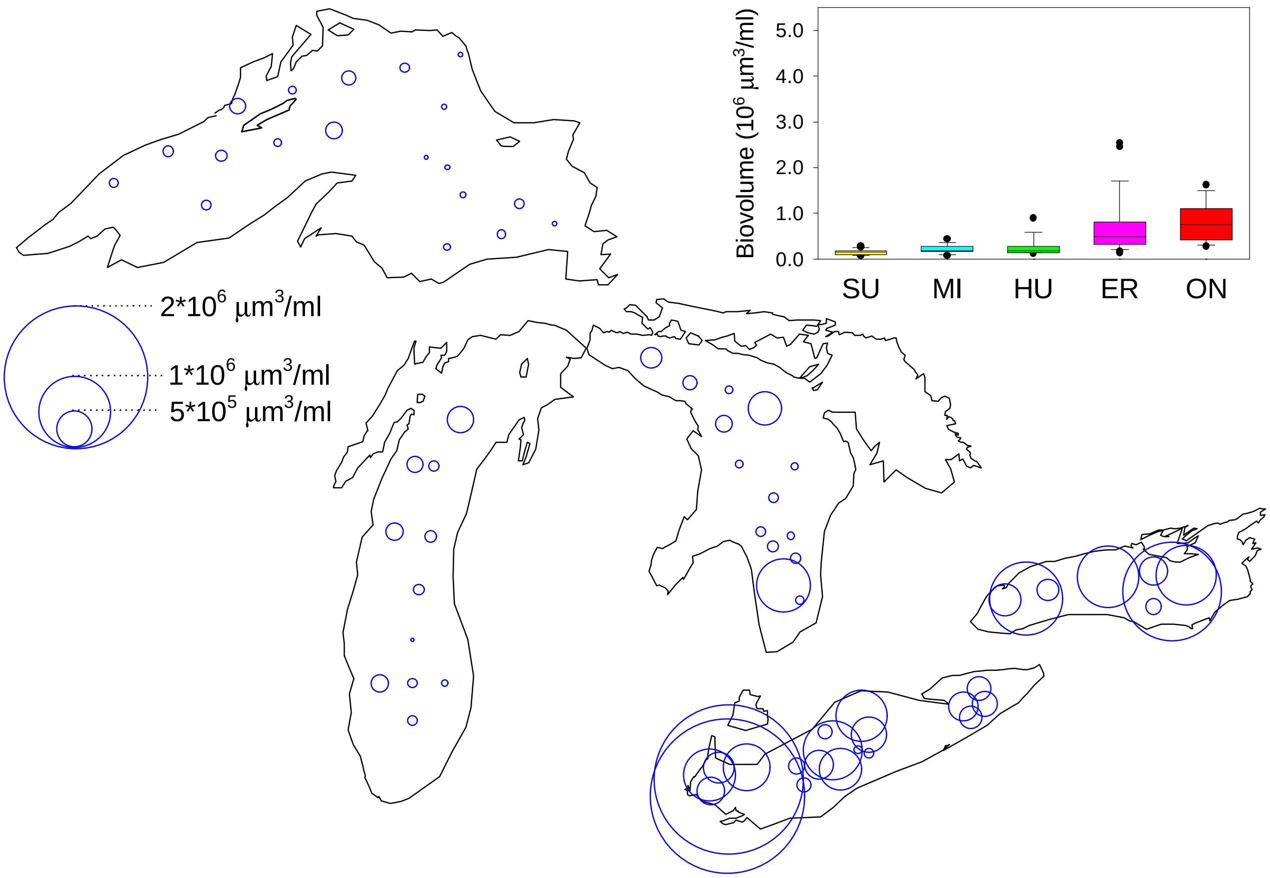


Figure 7. A.) Phytoplankton species richness, summer cruise, 1998. Boxes represent minimum, mean, and maximum numbers of taxa per station at each lake; circles represent total numbers of taxa found in each lake; B.) Contribution of major taxonomic groups to species richness.

There was considerably less site to site variability in phytoplankton biovolumes in the summer, compared to spring, varying from 6.96$\cdot$ $10^4$ $\mu m^3$ $ml^{-1}$ at a site in

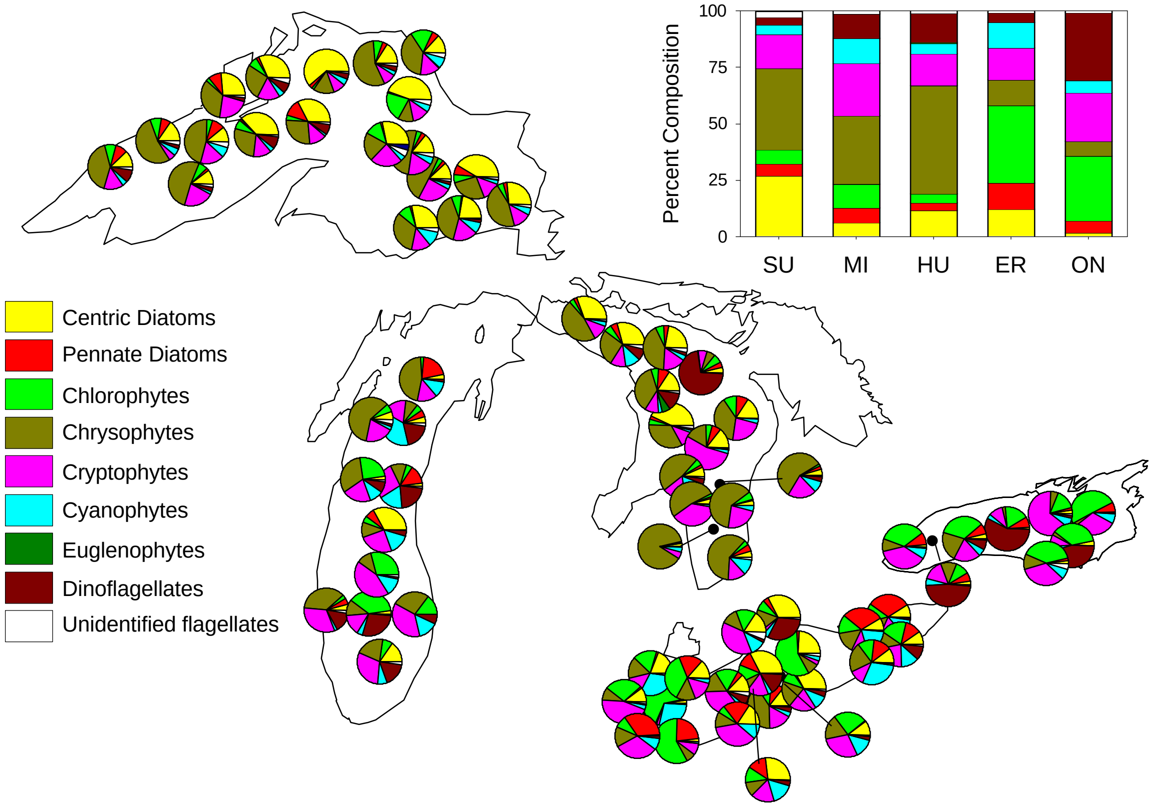
Lake Michigan to 2.54· $10^6$ µ$m^3$ m$l^{-1}$ at a site in Lake Erie (Figure 8). Lake-wide median biovolumes were also more similar in summer compared to spring, due mostly to larger biovolumes in Lake Superior. As in spring, though, a high degree of spatial heterogeneity in phytoplankton biovolumes was seen in Lake Erie.

Figure 8. Biovolume of the total phytoplankton community in the Great Lakes, summer 1998. Inset shows box plots of phytoplankton biovolumes for each lake.



The most notable change in summer phytoplankton communities was a shift away from diatoms (Figure 9; Table 2). Proportions of chrysophytes increased in the upper lakes, and proportions of chlorophytes increased substantially in Lakes Erie and Ontario. Populations of cyanophytes showed notable increases only in Lake Erie. Dinoflagellate populations also increased at many sites, with Lake Ontario in particular supporting particularly large populations. These, however, were most often the result of single large individuals of *Ceratium hirundinella* or *Peridinium* being found in a sample, so biovolume estimates of this division should be interpreted with caution.

Figure 9. Relative biovolumes of major phytoplankton groups in the Great Lakes, summer cruise, 1998. Inset shows whole-lake averages.



## Zooplankton

### Spring

Diversity of the crustacean communities on a site by site basis was relatively low across the lakes, with most sites supporting between 6 and 17 species, with the exception of Superior, where no more than 7 taxa were found at any site (Figure 10a). Total numbers of taxa found in each lake varied from 9 (Superior) to 20 (Erie).

Total crustacean abundances (excluding nauplii) varied from 39 animals m$^{-3}$ at ER 10 to over 12,000 at stations in Erie and Huron (Figure 11). Overall, however, within lake differences in abundances were relatively minor, with the dramatic exception of Lake Erie, where abundances varied over two orders of magnitude. Most sites supported similar numbers of organisms; lake-wide median abundances for Lakes Michigan, Huron and Ontario were between 4,034 and 5,716 animals m$^{-3}$. Abundances in Lake Superior were substantially lower (median=935 animals m$^{-3}$), while abundances in Lake Erie ranged from 35 to over 8,000 animals m$^{-3}$. The high degree of spatial variability in Lake Erie was not solely a result of inter-basin differences. While abundances in the eastern basin were uniformly low, both the central and western basins supported communities that varied in size by several orders of magnitude.

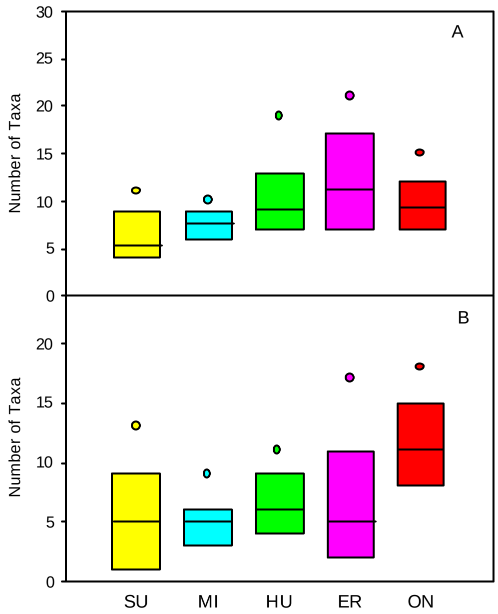


Figure 10. Minimum, maximum and mean number of taxa per site, and total number of taxa per lake, for A:) crustaceans and B:) rotifers, spring 1998.

During spring, crustacean communities across all five lakes were overwhelmingly dominated by copepods, although the relative importance of calanoids and cyclopoids varied from lake to lake. Immature copepods made up a substantial portion of the individuals found at all site. Lakes Michigan and Huron were dominated by calanoids, while Lake Ontario was dominated by cyclopoid copepods. Dominance varied from site to site in Lake Erie, with calanoids more prevalent in the western basin, and cyclopoids in the central basin. Sites in the eastern basin were composed almost entirely of very small populations of immature cyclopoids. In Lake Superior, calanoids and cyclopoids were often co-dominant. Overall most sites in the spring were dominated by a very small number of species, usually belonging to one or a few genera (Table 3).

Comparing the relative contribution of rotifers and nauplii to zooplankton community biomass is problematic, since the former are only enumerated from shallow tows, which have been shown to provide highly misleading estimates of adult crustacean biomass, particularly if taken during the day. On the other hand, deep tows in many cases probably underestimate crustacean biomass, since the deeper portion of the water column is probably devoid of most species; thus there is a dilution effect when calculating volumetric biomass. However, it was felt that the best estimate of the relative contribution of nauplii and rotifer biomass was to

Figure 11. Abundances of major crustacean groups in the Great Lakes, spring 1998. Inset shows whole lake averages.

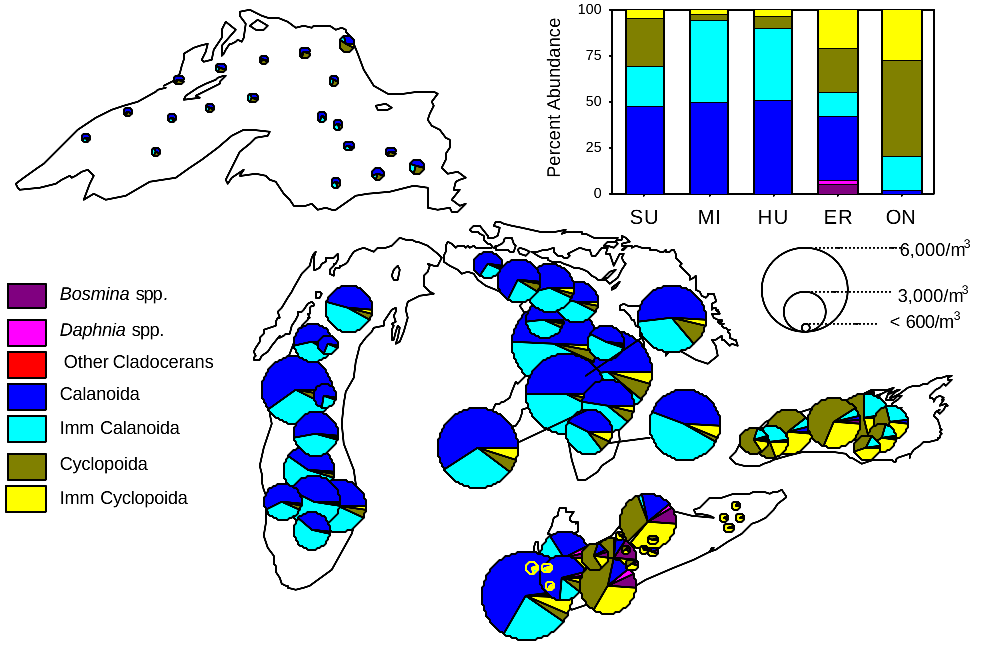
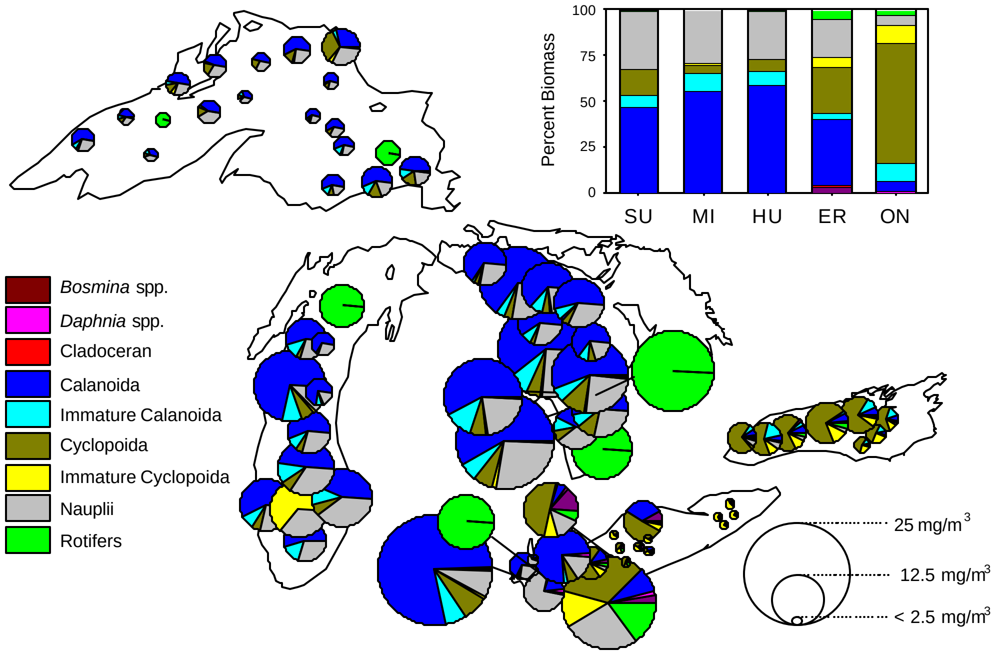
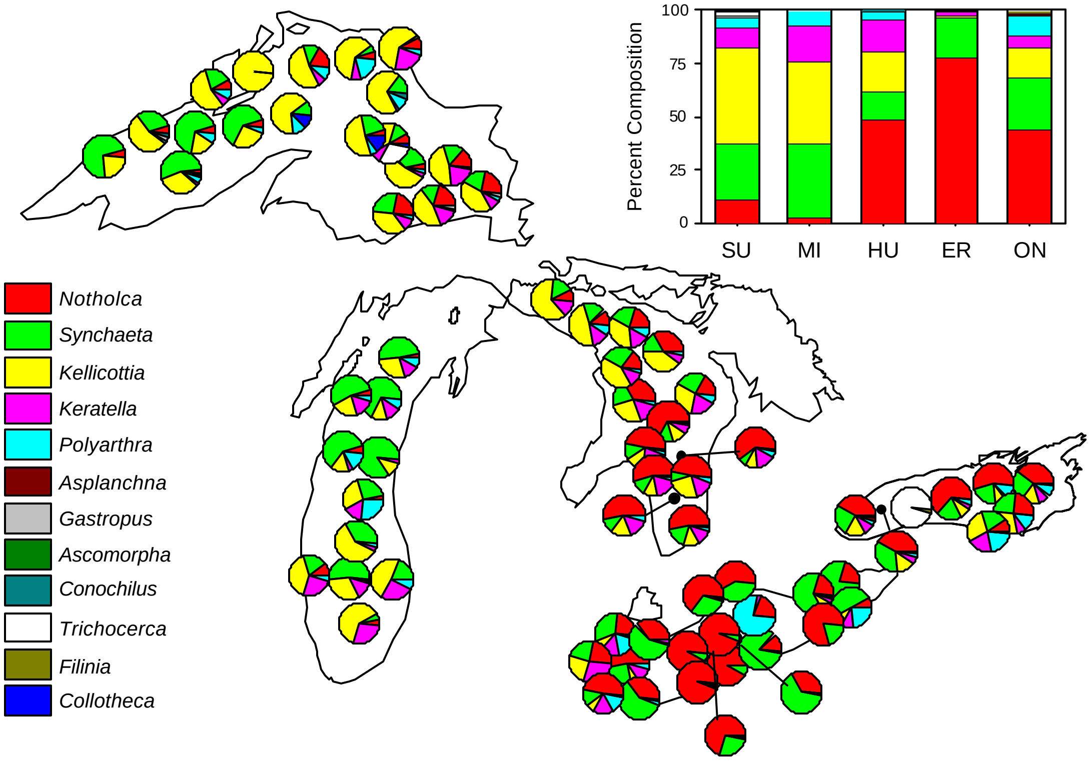


Figure 12. Total zooplankton biomass by major group in the Great Lakes, spring, 1998. Inset represents whole lake averages.



combine estimates of the former from shallow tows with estimates of the latter from deep tows, bearing in mind that at deeper (>40 m) sites, the latter might be underestimated.

Figure 13. Relative abundance of rotifer genera, spring cruise, 1998.
Inset shows whole-lake averages.



In spite of their relatively small size, nauplii contributed, on a lake-wide basis, about 20-30% of total estimated zooplankton biomass in all lakes except Ontario, where they contributed only 6% (Figure 12). Rotifers, on the other hand, were always less than 5% of zooplankton biomass, with the exception of a few sites in Lake Erie. Species richness of rotifers was similar to that of crustaceans, averaging between 6 and 12 species per site for the five lakes (Figure 10b). In all between10 and 19 species were found in each lake. In spite of this low species richness, some lake to lake differences in community composition were apparent, although communities tended to be fairly consistent over broad geographic areas (Figure 13). *Synchaeta* was present at most sites, while *Kellicottia*, and to a lesser extent *Keratella*, were more abundant in the upper lakes, particularly in Superior. The relative contribution of *Notholca* to rotifer abundance was greater in southern Lake Huron and the lower lakes.

## *Summer*

Species richness of the crustacean community was substantially higher during the summer, compared to spring, with most sites supporting between 9-15 species (Figure 14a). Total numbers of taxa found in each lake varied from 16 - 27. Again, Lake Erie had the greatest number of species overall, with nearly every species that was found in the other four lakes also found in Lake Erie.

Total crustacean abundances (excluding nauplii) were substantially higher during the summer than in spring in most lakes (Figure 15). Lake-wide median abundances in Erie and Ontario were over twelve and four times greater, respectively, than spring abundances, while lesser, but still substantial, increases were seen in Lakes Huron and Superior. In contrast, the median abundance in Lake Michigan decreased slightly from spring to summer.

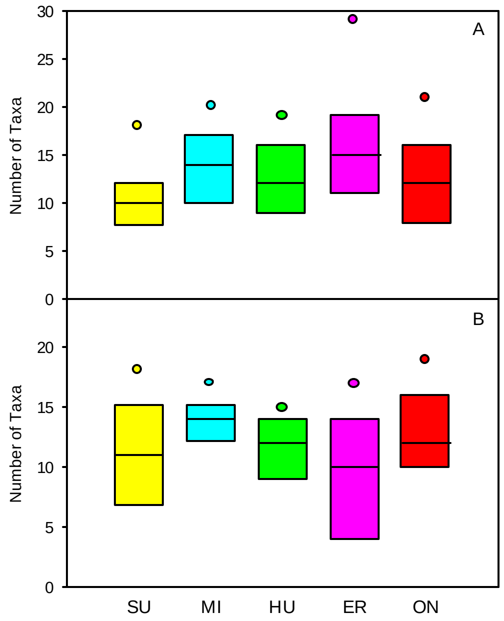


Figure 14. Minimum, maximum and mean number of taxa per site, and total number of taxa per lake, for A:) crustaceans and B:) rotifers, summer 1998.

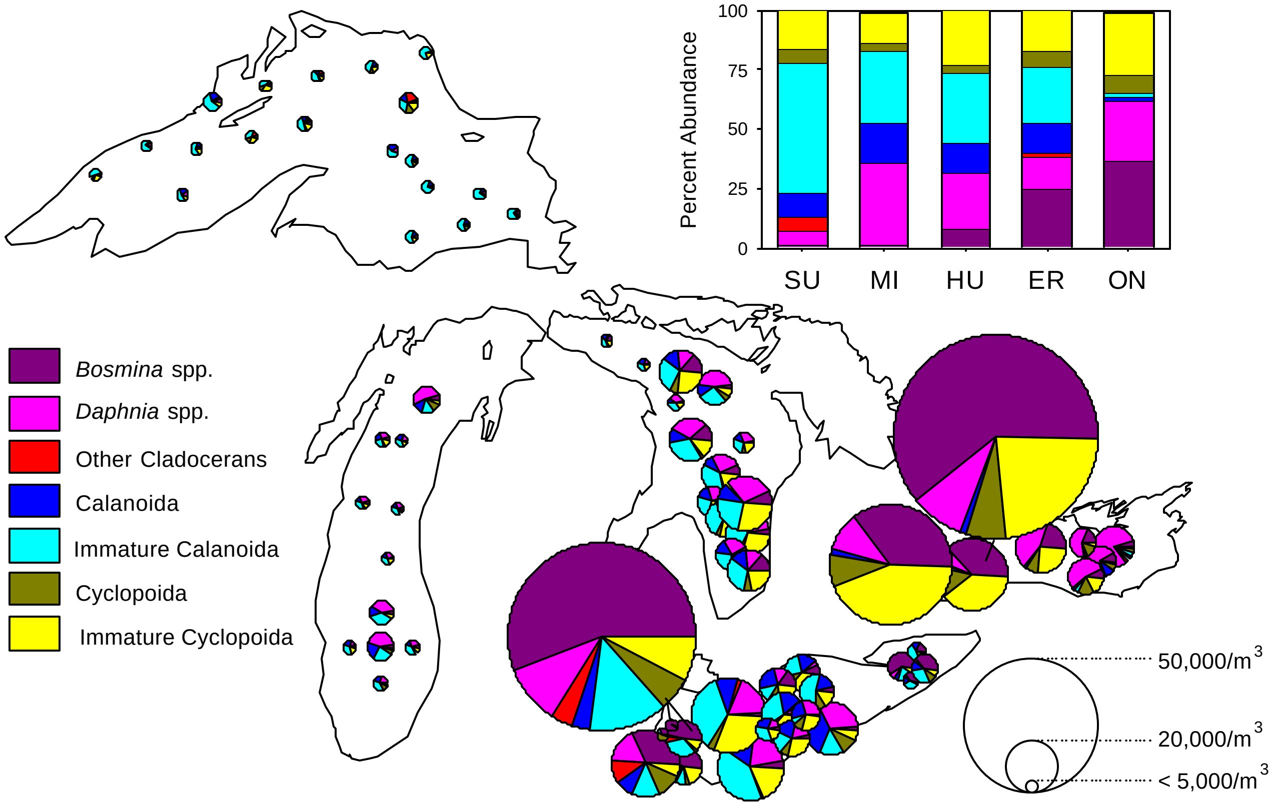
As in spring, copepods, and in particular immature copepods, contributed significant numbers to all sites. On a lake-wide basis, diaptomid copepodites were among the dominant individuals in all lakes but Ontario, accounting for 21-55% of total individuals. Cyclopoid copepodites also contributed a substantial number of individuals to all lakes, contributing 12-26% of individuals on a whole-lake basis. Cladocerans, largely from the genera *Daphnia*, *Bosmina* and *Eubosmina*, contributed a larger share of individuals during the summer in all lakes except for Superior (Table 4). As in spring, a high degree of spatial heterogeneity was found in Lake Erie; dramatic differences in species composition were also found between different sites in Lake Ontario. *Bosmina longirostris*, present in all five lakes, achieved very large populations in the western and eastern basins of Lake Erie and the western basin of Lake Ontario. Its numbers were greatly reduced in the eastern basin of Lake Ontario, apparently being replaced by *Daphnia retrocurva*, an organism otherwise found in substantial numbers only in western Lake Erie.

Three major predatory cladocerans were found in the lakes: the native *Leptodora kindtii*, a recent invader *Bythotrephes cederstroemi*, and *Cercopagis pengoi*, which appeared in the lakes for the first time in 1998 (Figure 16). Of the three, *Bythotrephes* was the most widely distributed, being recorded from 42 of the 72 sites sampled. It was present in all lakes with the exception of Lake Ontario, and attained its highest populations in the central basin of Lake Erie. The distribution of *Leptodora* was much more restricted, although it achieved a maximum abundance more than double that of *Bythotrephes*. Interestingly, its distribution showed little overlap with that of *Bythotrephes*, with substantial numbers of individuals found in the western basin of Lake Erie and Lake Ontario, areas where *Bythotrephes* was rare or absent. *Cercopagis pengoi* was first noted in Lake Ontario in late July of 1998, and by August appeared to be restricted to four sites in the eastern basin of the lake. The maximum abundance of *Cercopagis* was somewhat higher than that of *Bythotrephes* (465 individuals $m^{-3}$ compared to 317 individuals $m^{-3}$, respectively, as estimated from 20 m tows).

Individuals of *Bythotrephes* were not noted at sites where *Cercopagis* occurred; in contrast, sizable populations of *Leptodora* were found at sites containing

*Cercopagis*. Perhaps most interesting was the distinct decrease in *Bosmina* populations at sites containing *Cercopagis*, which, as noted above, appeared to be replaced by the larger-bodied *D. retrocurva*. This could have been the result of direct predation of *Cercopagis* on *Bosmina*.

Figure 15. Abundances of major crustacean groups in the Great Lakes, summer 1998. Inset shows whole lake averages.



Nauplii made up a much smaller percentage of total biomass in summer compared to spring, with the upper lakes averaging 4-7% and Lakes Erie and Ontario 15 and 23%, respectively (Figure 17). In the latter lake, biomass of nauplii at western sites was notably higher than at stations on the eastern side of the lake, again showing a negative relationship with the predator *Cercopagis*. Rotifer biomass, on the other hand, was substantially greater in the summer than in the spring and, as with nauplii, made up a greater percentage of total biomass in the lower lakes (10-21%), compared to the upper lakes (5-8%). Rotifer species richness during the summer was similar to spring values for the lower lakes, but most sites in the upper lakes exhibited an increase in numbers of rotifer species (Figure 14b). Rotifer community dominance by and large shifted away from *Notholca, Synchaeta* and *Kellicottia* to *Polyarthra*, *Ascomorpha*, and *Conochilus* (Figure 18). Substantial populations of *Synchaeta* still existed in Lake Superior in summer, and *Keratella*, which was moderately abundant in all lakes except Erie in the

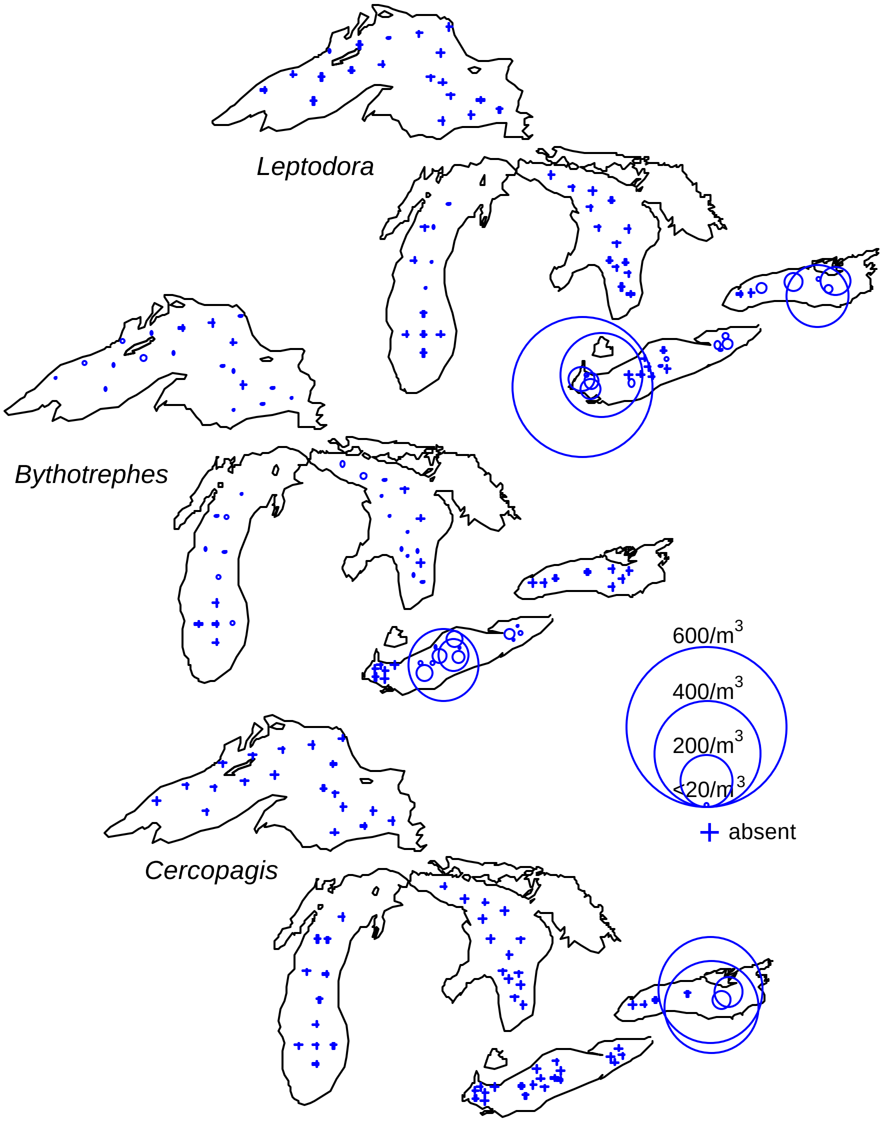


Figure 16. Abundances of predatory cladocerans in the Great Lakes, summer, 1998, as estimated from 20 m tows

abundant in all lakes except Erie in the spring, comprised a similar or somewhat higher percentage of rotifer communities in the summer.

The increase in species richness in summer resulted in stronger lake to lake, and in some cases within lake, differences in the distribution of rotifer species compared to spring. The upper lakes all supported distinct rotifer communities, while notable differences in community composition were seen between the western basin and the central and eastern basins of Lake Erie, as well as between the eastern and western basins of Lake Ontario.

Figure 17. Total zooplankton biomass by major group in the Great Lakes, summer, 1998. Inset represents whole lake averages.

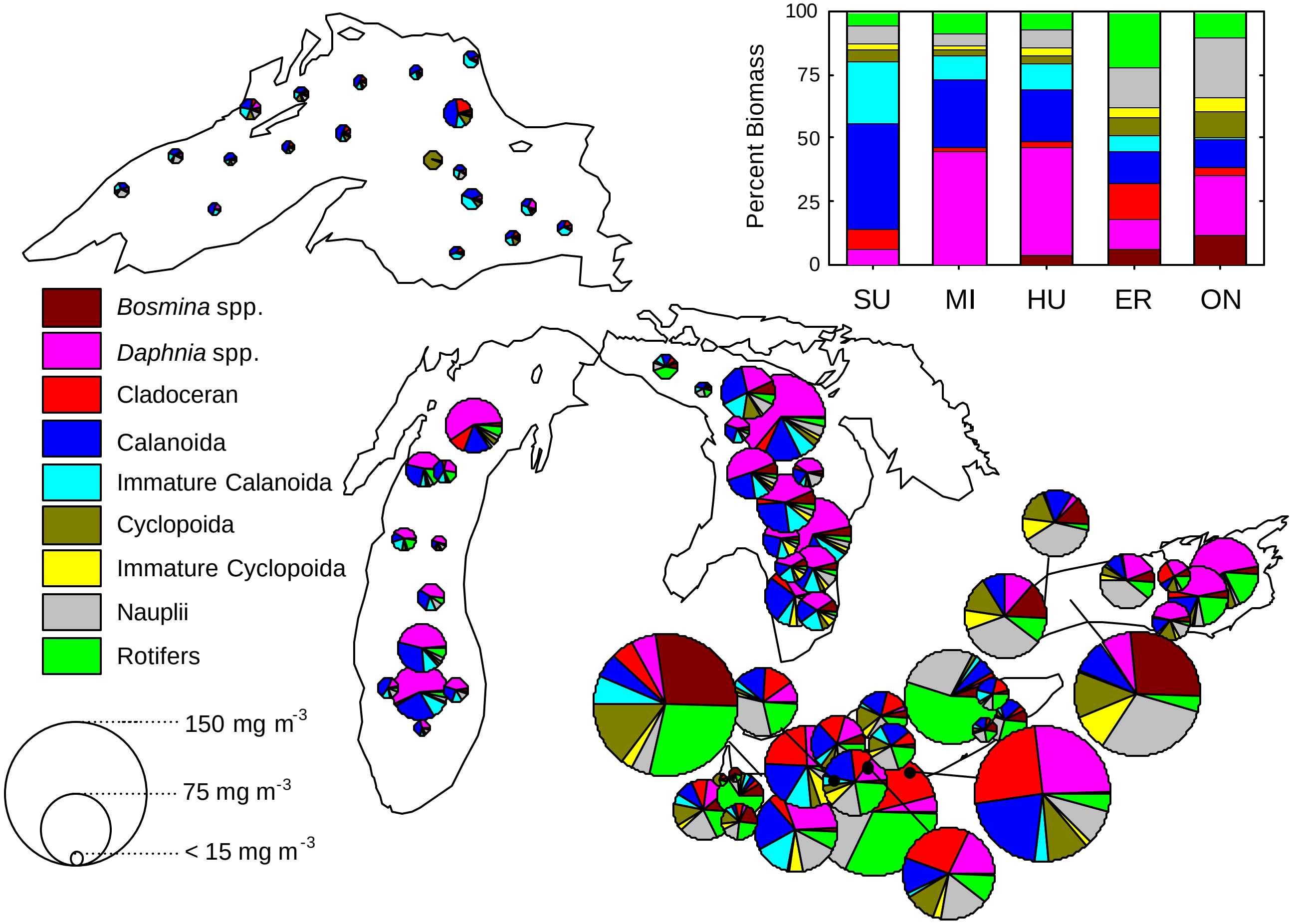
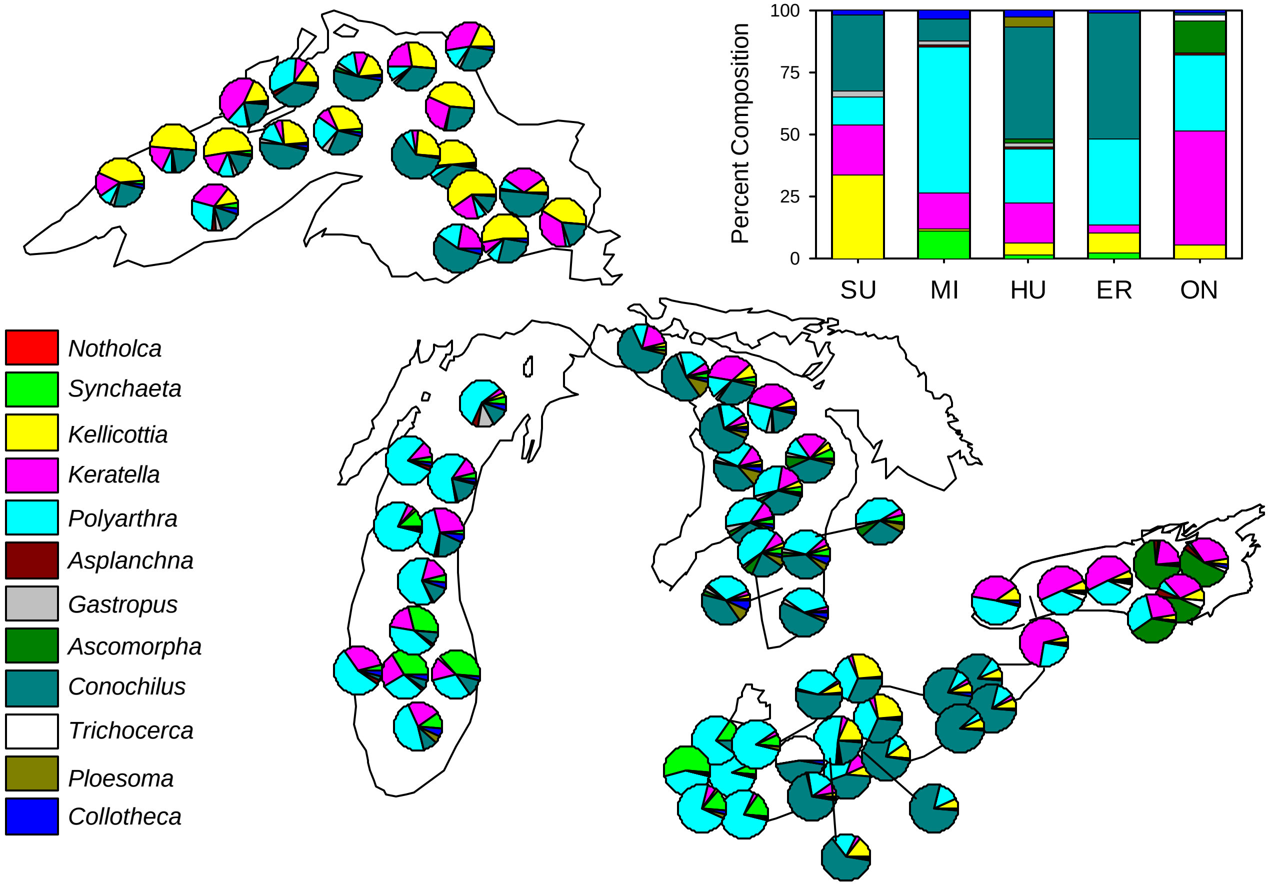
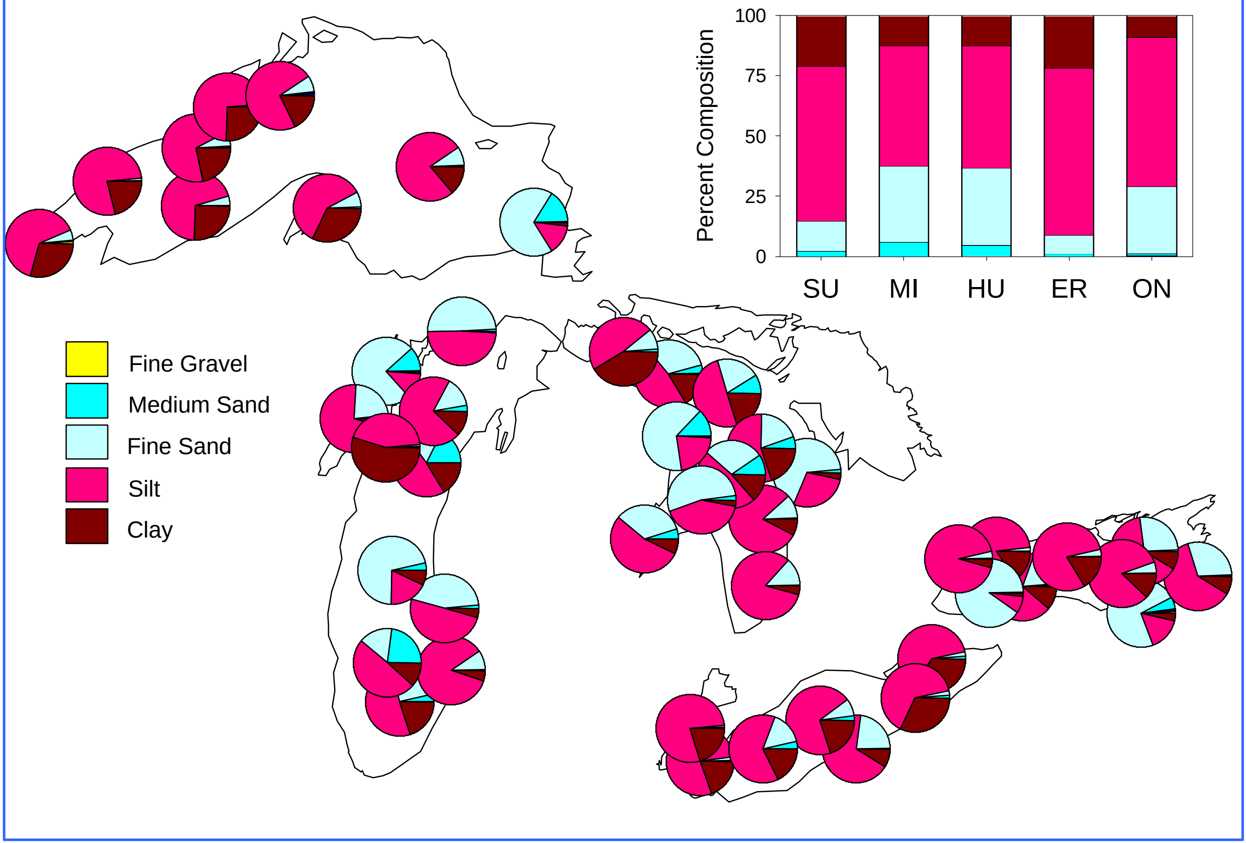


Figure 18. Relative abundance of rotifer genera, summer cruise, 1998. Inset shows whole-lake averages.



## Benthos

Figure 19. Sediment composition at benthic sites in the Great Lakes, summer 1998. Inset shows whole lake averages.



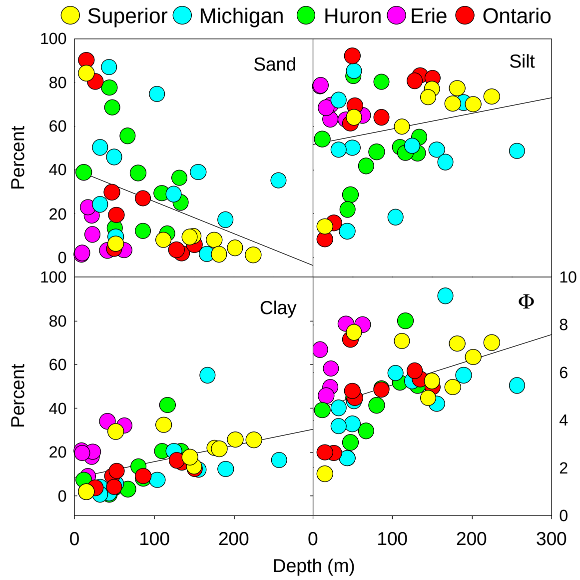
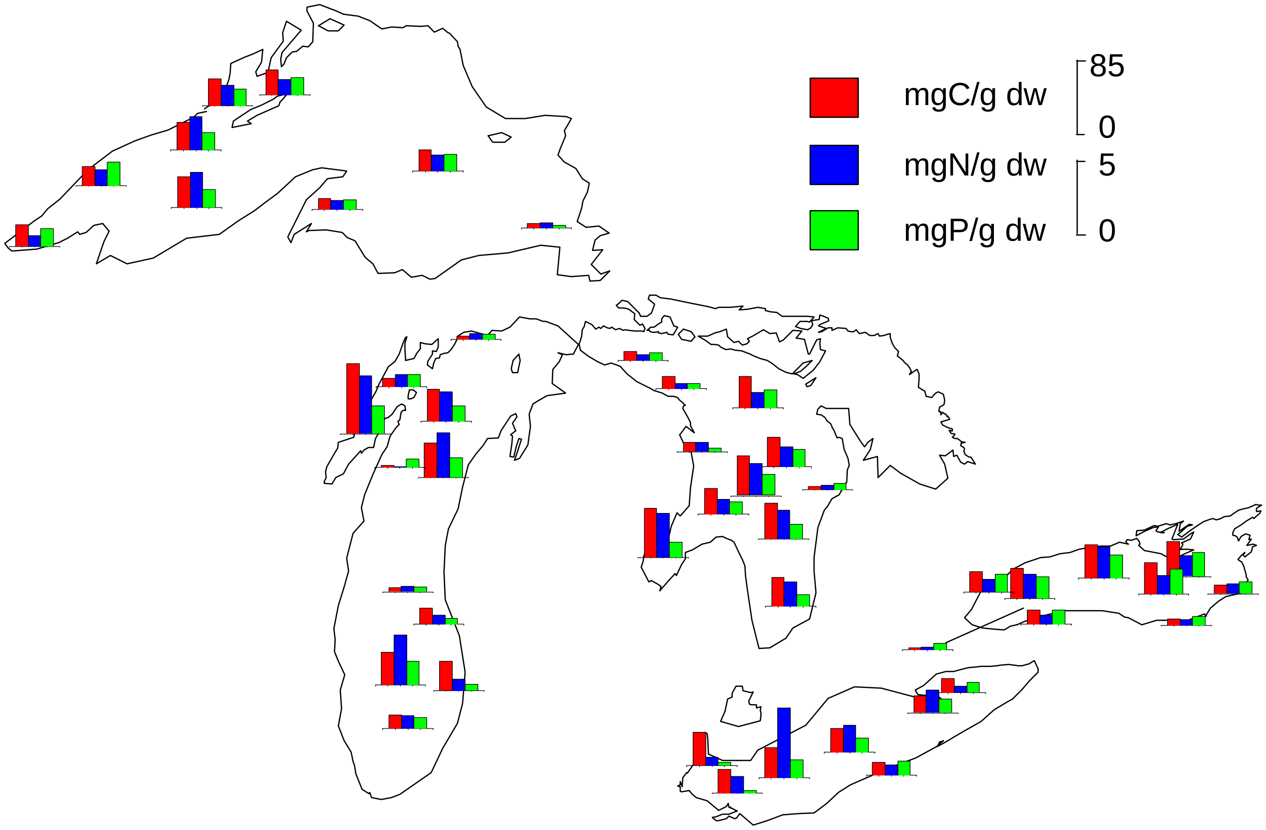


Figure 20. Relationship between depth and substrate characteristics. Lines indicate least squares regressions.

Benthos sampling depths ranged from 12 m to 257 m, averaging just over 100 m, and substrates were characterized by varying proportions of silt, clay and fine sand (Figure 19). Sites in Lakes Erie and Superior tended to have a slightly lower percentage of fine sand; otherwise substantial differences did not exist from lake to lake. There was a tendency towards finer substrates with increasing depth, with silt, clay and Φ (the inverse log of sediment grain size) all tending to increase with depth, while sand tended to decrease (Figure 20).

Sediment nutrient concentrations varied between 2.1-83.0 ($\bar{x}$ = 26.2) mg C gm DW$^{-1}$ for carbon; 0.05-4.9 ($\bar{x}$ = 1.3) mg N gm DW$^{-1}$ for nitrogen and 0.2-1.9 ($\bar{x}$ = 1.0) mg P gm DW$^{-1}$ for phosphorus, and were generally comparable to those found in 1997. High

Figure 21. Sediment concentration of carbon, nitrogen and phosphorus at benthos sites in the Great Lakes, summer 1998.



values occurred at Green Bay, Lake Michigan and Saginaw Bay, Lake Huron (Figure 21). In general, though, large lake to lake differences were not found in these parameters. Sediment nutrient content, most notably phosphorus, and percent water exhibited a tendency to increase with depth (Figure 22).

Most sites supported a very limited number of taxa, with maximum numbers of taxa per site ranging from 4 - 19 for the five lakes, and minimum numbers of taxa per site between 2 and 6 (Figure 23). There was a clear trend of greater species richness associated with higher trophic state; numbers of taxa increased along the sequence Superior->Huron/Michigan->Ontario->Erie. Lake Erie supported the greatest number of taxa overall (35), while benthic invertebrate communities in Lake

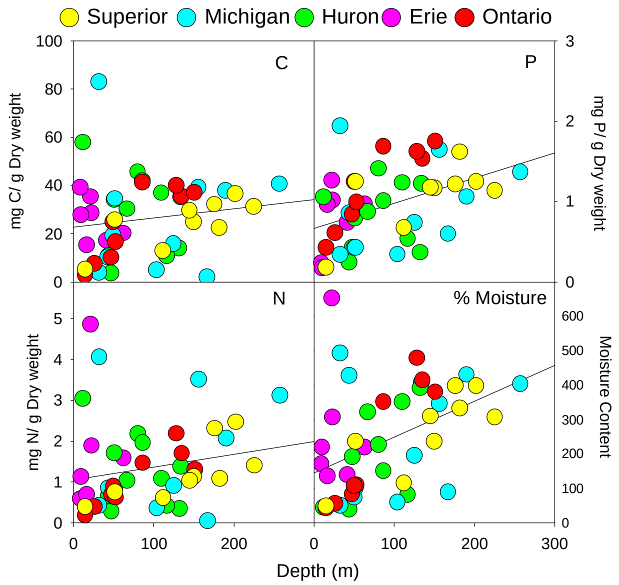
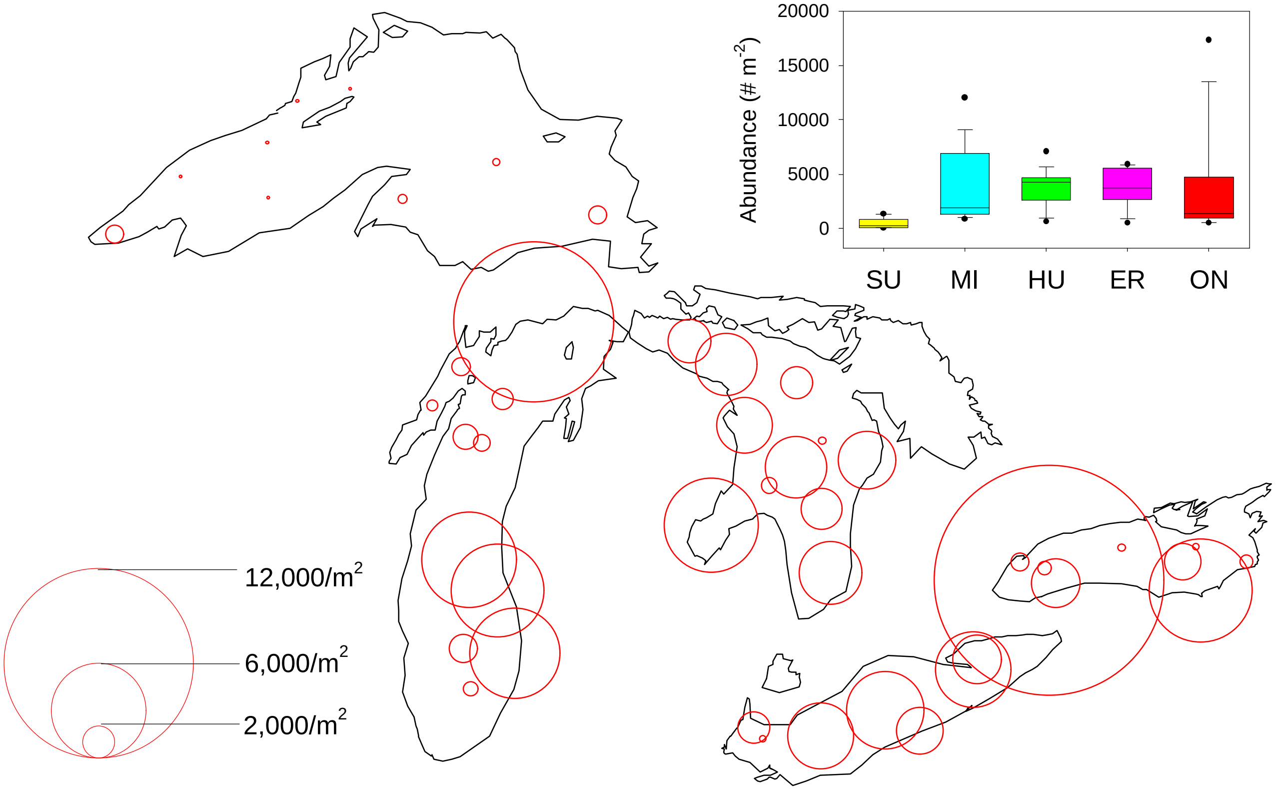


Figure 22. Relationship between depth and sediment chemistry. Lines indicate least squares regressions.

Figure 24. Areal abundances of benthic invertebrates in the Great Lakes, summer 1998. Inset shows box plots of benthic invertebrate abundances for each lake.



Superior were extremely taxa poor, with a total of only 6 taxa found in the lake.

Areal abundances of benthic organisms varied greatly within each lake, and to a lesser extent from lake to lake (Figure 24). Abundances varied from site to site within each lake by at least an order of magnitude, two orders of magnitude in the case of Lake Superior. Particularly high abundances were found at sites in northern Michigan and western Ontario. Lake-wide median abundances were somewhat more similar, varying from 1,400 to 3,700 organisms m$^{-2}$ for all lakes except Lake Superior, where the median abundance was only 424 organisms m$^{-2}$.

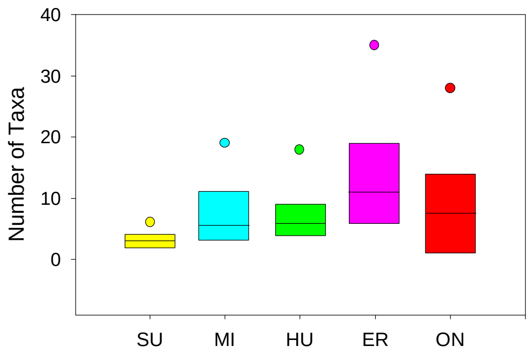


Figure 23. Minimum, maximum and mean number of benthic taxa per site, and total number of taxa per lake, summer 1998.

Figure 25. Relative abundances of major benthic groups
in the Great Lakes, summer 1998. Inset shows whole lake averages.

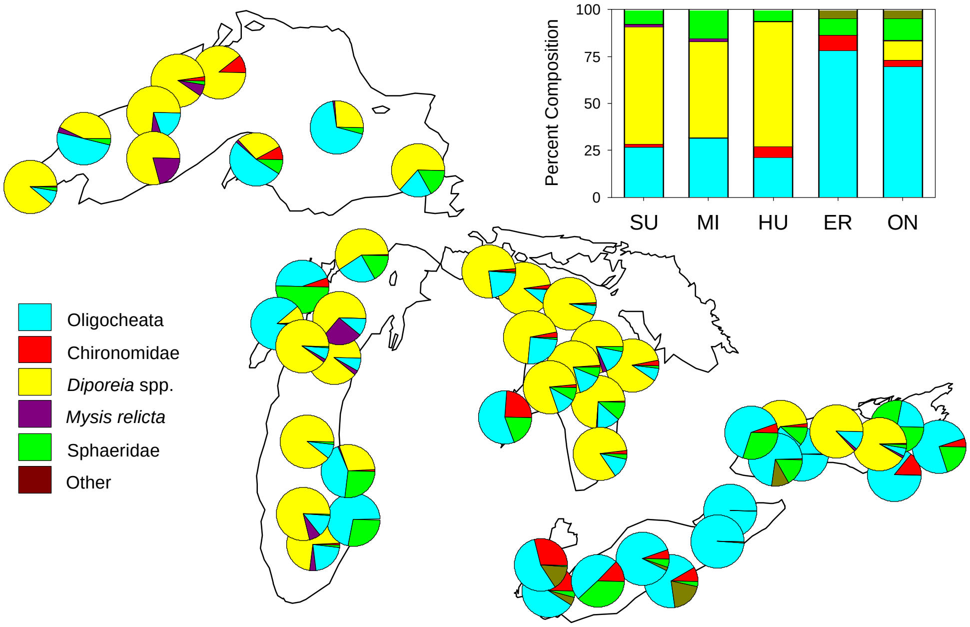
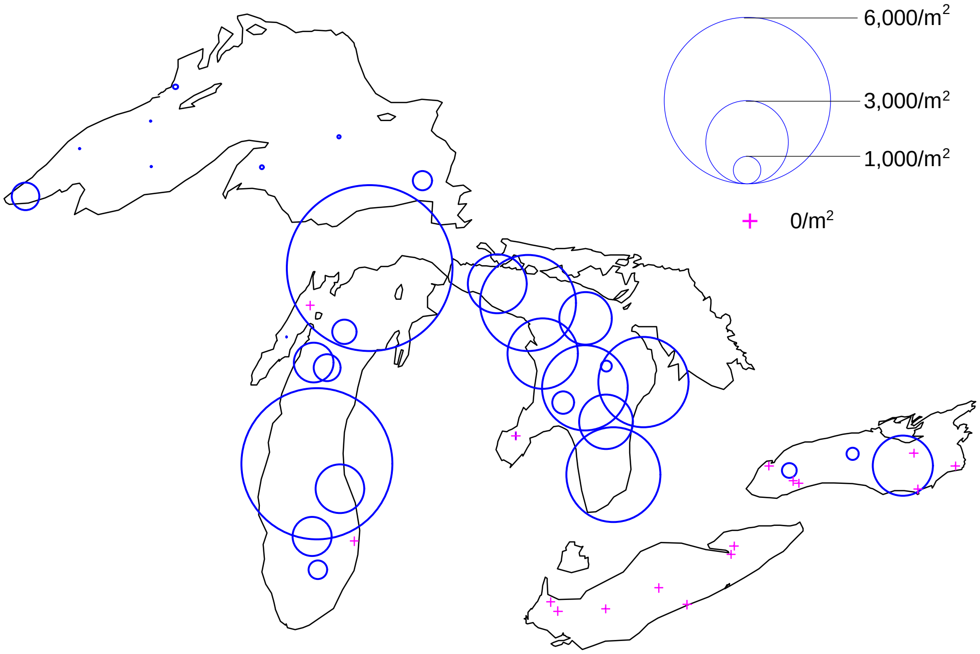


Figure 26. Abundance of *Diporeia* spp. in the Great Lakes, summer 1998



The amphipod *Diporeia* was by far the dominant benthic invertebrate in the upper three lakes, although it was absent from Lake Erie, nearshore sites in Lake Ontario, and Saginaw Bay in Lake Huron (Figures 25, 26). Oligochaetes were the second most dominant group, and made up a majority of individuals at those sites where *Diporeia* did not. They were the most diverse group, with a total of 26 different species identified in 1998. Members of the oligochaete family Tubificidae made up at least 50% of the oligochaete communities in all lakes except Lake Superior, where members of the family Lumbriculidae were the most common (Figure 27). The proportion of lumbriculids increased along the sequence Erie->Ontario->Huron/Michigan->Superior, which is in keeping with their preference for lower productivity environments. Tubificids, on the other hand, were more common in the lower lakes and at shallower sites in Lakes Michigan and Huron. Over a dozen genera of Chironomidae were also found in the lakes (Figure 28). The oligotrophic genus *Heterotrissocladius* was the only chironomid found in Lake Superior, and also dominated the off-shore sites of Lakes Michigan and Huron. Communities in the lower lakes were more diverse, supporting notable populations of *Chironomus*, *Procladius* and *Micropsectra*, among other genera.

Figure 27. Relative abundances of oligochaete taxa in the Great Lakes, summer 1998. Inset shows whole lake averages.

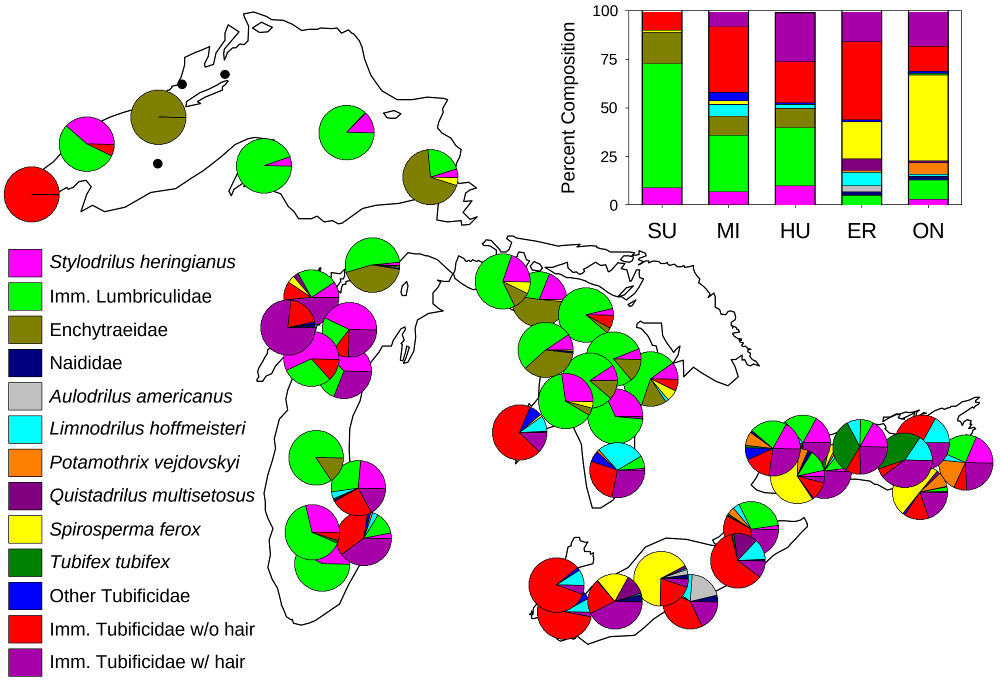
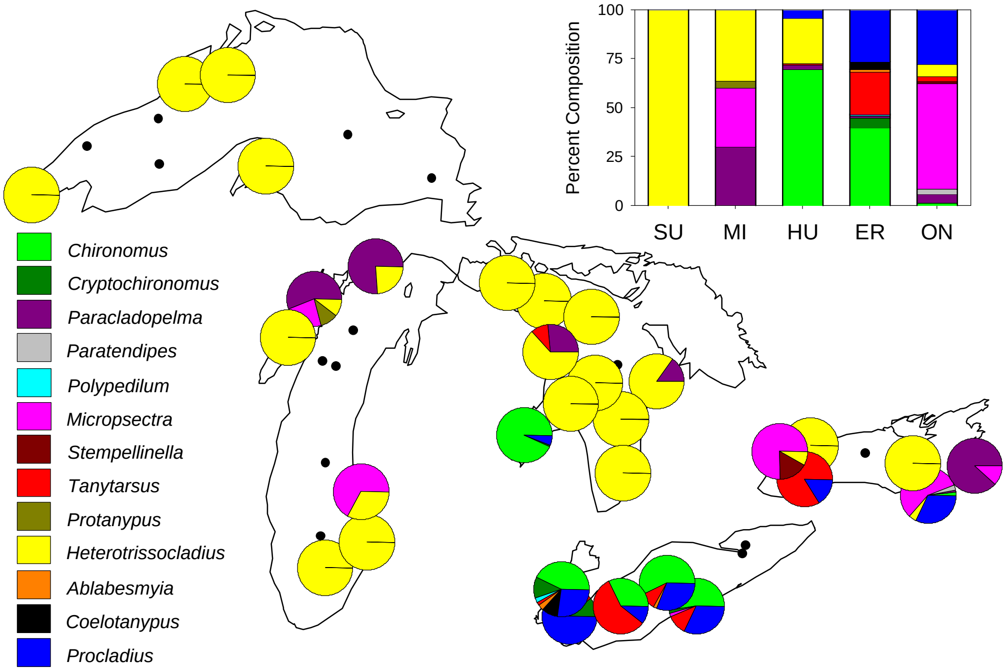


Figure 28. Relative abundances of chironomid genera in the Great Lakes, summer 1998. Inset shows whole lake averages.



# SUMMARY

Phytoplankton communities in the Great Lakes were highly diverse, with much of that diversity contributed by diatoms, which dominated the plankton of all lakes in the spring, with the exception of Lake Superior . Summer communities shifted away from diatoms, towards chrysophytes in the upper lakes and chlorophytes in the lower lakes. Zooplankton communities were considerably less diverse, and were composed in most cases of less than a dozen species. Crustacean communities in all lakes except Lake Ontario were dominated by diaptomid copepods in spring. During summer, both abundance and species richness increased, the latter owing largely to the appearance of populations of cladocerans. In the upper lakes, summer communities were dominated by diaptomid copepods, cyclopoid copepodites, and *Daphnia galeata mendotae* (co-dominant with *Holopedium gibberum* in Lake Superior), and showed a high degree of spatial homogeneity. Communities in Lake Erie exhibited both greater species richness and spatial heterogeneity. Lake Ontario was unusual in its relative lack of calanoid copepods, being dominated instead by cyclopoid copepods, along with *Bosmina* and *Daphnia*. A new predatory cladoceran in Lake Ontario, *Cercopagis pengoi*, appeared to have already had an impact on zooplankton community structure. Rotifer communities were a minor component of zooplankton biomass in the spring, but increased in importance in the summer. The benthos was notably species-poor in the Great Lakes. Profundal communities were very similar in all lakes except Lake Erie, and were dominated by an association consisting of the amphipod *Diporeia*, the oligochaete *Stylodrilus heringianus*, and the chironomid *Heterotrissocladius*, along with unidentified members of the Sphaeriidae. Communities in shallower regions varied greatly from site to site, but were usually characterized by lesser abundances or the absence of *Diporeia* and the dominance of oligochaetes.

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Table 1. Ten most dominant phytoplankton species, by biovolume, in spring 1998. Numbers indicate lake-wide average biovolumes ($\mu m^3$/ml) .

### Lake Superior

| Species | $\mu m^3$/ml |
|---|---|
| *Rhodomonas minuta* | 9,327 |
| *Aulacoseira islandica* | 8,669 |
| *Cyclotella comta* | 4,739 |
| *Cryptomonas erosa* | 4,661 |
| Haptophyceae | 4,537 |
| *Gymnodinium* sp. | 3,977 |
| *Anacystis montana* f. *minor* | 3,750 |
| *Oscillatoria minima* | 3,709 |
| *Stephanodiscus subtransylvanicus* | 3,007 |
| *Stephanodiscus niagarae* | 2,488 |

### Lake Michigan

| Species | $\mu m^3$/ml |
|---|---|
| *Aulacoseira islandica* | 86,441 |
| *Aulacoseira subarctica* | 73,867 |
| *Stephanodiscus subtransylvanicus* | 59,003 |
| *Stephanodiscus alpinus* | 17,273 |
| *Cryptomonas erosa* | 9,056 |
| *Cryptomonas ovata* | 5,854 |
| *Rhodomonas lens* | 5,403 |
| *Rhodomonas minuta* | 3,564 |
| *Gymnodinium helveticum* f. *achroum* | 3,527 |
| *Gymnodinium* sp. | 3,343 |

### Lake Huron

| Species | $\mu m^3$/ml |
|---|---|
| *Aulacoseira islandica* | 149,213 |
| *Oscillatoria tenuis* | 35,682 |
| *Aulacoseira subarctica* | 34,486 |
| *Tabellaria flocculosa* | 28,456 |
| *Rhodomonas minuta* | 16,133 |
| *Rhodomonas lens* | 8,027 |
| *Tabellaria fenestrata* | 7,797 |
| Haptophyceae | 7,448 |
| *Stephanodiscus subtransylvanicus* | 5,775 |
| *Cryptomonas pyrenoidifera* | 4,902 |

### Lake Erie

| Species | $\mu m^3$/ml |
|---|---|
| *Aulacoseira islandica* | 786,555 |
| *Stephanodiscus hantzschii* f. *tenuis* | 70,265 |
| *Stephanodiscus niagarae* | 56,404 |
| *Rhodomonas minuta* | 40,481 |
| *Stephanodiscus binderanus* | 32,028 |
| *Stephanodiscus alpinus* | 22,608 |
| *Stephanodiscus parvus* | 17,672 |
| *R. minuta* v. *nannoplanctica* | 14,304 |
| *Anacystis montana* f. *minor* | 10,718 |
| Unidentified flagellate #5 | 9,779 |

### Lake Ontario

| Species | $\mu m^3$/ml |
|---|---|
| *Aulacoseira islandica* | 242,768 |
| *Stephanodiscus niagarae* | 90,528 |
| *Stephanodiscus alpinus* | 64,429 |
| *Rhodomonas minuta* | 43,431 |
| *Thalassiosira baltica* | 41,246 |
| *Gymnodinium helveticum* f. *achroum* | 38,579 |
| *Cryptomonas erosa* | 19,535 |
| *Gymnodinium* sp. | 12,517 |
| *Cryptomonas ovata* | 11,597 |
| *Nitzschia lauenburgiana* | 9,062 |

Table 2. Ten most dominant phytoplankton species, by biovolume, in summer 1998. Numbers indicate lake-wide average biovolumes (µm³/ml)

### Lake Superior

| Species | µm³/ml |
|---|---|
| *Cyclotella comta* | 21,871 |
| *Dinobryon bavaricum* | 16,025 |
| *Cyclotella delicatula* | 8,637 |
| *Rhodomonas minuta* | 8,630 |
| *Dinobryon divergens* | 7,189 |
| *Dinobryon bavaricum* var. *vanhoeffenii* | 6,169 |
| *Cryptomonas erosa* | 4,748 |
| *Cryptomonas erosa* var. *reflexa* | 3,906 |
| *Fragilaria crotonensis* | 3,898 |
| *Dinobryon sociale* | 3,657 |

### Lake Michigan

| Species | µm³/ml |
|---|---|
| *Cryptomonas erosa* | 23,515 |
| *Chrysosphaerella* sp. | 13,085 |
| *Aphanocapsa delicatissima* | 13,067 |
| *Planktonema lauterborni* | 12,933 |
| *Fragilaria crotonensis* | 11,932 |
| *Gymnodinium* sp. | 11,763 |
| *Peridinium* sp. | 11,010 |
| *Dinobryon divergens* | 8,724 |
| Haptophyceae | 7,129 |
| *Rhodomonas minuta* | 6,933 |

### Lake Huron

| Species | µm³/ml |
|---|---|
| *Chrysosphaerella longispina* | 70,186 |
| *Ceratium hirundinella* | 18,740 |
| *Cyclotella comensis* | 14,190 |
| *Peridinium* sp. | 13,405 |
| *Dinobryon bavaricum* | 12,081 |
| *Cryptomonas erosa* | 12,045 |
| *Rhodomonas minuta* | 8,316 |
| *Cyclotella comta* | 6,852 |
| *Cryptomonas erosa* var. *reflexa* | 6,501 |
| *Fragilaria crotonensis* | 6,408 |

### Lake Erie

| Species | µm³/ml |
|---|---|
| *Pediastrum simplex* | 87,160 |
| *Pediastrum* sp. | 63,732 |
| *Fragilaria crotonensis* | 61,089 |
| *Cyclotella ocellata* | 40,522 |
| *Microcystis* sp. | 39,437 |
| *Cyclotella comensis* | 30,850 |
| *Rhodomonas minuta* var. *nannoplanctica* | 29,602 |
| *Rhodomonas minuta* | 21,605 |
| *Ceratium hirundinella* | 20,337 |
| *Cryptomonas erosa* | 19,021 |

### Lake Ontario

| Species | µm³/ml |
|---|---|
| *Ceratium hirundinella* | 161,822 |
| *Peridinium* sp. | 66,610 |
| *Cryptomonas erosa* | 44,073 |
| *Staurastrum gracile* | 42,877 |
| *Rhodomonas minuta* | 39,086 |
| *Fragilaria crotonensis* | 36,247 |
| *Rhodomonas minuta* var. *nannoplanctica* | 32,213 |
| *Oocystis borgei* | 25,723 |
| *Dinobryon divergens* | 25,374 |
| *Tetraedron minimum* | 23,912 |

Table 3. Dominant crustacean zooplankton in the Great Lakes, spring, 1998. Numbers indicate lake-wide average abundances/m$^3$.

### Lake Superior

| Species | #/m$^3$ |
|---|---|
| *Leptodiaptomus sicilis* | 474 |
| *Diacyclops thomasi* | 258 |
| *Limnocalanus* copepodites | 202 |
| Cyclopoid copepodites | 46 |
| *Limnocalanus macrurus* | 21 |
| Diaptomid copepodites | 18 |
| *Senecella* copepodites | 3 |
| *Mysis relicta* | 1 |
| *Senecella calanoides* | 1 |

### Lake Michigan

| Species | #/m$^3$ |
|---|---|
| Diaptomid copepodites | 2,265 |
| *Leptodiaptomus ashlandi* | 1,698 |
| *Leptodiaptomus sicilis* | 444 |
| *Leptodiaptomus minutus* | 394 |
| *Diacyclops thomasi* | 145 |
| Cyclopoid copepodites | 81 |
| *Limnocalanus macrurus* | 30 |
| *Limnocalanus* copepodites | 9 |
| *Tropocyclops prasinus mexicanus* | 9 |
| *Mysis relicta* | 3 |

### Lake Huron

| Species | #/m$^3$ |
|---|---|
| Diaptomid copepodites | 2,425 |
| *Leptodiaptomus ashlandi* | 2,000 |
| *Leptodiaptomus sicilis* | 737 |
| *Leptodiaptomus minutus* | 694 |
| *Diacyclops thomasi* | 306 |
| Cyclopoid copepodites | 240 |
| *Limnocalanus* copepodites | 130 |
| *Limnocalanus macrurus* | 70 |
| *Epischura* copepodites | 12 |
| *Diaptomus oregonensis* | 4 |

### Lake Erie

| Species | #/m$^3$ |
|---|---|
| *Diacyclops thomasi* | 657 |
| Cyclopoid copepodites | 615 |
| *Leptodiaptomus ashlandi* | 333 |
| Diaptomid copepodites | 200 |
| *Leptodiaptomus minutus* | 134 |
| *Bosmina longirostris* | 133 |
| *Skistodiaptomus oregonensis* | 127 |
| *Leptodiaptomus sicilis* | 116 |
| *Limnocalanus* copepodites | 79 |
| *Daphnia galeata mendotae* | 49 |

### Lake Ontario

| Species | #/m$^3$ |
|---|---|
| *Diacyclops thomasi* | 2,098 |
| Cyclopoid copepodites | 1,230 |
| Diaptomid copepodites | 531 |
| *Limnocalanus* copepodites | 200 |
| *Leptodiaptomus sicilis* | 49 |
| *Skistodiaptomus oregonensis* | 23 |
| *Eubosmina coregoni* | 14 |
| *Tropocyclops prasinus mexicanus* | 11 |
| *Bosmina longirostris* | 9 |
| *Limnocalanus macrurus* | 8 |

Table 4. Dominant crustacean zooplankton in the Great Lakes, summer, 1998. Numbers indicate lake-wide average abundances/m$^3$.

### Lake Superior

| Species | #/m$^3$ |
|---|---|
| Diaptomid copepodites | 2,764 |
| Cyclopoid copepodites | 1,189 |
| *Holopedium gibberum* | 447 |
| *Diacyclops thomasi* | 385 |
| *Daphnia galeata mendotae* | 372 |
| *Limnocalanus macrurus* | 128 |
| *Leptodiaptomus sicilis* | 114 |
| *Bosmina longirostris* | 44 |
| *Bythotrephes cedarstroemi* | 6 |
| *Senecella calanoides* | 6 |

### Lake Michigan

| Species | #/m$^3$ |
|---|---|
| *Daphnia galeata mendotae* | 2,666 |
| Diaptomid copepodites | 2,230 |
| Cyclopoid copepodites | 1,192 |
| *Leptodiaptomus sicilis* | 449 |
| *Diacyclops thomasi* | 341 |
| *Leptodiaptomus ashlandi* | 307 |
| *Bosmina longirostris* | 179 |
| *Leptodiaptomus minutus* | 161 |
| *Epischura* copepodites | 133 |
| *Limnocalanus macrurus* | 64 |

### Lake Huron

| Species | #/m$^3$ |
|---|---|
| *Daphnia galeata mendotae* | 3,768 |
| Diaptomid copepodites | 3,590 |
| Cyclopoid copepodites | 2,637 |
| *Bosmina longirostris* | 671 |
| *Diacyclops thomasi* | 617 |
| *Diaptomus minutus* | 557 |
| *Leptodiaptomus ashlandi* | 551 |
| *Leptodiaptomus sicilis* | 326 |
| *Epischura* copepodites | 187 |
| *Eubosmina coregoni* | 130 |

### Lake Erie

| Species | #/m$^3$ |
|---|---|
| Diaptomid copepodites | 3,880 |
| Cyclopoid copepodites | 2,049 |
| *Eubosmina coregoni* | 1,766 |
| *Daphnia galeata mendotae* | 1,559 |
| *Diaptomus oregonensis* | 1,293 |
| *Bosmina longirostris* | 1,258 |
| *Mesocyclops* copepodites | 697 |
| *Epischura* copepodites | 693 |
| *Mesocyclops edax* | 642 |
| *Daphnia retrocurva* | 451 |

### Lake Ontario

| Species | #/m$^3$ |
|---|---|
| *Bosmina longirostris* | 22,392 |
| Cyclopoid copepodites | 21,895 |
| *Daphnia retrocurva* | 14,206 |
| *Diacyclops thomasi* | 6,113 |
| *Eubosmina coregoni* | 1,330 |
| Diaptomid copepodites | 187 |
| *Limnocalanus macrurus* | 171 |
| *Leptodiaptomus sicilis* | 111 |
| *Cercopagis pengoi* | 90 |
| *Skistodiaptomus oregonensis* | 80 |