Compilation and evaluation of historical data and samples to support assessment of phytoplankton and zooplankton populations in Great Lakes Areas of Concern

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ABSTRACT

Currie, W.J.S. Bowen, K.L., Niblock, H.A. and 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. Can. Tech. Rep. Fish. Aquat. Sci. 3150: v + 152p.

This report collects all available data from past literature and unpublished DFO surveys, in three sub-reports, on two Areas of Concern (AOC) designated *requires further assessment* for the Beneficial Use Impairment (BUI 13): “degradation of phytoplankton and zooplankton populations”. Toronto Region and Thunder Bay AOC are data-poor, with no active plankton sampling programs. A single 2013 Toronto survey coincided with a large upwelling, with plankton densities lower than expected within Toronto Harbour, matching results from past surveys. MOECC Index archived plankton samples were counted, but were insufficient to evaluate BUI 13 due to high variability and sparse sampling. A minimum six samples annually are required to determine species composition. Plankton data are documented for Thunder Bay and Superior, but no samples were available for impacted areas near the Kaministiquia River and inner Thunder Bay Harbour.

RÉSUMÉ

Currie, W.J.S. Bowen, K.L., Niblock, H.A. and Koops. M.A. 2015. La compilation et l’évaluation des données historiques et des échantillons à l’appui de l'évaluation des populations de phytoplancton et zooplancton dans les secteurs préoccupants des Grands Lacs. Can. Tech. Rep. Fish. Aquat. Sci. 3150: v + 152p.

Ce rapport compile toutes les données trouvées dans trois sous rapports, compris de la littérature précédemment publiée, aussi bien que des enquêtes de MPO non publiées, sur le sujet de deux secteurs préoccupants (SP) qui ont été désignés comme exigeant une évaluation plus approfondie d’utilisations bénéfiques altérées (UBA 13): "la dégradation des populations de phytoplancton et de zooplancton". Les SP de la région de Toronto et de Thunder Bay ont une pauvreté de données, n’ayant aucun programme d'échantillonnage actif. Une seule enquête de Toronto, en 2013, a coïncidé avec une grande remontée d’eau, durant laquelle les densités de plancton dans le port de Toronto ont été plus faibles que prévu. Ces résultats étaient semblables à ceux d'enquêtes passées. Les échantillons de plancton archivés par l'indice de MEACC ont été comptés. À cause de la haute variabilité et l'échantillonnage peu fréquent, il n'y avait pas un nombre suffisant d'échantillons pour évaluer UBA 13. Un nombre minimum de six échantillons, annuellement, est exigé pour déterminer la composition en espèces. Les données de plancton sont documentées pour Thunder Bay et pour le lac Supérieur, mais aucun échantillon n'était disponible pour les zones affectées situés près de la rivière Kaministiquia et le port intérieur de Thunder Bay.

PHYTOPLANKTON AND ZOOPLANKTON POPULATIONS: AN INTRODUCTION

Surveys of plankton populations have always been fraught with difficulties due to the inherent patchiness of plankton in space along with rapid growth rates and ecological dynamics (e.g. predation) in time (Folt and Burns 1999, Lovejoy et al. 2001, Mackas et al. 1985). This is a major difference for plankton communities compared to benthos or fish, where organisms are generally longer-lived and have slower reproductive rates. Wide deviations from randomness make analysis of plankton data difficult and amplify uncertainties. This underlying variability has, to some degree, created challenges in many Great Lakes Areas of Concerns (AOC) in managing the "requires further assessment" (RFA) status of the Beneficial Use Impairment (BUI #13) Degradation of phytoplankton and zooplankton populations. These RFA sites need to be categorized as impaired or unimpaired. The current delisting guidelines for this BUI states:

> "When phytoplankton and zooplankton community structure does not significantly diverge from unimpacted control sites of comparable physical and chemical characteristics. Further, in the absence of community structure data, this use will be considered restored when phytoplankton and zooplankton bioassays confirm no significant toxicity in ambient waters" (IJC, 1991).

Unimpacted control sites rarely exist for AOCs since embayments are generally densely settled and most have similar urban impacts. As a result, an approach that compares the AOC to a nearby coastal site is often chosen. However, these sites generally have very different hydrological conditions so this approach often is of little utility because the ecological communities and the scales of patchiness are different. This is an example of using spatial data inside and outside the AOC for comparative purposes, which generally requires large numbers of samples to distinguish them. Another approach is to look at changes over time (temporal argument) but many AOCs have even less plankton sampling data over time.

While most AOCs lack extensive plankton surveys done over time (the exception is the Bay of Quinte), most of them have had periodic surveys that take place due to sampling for other programs, so some information on community structure is generally available. However, many of these datasets are unpublished, difficult to track down, and in some cases, require analysis of archived physical samples of plankton. Taxonomic identification of "lower trophic level" plankton, particularly for phytoplankton, is limited to a relatively small community of individuals, and the capacity to evaluate the data is in equally short supply. The Great Lakes Laboratory for Fisheries and Aquatic Sciences (GLLFAS) of Fisheries and Oceans Canada (DFO) has a long history of expertise in the study of lower food-web dynamics, so has been asked to tackle this BUI for many locations. This report documents a comprehensive review of the available data from previous surveys of plankton populations within two historically under-sampled Great Lakes AOCs: Toronto Region, Lake Ontario and Thunder Bay, Lake Superior. These findings will be useful to support future analyses to evaluate the status of BUI #13 for these sites.

The first section of this report documents a spatial survey, commissioned by Environment Canada, of the Toronto Region AOC using DFO's towed instrument technology (Section 1, "A Planktonic Survey of the Toronto Region AOC"). This section centers on a single survey of the entire coastal extent of the Toronto Region AOC from Etobicoke Creek to the Rouge River that took place over a single week in September 2013 (Sept. 9,11,13), which coincided with a major coastal upwelling in the Toronto area. Since this study was an opportunity to sample the entire planktonic ecosystem for the Coordinated Science Monitoring Initiative (CSMI) Lake Ontario year, zooplankton, phytoplankton, microbial plankton and primary production measures were also taken, which are included in this section to support future analysis. Past findings from the

literature on plankton surveys and a summary of unpublished data in the Toronto region are also compiled here.

The second section documents an evaluation of the use of archived plankton samples from the Ontario Ministry of the Environment (now OMOECC) Nearshore Index sampling program to assess the status of BUI #13 for Toronto AOC (Section 2: “Report on the Viability of Using MOE Index Plankton Samples to Evaluate BUI 13 for Toronto Harbour AOC”). The Index program samples nearshore sites, including several AOCs, 3 times per year, every 3 years in the lower lakes, and every 6 years in the upper lakes, beginning in 1994. Even if the Index samples, in and of themselves, are insufficient for an evaluation of plankton populations at a single AOC, they can provide a piece of evidence, which can be used in combination with other data collected from the site. Based on a comparison to the more intensive sampling in Hamilton Harbour by DFO, sampling frequency recommendations are made for future plankton sampling programs to adequately capture community composition.

Compared to the lower lakes, there is meagre published information on phytoplankton and zooplankton populations in Lake Superior. The third section presents and summarizes the plankton data that is available to date for the Thunder Bay area (Section 3: “A Report on Plankton Surveys Relating to the Thunder Bay AOC BUI 13”). All data that could be found for other, relatively more numerous, coastal, offshore and embayment areas in Lake Superior are made available for comparative purposes. This includes available published literature, Canadian government databases and compiled data from several unpublished studies conducted by federal and provincial agencies in Canada and the United States, including some previously uncounted archived zooplankton samples which we taxonomically enumerated. Though no data were found for locations within the directly impacted area of Thunder Bay Harbour, data contained in this report could be used to evaluate the status of BUI 13 following future surveys of this AOC.

SECTION 1: A SPATIAL SURVEY OF TORONTO REGION AOC

Executive Summary

This report documents the results of a plankton survey of the Toronto Region Area of Concern (AOC) by Fisheries and Oceans Canada (DFO) that took place on three days over a single week of September 9-13, 2013 in support of the evaluation of the *degradation of phytoplankton and zooplankton communities* Biological Use Impairment (BUI #13). The survey encompassed the entire spatial extent of the AOC from Etobicoke Creek to Rouge River with more spatial detail in and around Toronto Harbour. Though the primary intent of this study was to generate spatial information on the plankton distributions around Toronto Harbour using a towed device, an effort was extended to sample the entire planktonic ecosystem. The principal investigation involved a survey using towed sensors, which included optical measures of chlorophyll-*a* (phytoplankton), turbidity (suspended solids) and physical water characteristics such as temperature, pH, conductivity and oxygen (Section 1: "A Planktonic Survey of the Toronto Region AOC Using the Towed *SHRIMP* Sensor Array"). The towed array included a Laser Optical Plankton Counter which counted and sized particles (zooplankton) down to ~80-100 µm in size. To obtain taxonomy and not just size from the LOPC, depth-stratified zooplankton net samples were collected at a number of stations inside and outside the harbour (Section 2, "Toronto Harbour Zooplankton Sampling"). Since this study coincided with the 2013 Coordinated Science Monitoring Initiative (CSMI) Lake Ontario year, phytoplankton, microbial plankton and primary production measures were also taken at matching stations which are included in this report (Section 3, "Water chemistry, physical conditions, phytoplankton and microbial loop").

During the first week of September 2013, the entire Toronto coastline experienced a strong, widespread upwelling of cold hypolimnetic water as shown by the survey results in the distribution of physical characteristics (temperature), chlorophyll, and zooplankton densities. In particular, the area in Ashbridges Bay and along the scarp, where the main Toronto sewage treatment outflow is located, was highly affected by the upwelling. Elevated values of SRP and DOC are likely sourced from the outfall. The low zooplankton densities here are certainly related to the upwelling, so this confounds an examination of the effect of the sewage treatment outfall on plankton community structure.

Sampling in 2013 and in recent years suggests that Humber Bay experiences deep mixing and weak stratification, likely due to its orientation to the northwest, which faces into the dominant prevailing wind direction. Upwelling forces combined with the internal seiche of the lake is likely to create very specific physical mixing conditions in Humber Bay that are unlikely to be found in any other location within Lake Ontario, so comparisons to other embayments is difficult. Since the dominant circulation within Toronto Harbour is from Humber Bay through the western gap any assessment of the pelagic ecosystem should include stations within Humber Bay.

During the previous limited sampling of the Toronto Harbour area, eutrophic conditions were routinely found, but during the upwelling low phytoplankton biomass was found at all area stations, though highest and with lowest diversity in the inner harbour. Primary production was low within Toronto Harbour, being only slightly elevated from stations outside, the one exception at the Don River mouth where primary production values were >3 times larger. Stations in and around Toronto had a dominance of more tolerant, flagellated forms of phytoplankton and green-algae were a significant portion at inner harbour stations. Bacterial production was elevated in nearshore stations in Humber Bay and at the Western Gap of Toronto Harbour. LO8 (Humber Bay), which was sampled seasonally for the CSMI, had the highest primary production and bacterial production values of the season in the Sept survey during the upwelling.

Zooplankton populations have not been well studied around Toronto Harbour, but the few studies available from the coastal region around Toronto suggest that there is both annual and seasonal variability that include some trends in community composition over time. The existing historical data and results from this study suggest that Humber Bay and the inner harbour of Toronto, unlike other embayments in Lake Ontario, have much lower zooplankton densities than the surrounding region.

Inner Toronto Harbour exhibited very different conditions than the surrounding habitat in physical water characteristics, with elevated values for temperature, turbidity, nutrients and chlorophyll. In spite of this situation, which should promote a more eutrophic state and ideal growth conditions, there were exceedingly low zooplankton counts in Toronto Harbour compared to the surrounding Lake Ontario coast and other embayments of Lake Ontario. In particular, there were very few large-sized zooplankton. Embayments within Lake Ontario typically have much higher zooplankton densities than found in coastal habitats. This is likely not related to the upwelling since the inner harbour shows higher temperatures than found outside of the upwelling in the lake, though cold hypolimnetic water from the lake did intrude on the western side of the harbour, and the few historical surveys support this pattern. Given the flushing rate of Toronto Harbour near 10 days, at in-situ temperatures, cladoceran zooplankton should be able to reproduce several generations before being flushed into the Outer Harbour, and should be able to retain their position against this flushing through vertical migration and active swimming. This is supported by the high relative percentage of rotifers within the total zooplankton density. This suggests a possibility that the inner harbour environment is not a suitable habitat for zooplankton population growth. A more detailed examination of fish communities should be undertaken to determine any interacting effect of predation on plankton populations. Further study should involve seasonal sampling of zooplankton to determine population structure over the spring-fall period and perhaps population growth studies and/or toxicity studies using incubations.

A single sampling event in 2013 is insufficient to understand the current status of phytoplankton or zooplankton dynamics, so it is recommended that at least one full sampling season (early spring to late fall) be undertaken to determine seasonality and the effects of other environmental factors such as upwelling on plankton viability and community composition.

Section 1.1:
A Planktonic Survey of the Toronto Region AOC Using the Towed SHRIMP Sensor Array.

W.J.S. Currie

Rationale

This section documents the results of a towed sensor survey of a planktonic ecosystem for the entire coastal extent of the Toronto Region AOC from Etobicoke Creek to Rouge River (Fig. 1.1) that took place over a single week in September 2013 (Sept. 9,11,13). The use of towed instruments has the advantage of allowing a large spatial area to be surveyed in a short period of time and determine the spatial variability of measures. The primary instrument of this survey was the Spatially Hi-Resolution Intensive Mapping of Plankton (*SHRIMP*) towed array. This form of optical particle counter has been used in freshwater and estuarine systems for some years (Blukacz et al. 2009, Currie and Roff 2006, Finlay et al. 2007, Sprules et al. 1998, Vanderploeg and Roman 2006, Yurista et al. 2012). The sensor package is comprised of a Hi-Res Laser Optical Plankton Counter (HRLOPC), Conductivity-Temperature-Depth (CTD) probe with chlorophyll and turbidity optical sensors, and a YSI EXO sonde that has sensors for temperature, conductivity, pH, dissolved oxygen, total algae (chlorophyll-a and phycocyanin fluorometers), CDOM and turbidity (Fig. 1.2). A SeaSciences Acrobat towbody is used to actively control the depth with a resulting tow weight of 40 kg. This instrument package is similar to the LOPC transects of the 20m isobath of Lake Ontario by Yurista et al. (2012) with the exception that our HRLOPC is capable of sizing much smaller particle sizes. The tow-path of the instrument can be seen in the dotted line in Fig. 1.1. This is a daytime epilimnetic tow at a constant depth of 2.5-3.5 m. The nearshore tow along the coast from Etobicoke to Pickering followed the 7-10 m isobath. Interpolation was done between the tow tracks using the *griddata* – nearest neighbour function and the resulting surface smoothed over three neighbouring points with *smooth2a* within MatLab ver.2014a. All graphing was done using MatLab. Dashed lines indicate areas offshore where the instrument undulates as a “tow-yo” from the surface to ~ 25-30m depth (or 2-3m above bottom). The stations listed in Fig. 1.1 indicate sites where vertical profiles were done from 1 m above bottom to surface using the same instrument which provides a measure of the planktonic structure in the water column. The LOPC will count and size particles between ~80 µm – 3 cm of equivalent spherical diameter (Herman et al. 2004) which encompasses the majority of macrozooplankton, though some very small zooplankton may not be counted effectively (e.g. small juvenile stages, rotifers and ciliates). Since the LOPC has limited ability to discriminate taxonomic information, limited number zooplankton net tows at fixed stations were used to confirm plankton community composition (see Section 1.2).

Results

Physical-Chemical Measures

The mid epilimnetic 3m tow interpolated maps for the entire transect (3 days combined) are shown in Figs 1.3-4. Winds were variable on these days being mild on the first day (E 5-10 knots), elevated on the second day (SW 10 knots), but was inside Toronto Harbour so conditions were quite calm until a thunderstorm ended sampling, and on the final day winds were much increased (N-NW 10 knots gusting 15-20 knots). The physical-chemical maps indicate a clear strong upwelling around Toronto Harbour as seen in the lower temperature (~8°C), conductivity (~30 μScm^{-1}) and elevated pH (~1 pH). Temperature is highest offshore (16°C) and in the inner harbour (17 °C). The upwelling was driven by persistent winds from the west from September 2-6, 2013 (Fig. 1.4). This drove surface water offshore and upwelled cold hypolimnetic water along the Toronto scarp which can be seen clearly in the sea-surface

temperature satellite image for September 11 (Fig. 1.5). The upwelling zone extended into the nearshore region of Humber Bay as seen in the temperature distribution on the magnified maps of Toronto west region (Fig. 1.6). The upwelled water also enters partially into the western gap of Toronto Harbour since the Harbour is much warmer to the east than the west. This intrusion is primarily though the hypolimnion as the hypolimnetic water in the Harbour is similar in temperature to that of nearshore Humber Bay. Since the circulation of Toronto Harbour is west-east, the epilimnetic temperature of Outer Harbour is still much warmer than that surrounding Toronto (~5°C) with some intrusion along the Leslie Spit. Though upwelling events are common around Toronto in late August and September, this is an intensive upwelling event which is likely to influence the distribution of zooplankton and phytoplankton.

The algal and turbidity signals are considerably reduced in the zone of upwelling (Fig 1.3, 1.6). The chlorophyll-a values are near 3 μgL^{-1} in the upwelling zone but are 7-8 μgL^{-1} offshore and highest (15 μgL^{-1}) within the Harbour around the Don River plume and along the eastern Harbourfront. The phycocyanin results (the dominant pigment of blue-green algae) mirror this to some extent but are generally low offshore and are high only around the Don River and eastern Harbourfront. The distribution of phytoplankton will be addressed in more detail in Section 1.3. Turbidity is elevated throughout Toronto Harbour extending into the Outer Harbour with additional small peaks near the Humber River plume. The sensor was calibrated for a wide-range of turbidity so even small values (<1 NTU) amount to a very different clarity value (see Section 1.3, Table 3.1). The Don River plume was visibly brown coloured during the survey but the area around the entire Harbourfront also was visibly murky which matches the patterns seen by the towed sensors. Turbidity was also considerably elevated to the east of Toronto, steadily increasing towards Pickering. This could be due to the Rouge River, but also might be due to suspended particulates associated with surface transport out from the upwelling, cells within the water column or calcium precipitates which occur during whiting events (such an event was observed lakewide in August 2013). The very large spike of specific conductivity (>100 μScm^{-1} than the surrounding lake water) along the eastern shore of the inner harbour occur immediately adjacent to the Lafarge wharf and is likely due to increased dissolved ions (calcium, magnesium, carbonate) associated with offloading and storage at this location.

Zooplankton Particle Counts

The corresponding mid-epilimnetic tow interpolation maps of particle distribution from the Laser Optical Plankton Counter (LOPC) are showing in Figs. 1.7-8. Most zooplankton are roughly elliptical in shape so sizes from the LOPC output are standardized to units of Equivalent Spherical Diameter based on the shading silhouette of the particle (Herman et al. 2004). Taxonomic groups of zooplankton cannot be cleanly separated simply on the basis of size, but harmonized size-categories have been used for Hamilton Harbour and the Lake Ontario Western Basin which are dominated by known groups (Table 1.1). These species are measured for size during taxonomy (see Section 1.2) but since these measurements are standardized for length-weight calculations, they must be transformed by empirically based-functions of body shape and transparency to calculate an ESD for comparison to LOPC data (see (Liebig and Vanderploeg 2008, Watkins et al. 2011)). There were no clear discontinuities in the normalized size-spectrum (Herman and Harvey 2006) suggestive of dominant species in the data which would be indicated by peaks in the log-ESD histogram (see inset Fig. 1.2) so the size categories in Table 1.1 are appropriate.

The broad-scale distribution (Fig. 1.7) shows total particle counts are highest in the Outer Harbour of Toronto, but looking at the sizes in more detail, are exclusively dominated by the smallest size categories of 75-150 µm and 151-300 µm. This is likely composed of dreissenid veligers, juvenile stages of crustacean zooplankton, rotifers and *Bosmina*. Total counts are

lowest in the zone of the upwelling directly east of Toronto Harbour (near zero). Humber Bay and to the east of Toronto Harbour also have localized patches of high counts within the 151-300 µm sizes (likely dominated by *Bosmina* or *Eubosmina* but see Section 1.2). Counts of sizes above 300 µm are almost entirely absent from within Toronto Harbour and Outer Harbour (a single particle is encountered for every 2-3 L sampled). The larger zooplankton size categories of 301-405 µm are elevated near the outlet of Etobicoke Creek to the west and in patches of high densities in the nearshore from Scarborough to near the Rouge River, though the region closest to the Rouge River had very low counts approaching the values in the upwelling. The largest sizes (406-600 µm and 600+ µm) are found occasionally in small patches but in a high density swath in the nearshore from Ashbridges Bay to the Scarborough Bluffs east of Toronto. This might be due to a concentrating effect of the upwelling driving surface water from around the Toronto Scarp to the east along the shoreline. The temperature of this coastal water was in the 12-13°C range, so cooler-water metalimnetic species such as *Limnocalanus* and *Diacyclops thomasi* might be closer to the surface than they would be normally.

In the higher resolution maps of the Toronto Harbour vicinity (Fig. 1.8), the peaks in total counts dominated by the smallest particles can be seen in localized patches in the Outer Harbour and along the eastern coast of the Harbour especially in the Don River plume. Generally sizes >300 µm are highest outside of the harbour in Humber Bay away from shore in the area less affected by the upwelling. An isolated patch of the 301-600 µm sizes can be seen in the upper Outer Harbour area but this region nearer the marina could not be fully surveyed due to the extremely high boat and parasailing activity in the area. A localized patch immediately to the western edge of the Don River plume along the “Sugar Beach” harbour-front (in the area of the L12 station) had reasonably high counts of almost all of the size ranges including the largest size category.

The vertical profiles done at the inner and outer harbour stations (Fig. 1.1) from Sept. 11, 2013 can be seen in Fig. 1.9. At the eastern harbour stations (e.g. L12, IH13) the temperature profile (in red) shows the epilimnetic water is warmer (and the mixed depth is deeper (~4m) than found at the far western stations (ST1, IH1). The central harbour stations are intermediate in temperature though they have very different mixed depths to each other: 5 m at MOE1364, the geographic center used by OMOECC and only 2.5m at TH1364 used by the City of Toronto which corresponds to the deep hole. The hypolimnetic temperatures of all of the stations are near 9°C except the shallow L12 station near the Don River. The outer harbour stations (TH1 and OH1) are more similar to the far west inner harbour stations for stratification (shallow mixed depth) and temperature. The chlorophyll-a profile (in bold dark-green) is generally related to the depth of stratification with the peak (if one occurs) at the density interface associated with the lower epilimnion and metalimnion (thermocline). Values of chlorophyll-a ranged from a low of around 2 at the western stations (ST1) to a high of around 9 near the Don River (L12) station. The total zooplankton density (in blue) and the individual size-categories indicate that the eastern stations and the central station (L12, IH13 and MOE1364) have the highest densities in the meta and hypolimnion. The western stations (ST1 and TH1364) have the highest zooplankton densities in the shallow epilimnion or no peak at all (IH1). The outer harbour stations (TH1, OH1) are again similar to the western harbour stations with shallow epilimnetic peaks in particle densities. The largest particle sizes >300 µm (in yellow, pink or black) are generally at or near zero but can be seen at a few stations (ST1, IH13, TH1364 and TH1) at the total zooplankton density peak depth, albeit in a more narrow depth band. It is worth noting that there was a considerable difference between the central stations (TH1364 and MOE1364) in terms of stratification, location of chlorophyll-a peak and distribution of particle sizes.

The vertical profiles done at the stations west of Toronto Harbour (3508, LO8) on Sept. 9, 2013 and to the east in Ashbridges Bay (AB2, AB1, 1325, AB3) and off Pickering (708, 1330) (see

Fig. 1.1) on Sept. 13, 2013 can be seen in Fig. 1.10. Both of the western stations are very shallow nearshore stations that show a fairly deep mixed depth of 3 - 4.5 m. The 3508 (Etobicoke) station had a cool epilimnion of 12°C and a hypolimnion of 8°C indicating an influence of the upwelling. This station had a very modest metalimnetic peak in chlorophyll-a but a strong peak in total zooplankton density dominated by small particle sizes. The Humber Bay (HB3/LO8) location is near the input of the Humber River but had a similar epilimnetic temperature to Etobicoke though little hypolimnion. Unlike many locations the chlorophyll-a max extended from the surface down to 4m and peak zooplankton particle counts were very close to the surface.

The Ashbridges stations (shallow to deep AB2, AB1, 1325, AB3) indicated that the two nearshore stations were highly influenced by the upwelling with cold surface water extending down for most of the water column. The shallowest station AB1 had a slight deep peak in chlorophyll-a but extraordinarily low counts of zooplankton. Subsequent net hauls found mostly very small nauplii and veligers (see Section 1.2, Fig. 2.5). The slightly deeper 1325 station had more of the water column at a higher chlorophyll-a level but zooplankton counts were also extremely low with a peak only near the bottom. It should be noted however that at 1325 there was a relatively high percentage of larger zooplankton particles throughout the water column suggesting this might be near the edge of the upwelling front. The offshore station AB3 has a more typical temperature profile, and the surface waters are slightly warmer with the intrusion of upwelled water seen from 5m down to ~15m. Since there are multiple density interfaces peaks in chlorophyll-a are found at 5-7m and again around 30m with corresponding increases in zooplankton particle counts at these depth as well. The larger particles >300 µm are found only in the top 8m which is the zone above the upwelling intrusion.

The Pickering stations (708 and 1330) do not include a very nearshore station since this was near the power plant exclusion zone. The water temperature was only slightly elevated (14°C) at station 708 indicating the previous effect of the widespread coastal upwelling and was only slightly stratified. The profile at this station is very similar to that found at 1325. The offshore station at Pickering had little indication of any effect of upwelling, with a warm mixed depth down to 7m of 16°C, a very wide metalimnion down to 28m and a hypolimnetic temperature of 4-5°C. The offshore site had a very wide deep chlorophyll-a maximum down to the bottom of the metalimnion but a local peak at 9m was also associated with a very small peak in zooplankton densities, including the large fraction >300 µm at the thermocline. A wider band of increased zooplankton particle densities was also found between 14-22m.

Tow-Yos

The tow-yo transects of the top 25-30 m of the water column are shown in Figs. 1.11-13. Winds ranged from 5-15 knots, from the E the first day and then W, which built up during the week and were quite gusty on the final day of sampling (Fig 1.4). The nearshore to offshore transect from the first day of sampling (Sept. 9) crossing the scarp from AB2 to TH4 (see dashed line Fig. 1.1) clearly illustrates that the start of the transect is within the upwelling, with most of the water column near 6°C and a much lower conductivity value matching that of the hypolimnion (Fig. 1.11). The chlorophyll-a value is very low near the start of the transect, though turbidity is slightly elevated (but still a very low value) suggesting a source of turbidity that is not related to the upwelling. The zooplankton particle counts are also extremely low in this location for all size categories. As the transect progresses offshore surface temperature and specific conductivity increases and a deep chlorophyll maximum (~10m) begins to appear and strengthens toward the end of the transect. By the end of the transect just offshore of the Outer Harbour the effect of the upwelling is much reduced, with surface temperatures of 16°C and specific conductivity 50 μScm^{-1} units higher than the start. The turbidity initially decreases as the transect moves

from the nearshore and increases offshore in the surface waters. This may be due to carbonate precipitate associated with the widespread lake whiting event which took place in late August. All zooplankton particle size category counts increase along the transect offshore with initially large particles (406-600 µm) at depth (~20m), which are likely *Daphnia* sp. or large calanoid copepods, with smaller size categories increasing in the hypolimnion (below 10m) further along the transect likely dominated by nauplii and veligers and the larger zooplankton found higher in the water column near 10m depth (see Section 1.2 for more details).

The second tow-yo transect (Fig. 1.12) on Sept. 9 was from offshore to inshore near Port Credit and then toward the middle of Humber Bay (LO9 – 1325 – TH4) (dashed line Fig. 1.1). The temperature stratification is strong and consistent over the transect, and along with conductivity values this indicates the surface of this section was not highly influenced by the upwelling, but the very cold hypolimnion (~5°C) at only 15m indicates that deep hypolimnetic water has been transported from offshore. The chlorophyll-a data indicates much higher values in the epi and metalimnion which increases in the nearshore but becomes lower moving toward the entry to Outer Harbour. This last section also indicates elevated turbidity around the middle of Humber Bay. The zooplankton size data indicates that the deeper sections of the transect have elevated small size categories (75-300 µm) in the hypolimnion while the larger fraction (>300 µm) are found in thin layers in the metalimnion or epilimnion. The highest values of the large fraction (406-600 µm) are found in the nearshore off Port Credit (middle of transect) as shown by two strong bands of counts around 15m and 5m. This pattern continues in a weaker fashion out to the middle of Humber Bay suggesting these may be different groups of zooplankton with differing temperature preferences (e.g. *Daphnia* and copepods).

The final tow-yo transect for the top 30m of the water column was on Sept. 13 moving west from offshore Pickering to Ashbridges Bay (1330-1326) along the 60m isobath (Fig. 1.13). Winds were much increased on this day blowing 10 knots from the N-NW and gusting 15-20 knots. Temperature stratification was very consistent with warm epilimnetic water (15°C) with slightly reduced temperature towards Ashbridges Bay, a wide metalimnion and hypolimnion around 25m depth. The chlorophyll-a peak was in the epilimnion and increased towards Ashbridges Bay. A deep finger of chlorophyll-a that extends down to 20 m can be seen about ¾ along the transect which is likely driven by a hypolimnetic intrusion creating a downwelling near the edge of the upwelling front. This idea is reinforced by the very low temperature and turbidity underneath the intruded water mass. A similar pattern can be seen in the turbidity signal, though turbidity is overall much higher around Pickering. The patterns of the large zooplankton particles (406-600 µm) also follow that of the chlorophyll-a signal (concentrated in the epilimnion) and also shows the downwelling region. The additional layer at 20-30m is matched by the distribution of smaller particle sizes (<300 µm) which are highly concentrated at this depth for much of the transect. Again, this is likely due to zooplankton with different temperature preferences.

CSMI Western Basin Transect

Since this study took place over a very short period of time (several days), to capture some of the seasonality, some data has been included here from DFO's Western Basin Transect associated with the Coordinate Science and Monitoring Initiative on Lake Ontario in 2013 (Fig. 1.14). The transect started off Port Dalhousie and continued across Lake Ontario to Humber Bay (L08) including the offshore Humber Bay station at 60m (LO9). Transects were carried out on June 12 (late spring), Aug. 24 (summer) and Nov. 3 (late fall – post stratification). The northern section of the 30m tow-yo nearest Toronto is shown in Figs. 1.15-16 with the section between LO9-LO8 indicated by a black bar. Humber Bay was consistently deeply mixed throughout the year, cooler than offshore water and generally did not exhibit a deep chlorophyll

maximum that was persistent offshore from June-Oct (Fig. 1.15). This suggests that the water column in Humber Bay is being continually disturbed by lake mixing processes likely due to its orientation facing to the NW. This is in the direction of the dominant westerly prevailing wind which is likely to promote upwelling. This zone seems to extend out past LO9 into 70-80m of water depth. The zooplankton particle densities (Fig. 1.16) reinforce the idea that Humber Bay has a distinct hydrodynamic regime from the offshore of Lake Ontario. In June, the 300-600 µm (and 600+) sized fraction occur in a thin layer from 5-10m associated with ~12°C water. These are likely large adult copepods. The smallest sizes are found more offshore in the epilimnion. During August the very deep mixing with a very wide metalimnion can be seen in the temperature and conductivity plots (Fig. 1.15). Only the smallest sizes of zooplankton particles (<300 µm) were found in Humber Bay during summer, highly concentrated into the epilimnion at temperatures ~ 17°C though they also were found at lower densities deeper in the water column. These are likely dominated by deissenid veligers, nauplii, small Bosminids and copepodids (See Section 1.2, Fig. 2.5). The post-stratification November transect indicated the system was fully mixed (Fig. 1.15) and that there was extremely low densities of any size category of zooplankton particles with Humber Bay the same as the offshore.

For the CSMI program, vertical profiles were taken during the day and night during June and August and during the day in September and November at LO8 and LO9 (Figs. 1.17-18). The 60m LO9 station temperature profiles indicate the complex mixing and instability at this station throughout the year. In June, the chlorophyll-a distribution has no clear single maximum but is rather distributed down to the top of the hypolimnion at 50m. There is also no obvious peak in total zooplankton counts in the water column, but when the larger particle sizes are examined, it is clear that they account for a very large percentage of the total counts in the epilimnion around 8m depth. Specifically, counts in the 406-600 µm size category is larger than the 151-300 µm counts indicating relatively high densities of large zooplankton of this category certainly dominated by large adult copepods and *Daphnia*. During the night, these large zooplankton disperse slightly to 5-15m but remain at high densities over this depth range. During August, the chlorophyll-a signal is consistent down to about 30m, again with no strong peak. The total zooplankton counts indicate a number of peaks (5, 8, 27m) dominated by the smallest sizes <300 µm. There are increased peaks and coalesced peaks during the night of these small particles which are likely nauplii and veligers. The 300-405 µm fraction is distributed fairly evenly from the surface down to 32m during the day and the surface down to 25m at night. This fraction is likely *Bosmina* sp (Section 1.2, Fig. 2.5). During the Toronto survey in September, the stratification was more stable with a much narrower metalimnion. This was driven in part by a larger proportion of the column being hypolimnetic water that was moved up (to ~15m) as a result of the large scale upwelling. The chlorophyll-a signal had little vertical pattern other than being slightly elevated in the epi and metalimnion. The total zooplankton counts were highest in the hypolimnion with several strong peaks associated with the <300 µm size fraction. The 300-405 µm size fraction was distributed fairly evenly down to 45m but the 406-600 µm category, likely *Daphnia* sp. and *Diacyclops thomasi*, was concentrated in the top 10m, though at low densities. During the isothermal November transect, the profile exhibited very low values and little vertical patterns of chlorophyll-a or zooplankton distribution.

At the shallower Humber Bay LO8 station during June, the night profile displayed higher counts in the epilimnion. As noted above, Humber Bay in June had a patch of elevated large zooplankton counts (406-600 µm) which seem to be deeper in the water column during the day (6m) and rise to the surface at night. The elevated night surface counts were still dominated by the smallest size fraction which is likely comprised of veligers or copepod nauplii. During the August sampling, the larger sized zooplankton fraction were absent within Humber Bay and there is little change during the night for vertical zooplankton distribution. There were slightly

elevated counts throughout the water column of 300-405 µm size fraction at night which is likely an influx of *Bosmina* or small copepods. The profile on Sept 9 during the Toronto survey clearly shows a midwater intrusion of cold 7 °C water in the temperature profile related to the upwelling. The zooplankton particle density reflects this with higher counts above and below the intrusion, especially in the larger sizes >300 µm which occur in the water temperatures ~13-14°C. The November profile is isothermal and cold (6°C) has very low zooplankton counts with no vertical structure.

Other Surveys

There are few published surveys of Lake Ontario using Optical Plankton Counters (Sprules and Goyke 1994, Sprules et al. 1998, Yurista et al. 2012). The results of Sprules et al. (1998) which used the much older, lower-resolution light-beam instrument were focused on the calibration of the size distributions with biomass and did not specifically survey the lake. The other LOPC survey in Lake Ontario (Yurista et al. 2012) investigated the entire nearshore in September and a portion of it during August 2008. The LOPC used was the first generation instrument which has a minimum ESD size resolution of 150 µm, so misses the entire first size-bin of our survey using the HR-LOPC which had the highest counts. This study was intended to examine the broad landscape patterns of physical-chemical and zooplankton distribution and was not meant to discriminate impacts on smaller regional scales due to the high variability found within the measures. Also, the dominant drivers of the large-scale patterns were limited to temperature, conductivity and chlorophyll-a. As such those methods are inappropriate to determine land-effects on plankton distributions for localized embayments such as Toronto Harbour or Humber Bay (P. Yurista, EPA, personal communication, 2015, but see for more detail (Yurista et al. 2015)). Furthermore, the inshore cross-contour tows were only used to determine if the 20m isobath transect was representative of the nearshore conditions, but it should be noted that the inverse comparison is not applicable.

Summary and Conclusions

This survey was done to assist in the evaluation of the Degradation of phytoplankton and zooplankton communities BUI (#13) for the Toronto Region AOC, currently classified as requires further assessment in the Stage 1 analysis. This was a one-time survey during the week of Sept 9-13, 2013 of the Toronto Region from Etobicoke to Pickering, which encompassed the boundaries of the AOC. The intent of the survey was to determine the distribution of zooplankton, chlorophyll and physical water characteristics using DFO's towed *SHRIMP* sensor array. To accentuate this spatial survey, for the 2013 Coordinated Science and Monitoring Initiative (CSMI) year on Lake Ontario, station sampling was done for physical characteristics, water chemistry, and collection of phytoplankton, microbial loop and zooplankton for taxonomy which are being made available.

The results of the other LOPC survey in Lake Ontario (Yurista et al. 2012) that investigated the nearshore were intended to examine the broad landscape patterns of physical-chemical and zooplankton distribution and are not applicable for determining impact of local embayments or river outputs into the coastal zone.

In September 2013, the entire Toronto coastline experienced a strong, widespread upwelling during the period prior to this survey which greatly affected the distribution of physical characteristics, chlorophyll, and zooplankton densities. In particular, the area near Ashbridges Bay along the scarp was highly swamped by the upwelling making any determination of impact by factors such as the sewage treatment outfall impossible for this survey.

Toronto Inner Harbour was very different than surrounding habitat in physical water characteristics with elevated values for temperature, turbidity and chlorophyll. Sampling in 2013 and in other years suggests that Humber Bay experiences deep mixing and weak stratification, likely due to its orientation to the northwest, which faces into the dominant prevailing wind direction. Upwelling forces combined with the internal seiche of the lake is likely to create very specific physical mixing conditions in Humber Bay that are unlikely to be found in any other location within Lake Ontario, so comparisons to other embayments must use caution. Since the dominant circulation within Toronto Harbour is from Humber Bay through the western gap any assessment of the pelagic ecosystem should include stations within Humber Bay.

There were exceedingly low zooplankton particle counts in Toronto Harbour compared to the surrounding Lake Ontario coast and other embayments of Lake Ontario. In particular, there were very few large-sized zooplankton counts. Embayments within Lake Ontario typically have much higher zooplankton densities than found in coastal habitats. This is likely not related to the upwelling since the inner harbour shows even higher temperatures than found outside of the upwelling in the lake, though there was hypolimnetic water from the lake intruding on the western side of the harbour. Given the flushing rate of Toronto Harbour near 10 days (Haffner et al. 1982), at these temperatures Cladoceran zooplankton should be able to reproduce several generations before being flushed into the Outer Harbour and are likely able to retain themselves against this flushing rate through vertical migration and active swimming (Genin et al. 2005, Speirs and Gurney 2001), thus increasing the retention time. This suggests a possibility that the inner harbour environment is currently not a suitable habitat for zooplankton populations. Additional data on fish planktivory should be assembled to determine if this an interacting effect. Further study should involve seasonal sampling of zooplankton to determine population structure over the spring-fall period and possibly population growth studies using incubations (Harris et al. 2000).

Section 1.2:
Toronto Harbour Zooplankton Sampling

K.L. Bowen

Introduction:

The Toronto and Region Area of Concern (AOC) covers a large geographical area on the northwestern shore of Lake Ontario, extending from Etobicoke Creek in the West to the Rouge River in the east (Environment Canada and Ontario Ministry of Environment, 2011). It includes 42 km of waterfront, and encompasses both the inner Toronto Harbour, the outer harbour bounded by the Leslie Spit, and nearshore waters of Lake Ontario. One of the Beneficial Use Impairments (BUIs) that has been identified in the Toronto AOC is the "degradation of zooplankton and phytoplankton populations" (Environment Canada and Ontario Ministry of Environment, 2011). Given the lack of available data on this subject, it has been given the status of "needs further assessment". The above report states that the key action that is associated with this BUI is to "undertake an assessment of this environmental challenge and develop a delisting target".

The purpose of this report is to present and summarize the limited amount of zooplankton data that is available to date. The primary focus will be reporting on two previously unpublished studies conducted in 2010 and 2013 by the Great Lakes Laboratory for Fisheries and Aquatic Sciences, part of Fisheries and Oceans Canada (DFO), Burlington Ontario. These spatial studies provide a "snapshot' of conditions in the Toronto area during the times of study. More information on the rationale behind the 2013 survey is given in Section 1.1 of this report.

Methods

Background Information:

Despite its location adjacent to a large urban centre with research infrastructure, little has been published on zooplankton in the Toronto Harbour area. One of the earliest and most comprehensive studies of Lake Ontario was conducted from June to October 1967, and included a detailed nearshore to offshore August survey in the Toronto area (Patalas 1969). Patalas concluded that harbour water influenced Lake Ontario zooplankton populations in the vicinity of Toronto, and suggested that pollution and local enrichment may have contributed to these differences. Specifically, he reported higher nearshore densities of the predatory taxa *Leptodora* (Cladocera) and *Diacyclops thomasi* (Cyclopoida) in the west and central areas off Toronto, and depressed populations of the small cladoceran *Bosmina*, especially to the east. Other lakewide studies have sampled coastal and offshore areas adjacent to Toronto (e.g., LO8 and LO9 in Figure 2.2). These include a 1970 study by Watson and Carpenter (1974), the LOTT surveys of 1991 to 1997 (Morris and Sprules 2003, Johannsson 2003) and CSMI studies in 2003 (Holeck et al. 2008) and 2008 (Rudstam et al., 2015). However, none of these surveys sampled inner or outer Toronto Harbour, nor reported specifically on individual stations in the Toronto area. Since 1994, zooplankton in the inner harbour and several nearshore sites have been sampled sporadically by the OMOE (see Section 2).

August 2010 Nearshore Study:

From 06 to 12 August 2010, a total of 43 nearshore stations were visited in western Lake Ontario and adjacent embayments as part of a Fisheries and Oceans Canada (DFO) study on nearshore plankton spatial distribution (Figure 2.1). Many of the coastal Lake Ontario stations followed roughly along a 10 m depth contour. Nearshore to offshore transects were also sampled in Burlington, Oakville, Port Credit, Grimsby, Humber Bay and Ashbridges Bay. Two stations were located in Humber Bay (HB), five in the Inner Toronto Harbour area (IH), five in

the offshore area adjacent to Toronto Harbour (Off), and two in Ashbridges Bay (Ash) to the east. This report will focus only on these 14 Toronto area stations. Coordinates and information on these stations are given in Table 2.1. A summary of this information is being included but the full details of the Lake Ontario Ecosystem Research Initiative (ERI) study will be published in a forthcoming manuscript.

Chlorophyll *a* was measured in epilimnetic water from three stations, using the same methods as described in Section 1.3 of this document. Secchi depth (an indication of water transparency), station depth and a vertical profile with a fluoroprobe were taken at each station. Water temperature, pH, conductivity and dissolved oxygen were taken at a depth of 1 m at each station using a YSI 6600 multiparameter water quality sonde, and vertical profiles were taken at selected stations. Surface water turbidity was measured using a LaMotte 2020e benchtop unit.

Zooplankton were collected at each station by taking a single vertical total water column (TWC) net haul from 2 m off bottom to the surface, using a metered, 64 um mesh, 40 cm diameter Wisconsin net. 14 samples collected in the Toronto area and 11 nearshore samples from the western basin of Lake Ontario have been analyzed. Epilimnetic rotifers were counted from three stations in the Toronto area (1364, 2047 and 431). For rotifers, 12 to 16 L of water were collected from 0-5 m with an integrator bottle, narcotized with carbonated water and filtered through 20 um mesh. Both zooplankton and rotifers were preserved in 4% sugar buffered formalin. For both zooplankton and rotifers, counting and measuring procedures were based on the stratified counting method of Cooley et al. (1986), using a minimum of 400 animals per sample as outlined in Bowen and Johannsson (2011).

August 2012 Sampling
On 26 and 29 August 2012, TWC 64 µm mesh net hauls were taken at the mid-Toronto Harbour stations (725 and 1364) (Figure 2.1). Other information collected included Secchi depth and temperature, pH, conductivity and dissolved oxygen using a Hydrolab Minisonde 4A.

Toronto Harbour 2013 Surveys
From 09 to 13 September 2013, a spatial study of the Toronto Area of Concern (AOC) was undertaken by DFO to better understand plankton distributions within the region. Four stations were sampled in Inner Toronto Harbour (IH), six in the nearshore (NS) between Humber Bay and Ashbridges Bay (including one outer Harbour station), four in the adjacent offshore area (Off), and five east of Toronto (East), including two in the Pickering area (Figure 2.2). In addition to these point stations, a second vessel surveyed horizontal transects in the AOC using a towed sensor, as described in Section 1.1.

At most of the point stations, water temperature, station depth, Secchi depth and light attenuation using a Licor unit were taken. The latter two measurements were not possible at the Pickering stations (708 and 1329) as these were sampled after sunset. If the station was thermally stratified, zooplankton were collected from the epilimnion (epi), metalimnion (meta) and hypolimnion (hypo, if present) using a 40 cm diameter, 64 µm mesh net (Table 2.2). A TWC vertical net haul was also taken at each station using a 50 cm diameter, 153 µm mesh Wisconsin style net. Stations deep enough for a hypolimnion to occur included LO9, TH4, AB3, 1326, 1329 and 708. Despite thermal stratification, only a single TWC 153 µm net was taken at each of AB3 and TH4 in the offshore due to deteriorating weather and time constraints. The IH stations and ST1 were only 8 to 10 m deep, and although a shallow epilimnion was present, the epi and meta nets were pooled for analysis. Rotifers were collected at the stations indicated in Table 2.2 using the same methods as in August 2010. All samples were preserved and counted as in August 2010.

Additional 2013 zooplankton and rotifer samples were collected at LO8 (Humber Bay) and LO9 (offshore) on 12 June, 24 August and 21 October. This was part of DFO's involvement in the 2013 Cooperative Science and Monitoring Initiative (CSMI) program in Lake Ontario (CSMI 2013 Coordinating Committee 2014). This was carried out in a similar manner as the September spatial survey, and is summarized in Table 2.2. Additional TWC nets were also taken at these stations on 14 August (153 µm) and 03 November (64 µm) as part of CSMI.

Results and Discussion:

Physical Parameters - August 2010:
Nine coastal stations in the Burlington Oakville (northwest) area were sampled on 06 August 2010, when surface temperatures averaged 20.4°C. An upwelling event occurred over the next two days, and on 09 August, the surface temperature at K22 on the west side of Humber Bay was only 16.9°C (Figure 2.3 top). By 11 and 12 August, this upwelling event was dissipating in the Toronto area, and temperatures ranged from 19.2°C to 21.9°C (Table 2.1). Similarity in temperatures between Inner Toronto Harbour and the surrounding areas suggest the Inner Harbour is influenced by exchange of water from outside the harbour.

Turbidity was highest at stations 1364 and 725 in the Inner Toronto Harbour (Figure 2.3 bottom), likely due to loading from the Don River. Turbidity was also relatively high at K22 (Secchi depth = 2 m), probably due to discharge from the Humber River. Water clarity was higher at TH1 and 726 on the western side the harbour, and at TH2 just outside the eastern gap, probably due to exchange with the lake. Generally, water flows into Toronto Harbour from Lake Ontario through the western gap and exits through the eastern gap (Haffner et al. 1982).

The Toronto Harbour stations were well oxygenated, with values above 9 mg L^{-1} throughout the water column. Relatively efficient exchange of water with the lake, along with shallow water depths in Toronto Harbour prevent strong temperature stratification and oxygen depletion from occurring (Haffner et al. 1982).

Physical Parameters - September 2013
Thermal structure, surface temperatures, Secchi and light attenuation for the September 2013 cruise are detailed in Sections 1.1 and 1.3. An upwelling event took place during the survey, with the coldest surface temperatures observed in the Ashbridges Bay area (e.g., 10.7°C at AB1 to 12.5°C at AB3). This compares to surface temperatures of 13.6 to 15.9°C at the remaining nearshore and offshore stations, and 16.2 to 17.6°C in the Inner Harbour. The highest turbidity, as indicated by Secchi depth, was observed at L12 and 1364 in the Inner Harbour, likely due to the Don R. discharge, and HB3 near the mouth of the Humber River. Water clarity was greatest in Ashbridges Bay where the upwelling was strongest, and at Etobicoke station 3508.

Zooplankton August 2010 Density, Biomass and Community Composition
In August 2010, the lowest mean zooplankton density was observed in Humber Bay at 9.7 ±37.6 animals L^{-1} (Table 2.3; Figure 2.4 top). Mean densities at the remaining Toronto areas ranged from 52.4 ± 59.8 animals L^{-1} in Ashbridges Bay to 57.3 ±14.0 animals L^{-1} in the Inner Harbour. Dry biomass generally followed similar trends, with the highest values in the offshore (105.8 ± 14.4 mg m^{-3}), and the lowest in Humber Bay (18.2 ±10.4 mg m^{-3}). Biomass in Inner Toronto Harbour averaged 65.5 ± 5.5 mg m^{-3}, which was within the range seen in the adjacent nearshore areas. However, Toronto Harbour values were about an order of magnitude lower than those observed in Hamilton Harbour or in the coastal nearshore of Lake Ontario during the same survey. August zooplankton densities and biomass in central Hamilton Harbour are

typically two to three times higher than in Toronto Harbour (means of 106 animals L^{-1} and 138 mg m^{-3} from 2002 to 2012, respectively; K. Bowen, unpublished data). This indicates that zooplankton in Toronto Harbour are less productive than expected. Residence time of water in Toronto Harbour is about 10 days, compared to a much longer residence time of about 90 days in Hamilton Harbour (Haffner et al. 1982). That study states that efficient water exchange with Lake Ontario results in lower nutrient concentrations and algal biomass in Toronto than in Hamilton, despite high nutrient loadings into each system. Effectively, the loading within Toronto Harbour are exchanged with the nearshore of Lake Ontario, resulting in the dilution of production over a larger area.

Both zooplankton densities and biomass values were unusually low at K22 near the mouth of the Humber River and at 431, the shallowest station in Ashbridges Bay (Figure 2.4). The reasons for this are unclear, but may have related to the upwelling event and/or flushing from the river at K22. During an upwelling, nearshore water (and the animals within it) is temporarily displaced by cooler hypolimnetic offshore water. As a result, upwellings can cause pronounced, short-term changes in zooplankton populations, especially close to shore along exposed coastlines (Haffner et al. 1984a).

In August 2010, zooplankton composition was somewhat variable throughout the nearshore areas of Lake Ontario and Toronto Harbour, with cladocerans usually comprising between 48% and 92% of biomass. The central Toronto Harbour station consisted of only 18% cladocerans. *Daphnia retrocurva* was the most common cladoceran in the inner harbour, whereas the slightly larger *Daphnia galeata mendotae* dominated Humber Bay and the offshore. *Daphnia* density was highest in the outer harbour, with a mean of 16.2 animals L^{-1}. This supports the idea that zooplankton production is being exported by the circulation patterns in Toronto Harbour. The small cladoceran *Bosmina* sp. was common in the inner harbour (11% by biomass), particularly at station TH2 outside the Eastern Gap and 726 (Figure 2.4). The predatory *Leptodora kindtii* was a dominant species in Humber Bay (20%), especially at station 2047. This station also supported the highest biomass of another smaller predatory cladoceran, *Polyphemus pediculus*. Predatory cladocerans comprised 52% of the total biomass at 2047. Total zooplankton biomass was relatively low (28.6 mg m^{-3}) at this station, possibly due to effects of high invertebrate predation. In comparison, predatory cladocerans averaged only 5% at the remaining stations (range: 0.1 to 15%). This included the invasive cladoceran *Cercopagis pengoi*, which never exceeded 5% of the community by weight (mean = 8.9 mg m^{-3} or 1.2%).

Cyclopoid copepods were usually a minor component of the coastal Lake Ontario and Toronto Harbour stations in 2010, comprising only 0.1% to 12% of the biomass. The highest cyclopoid biomass value was 5.2 mg m^{-3} at TH4. Copepodids (juveniles not identified to a lower taxonomic level) and *Diacyclops thomasi* were most commonly encountered. Calanoid copepods represented between 0.4% and 18% of the total biomass, and were dominated by copepodids and adult diaptomid copepods. Calanoids are normally indicative of cooler, less productive offshore waters, and their biomass averaged only 1.5 mg m^{-3} or less at the inner harbour, Humber and Ashbridges areas. In coastal Lake Ontario, the highest calanoid biomass values were observed at the deepest stations, TH4 and TH5 (23.1 and 12.0 mg m^{-3}, respectively).

Veligers, the pelagic larvae of invasive dreissenid mussels, were numerically the most dominant taxa at most of the 2010 stations, with densities in the Toronto area ranging from 0.4 to 88.5 animals L^{-1} (Figure 2.4). Although variable, they were particularly dominant at the mid-Toronto Harbour station 1364 and 909 in Asbridges Bay. Due to their small size, they were less dominant in terms of biomass, but still averaged between 1% (0.3 mg m^{-3}) at 2047 in Humber Bay and 79% (64.8 mg m^{-3}) at 1364. Although biomass in the Inner Harbour was variable, it

averaged 20.5 mg m^{-3} (28%). Most of those in the open water were likely Quagga mussel larvae (*Dreissena bugensis*), but zebra mussel larvae (*D. polymorpha*) may be found in the nearshore and harbour areas adjacent to hard substrates such as breakwalls and piers.

Late August 2012 - Density, Biomass and Community Composition

On 29 August 2012, water temperature was 21.3 C and Secchi depth was 1.5 m in mid-Toronto Harbour. Zooplankton density and biomass averaged 25.6±3.8 animals L^{-1} and 42.7±5.1 mg m^{-3}, respectively (Table 2.3). In terms of biomass, the community was dominated by cladocerans (93%), which was the highest proportion of this group at any site in the three surveys reported here. The dominant cladocerans were *D. retrocurva* (25%) and *Holopedium gibberum (*25%). *Holopedium* has a gelatinous sheath which can make it more resistant to invertebrate predators (Yan and Pawson, 1997), and can be abundant in the open water of Lake Ontario in late summer. Copepods and veligers comprised only a small portion of the biomass in Aug. 2012.

2013 Toronto Area Surveys - Density, Biomass and Community Composition

Although the epi, meta and hypo samples were generally counted separately at the deeper stations in 2013 (Table 2.2), the values presented below and in Table 2.3 are depth-weighted means for the TWC (i.e., the proportion of the water column occupied by each depth strata was taken into account when calculating the mean value). Both the epi and total water column density and biomass values for these stations are plotted in Figure 2.5. No consistent relationships between the epi and TWC values were evident, and community composition often differed between the two estimates. Unless specified otherwise, values presented below are for the TWC.

During the September 2013 spatial survey, mean zooplankton density and biomass were very low in the Inner Harbour and the nearshore surrounding the harbour, with values ≤12 animals L^{-1} and ≤8.3 mg m^{-3}, respectively (Table 2.3, Figure 2.5). These Inner Harbour zooplankton populations were substantially lower than those observed during the 2010 and 2012 August surveys. The Inner Harbour was dominated by cladocerans (62% by biomass), especially *Bosmina* sp. and *D. retrocurva*, and cyclopoid copepods (18%). Cyclopoids were somewhat more dominant in the nearshore (26%). In Sept. 2013, mean zooplankton biomass was intermediate in the offshore (41.5 ±11.8 mg m^{-3}) and highest at the eastern stations (74.3 ±33.9 mg m^{-3}). Cladocerans were less dominant in these areas, comprising <40% of the biomass.

Cyclopoid copepods were the most dominant group in the offshore and east in Sept. 2013, comprising 61% and 42% by biomass, respectively. These were predominantly *D. thomasi* and juveniles. Cyclopoid biomass values were variable among sites, with the highest level at station 1325 in the east (122.6 mg m^{-3}). Values at the remaining offshore and east stations ranged between 7.4 and 57.3 mg m^{-3}, but <3 mg m^{-3} at the Inner Harbour and nearshore sites. Nauplii (larval copepods) were abundant at the eastern stations in 2013, but comprised only a small portion of biomass due to their very small size. Cyclopoids were much less dominant in 2010 and 2012, with biomass comprising ≤6% at all sites except Hamilton. Cyclopoid densities at all the Toronto area sites averaged 8.2 ± 3.6 animals L^{-1} in Sept. 2013, compared to only 2.8 ± 0.6 animals L^{-1} in Aug. 2010. This appears to reflect a lakewide trend in increased cyclopoid abundance in 2013, and will be explored in more detail through the CSMI program.

Calanoid copepod biomass was low at all sites in Sept. 2013 (<5 mg m^{-3}). The proportion of calanoids was highest in the east (8%), especially at the Pickering area sites which were sampled at dusk. The large, deep water calanoid *Limnocalanus macrurus* and the diaptomid calanoids were uncommon at all sites, but generally these taxa were most abundant at the deeper stratified sites. The presence of *Limnocalanus* at shallow site LO8 in Humber Bay,

coupled with the very low total zooplankton biomass at this station, was likely caused by the upwelling event observed during the survey.

Veliger larvae were generally less abundant in September 2013 than in 2010, averaging 9.0 ± 3.5 animals L^{-1} and 30.4 ± 7.5 animals L^{-1} at all study sites, respectively. However, they still represented 33% by density and 17% by biomass in the Inner Harbour in 2013. Veliger density and biomass values were highest at AB1, at the edge of the upwelling site (66.9 animals L^{-1} and 14.2 mg m^{-3}, respectively), although biomass was ≤3.0 mg m^{-3} at most sites.

It is interesting to note that zooplankton populations were particularly low at AB2 in Ashbridges Bay in September 2013 (2.4 animals L^{-1}), possibly due to the dilution effects of the upwelling event at this station. In August 2010, this area also supported the lowest densities of zooplankton (2.9 animals L^{-1} at 431) though any upwelling effect was minimal at this time (Fig. 2.3). The Toronto Main Sewage Treatment Plant discharges effluent in the vicinity of this station. *Daphnia* toxicity laboratory studies conducted by Munawar et al. (1993) showed decreased survival in water overlying sediment collected from 431. Even in August 1967, *Bosmina* densities also appeared to be depressed on the east side of Toronto (Patalas 1969).

Seasonal and Temporal Trends

There were strong seasonal trends in zooplankton populations at LO8 (Humber Bay) and LO9 (offshore 60 m), the two Toronto area stations sampled repeatedly in 2013 as part of the CSMI program (Figure 2.6). Biomass was low in June, and consisted mostly of cyclopoids and veligers. Values increased to the highest levels in August 2013 at both stations. Biomass peaked at 106.4 mg m^{-3} at LO8 on 24 August, but was only 4.6 mg m^{-3} two weeks later during the upwelling. The August community was dominated by *Bosmina*, *Eubosmina* and cyclopoid copepodids. Similar trends were observed at LO9, although the drop in TWC biomass was not as dramatic (56.2 mg m^{-3} on 14 August, compared to 19.5 mg m^{-3} on 09 September). In the epilimnion (epi) at LO9, biomass of veligers and bosminids were much higher on 24 August than in September, although *Daphnia*, predatory cladocerans, other cladocerans and cyclopoids had increased in September. TWC biomass was similar at the two stations in September and October, although the community was dominated by calanoid copepods later in the fall.

Seasonal results from the 2003 and 2008 CSMI programs (Holeck et al. 2008, Rudstam et al. 2015) are included in Figure 2.6 for comparison. Unfortunately veliger data were not available for the TWC in 2003 and 2008, as these were sampled with a 153 µm net that does not effectively retain veligers. In 2003, TWC zooplankton biomass was very low at both LO8 and LO9 in April, and peaked in late September, with a value of 106.6 mg m^{-3} at LO9. Cyclopoid copepods were a dominant part of the community in August and September. *Daphnia* were also abundant in the TWC at LO9 in September, and the predatory cladoceran *Cercopagis* was dominant at both stations in August. Epi veliger biomass was relatively low. In 2008, community composition had changed dramatically (Rudstam et al. 2015), with a drop in cyclopoid biomass and an increase in veligers in the epi. Calanoids were dominant at LO8 in April and the LO9 TWC samples in July and September. Cyclopoids had regained importance in the TWC in June and August 2013. As cyclopoids are predominantly found in the meta and hypo, epi zooplankton composition was similar in July 2008 and August 2013 at LO9.

Zooplankton was also sampled every three years at nearshore index sites in Lake Ontario by the Ontario Ministry of Environment (OMOE) starting in 1994 (see Section 1.2). Samples were collected at three depths through the water column using a Schindler-Patalas trap in spring, summer and fall in 1994, and every three years starting in 2000. The three traps from each station-date were pooled and counted using the same methods described in this report. The

stations in the Toronto area included Etobicoke (3508) in 2006 and 2009, five years at Humber (LO8) and Inner Toronto Harbour (1364), and at Pickering (708) from 2000 onwards (Figure 2.7). In summary, the highest zooplankton biomass value was observed at LO8 in August 1994 (336 mg m^{-3}) due to a population spike. On this date, the community was comprised primarily of bosminids, cyclopoids and *Daphnia.* Densities at LO8 on August 1994 and August and October 2000 ranged between 70 and 151 animals L^{-1}, but were otherwise below 30 animals L^{-1} at all stations. The highest biomass values in the Inner Harbour were observed on August 1994 (45.6 mg m^{-3}) and August 2009 (58.9 mg m^{-3}), due to a large number of *Daphnia*. Cyclopoids and bosminids were also high on these two dates, respectively. Otherwise, zooplankton biomass values were usually very low (below 25 mg m^{-3}) at these four stations. For the remaining 2006 and 2009 samples, biomass values for cyclopoids, bosminids and veligers were generally low, though veligers were at times numerically abundant. Calanoid biomass tended to increase at all stations in 2009. *Daphnia* and predatory cladocerans (primarily *Cercopagis*) were periodically important during the summer.

In comparison, the total biomass value during the September 2013 survey (dashed lines in Figure 2.7) at LO8 was substantially lower than values observed during the previous index surveys by OMOE, but the reverse was true at the Etobicoke site. The Inner Toronto Harbour and the Pickering sites fell within the index sample range for some summer dates. This further illustrates the inter-annual variability at the Toronto area stations.

The dramatic seasonal trends observed in 2013, accompanied by inter-annual variability over the last two decades, illustrate the difficulty in trying to quantify zooplankton populations in a given area based sporadically on only one or two surveys. The 2013 spatial survey only shows a snapshot in time, and results would likely have been quite different if the survey were carried out even two weeks earlier. These results support the idea that sampling should be carried out on a more frequent basis (biweekly to monthly) at one or two stations, and accompanied by a small number of spatial surveys to better understand spatial variability in the study area.

Cladoceran Mean Size

The mean length of herbivorous cladocerans, and *Daphnia* specifically, can be used as an indicator of fish predation rates (Brooks and Dodson 1965, Mills et al. 1987) or disruptions to large cladoceran reproduction. Planktivorous fishes such as alewife, white perch, and the juveniles of many species such as yellow perch and various sunfish, selectively target larger individuals (Brooks and Dodson 1965, Cooley et al. 1986). When planktivory rates are high, the mean size of cladocerans is often suppressed and the community is dominated by smaller species. In August 2010, cladoceran length averaged 781 µm in the open lake, compared to 631 µm in the Inner Harbour and Humber Bay (Figure 2.8). By Sept 2013, means had dropped to 520 µm in the east and offshore, and 373 µm in the Inner Harbour and nearshore. Both herbivorous cladocerans and *Daphnia* were uncommon in the latter two study areas in 2013 (Figure 2.8). Furthermore, mean cladoceran size was usually below 500 µm at LO8 and LO9 during the 2013 CSMI sampling season (Bowen, unpublished data). The few *Daphnia* that were present in the inner harbour in Sept. 2013 tended to be the same size or slightly larger than those in 2010. This suggests that the loss of *Daphnia*, rather than a change in size of those present, was the primary driver in the drop in mean cladoceran size.

Declines in *Daphnia* abundance and the decrease in mean cladoceran size both suggest higher rates of planktivory in 2013 than in 2010, especially in the harbour and nearshore. Alewife is the primary planktivorous fish in Lake Ontario (Johannsson and O'Gorman 1991, Rand et al. 1995). In 2010, adult alewife abundance in the U.S waters of Lake Ontario reached its lowest level since 1978, but by 2013 had recovered to levels more consistently seen during the 2002 to

2012 period (Walsh et. al. 2014). This same study indicates that yearling alewife in 2013 hit the highest level observed in southern Lake Ontario since 1978 when monitoring began. Alewife was also the dominant species in Humber Bay during the 2013 CSMI fish surveys in both trawl nets and vertical gill nets, followed by rainbow smelt (trawl nets) and emerald shiner (gill nets) (Milne, 2014). Toronto Harbour electrofishing surveys by DFO in 2009 also found alewife to be the most abundant species, followed by yellow perch, emerald shiners and white suckers (C. Boston, unpublished data). The Ontario Ministry of Natural Resources and Forestry's Nearshore Fish Community Index Trap Netting program in the Toronto Harbour area from 2006 to 2012 indicates that brown bullheads are the most dominant species in terms of numbers, followed by pumpkinseed, yellow perch and alewife (Hoyle 2013). This gear targets fish >90 mm, so would not capture many smaller planktivorous species such as younger alewife or shiners.

Rotifers

Rotifers were enumerated from three epi samples collected in August 2010 and five in September 2013 (Figure 2.9). Rotifers can be very numerous in the water column (e.g. up to 630 animals L^{-1} at 431 in August 2010), but due to their very small size their contribution to total biomass is generally considerably less than that of zooplankton. However, their parthenogenic reproduction rates are often rapid, and they may be consumed by predatory zooplankton such as *Cercopagis* (Makarewicz and Lewis 2015, Pichlová-Ptáčníková and Vanderploeg 2009) and cyclopoid copepods (Stemberger 1986). Rotifers can play an important role in energy and nutrient transfer in the aquatic food web (Makarewicz and Likens, 1979). Rapid turnover rates also mean that rotifer species can quickly bloom and disappear, and large pulses may be missed by infrequent sampling. The most abundant rotifer taxa in the Toronto area samples included *Polyarthra vulgaris*, *Keratella cochlearis*, *Synchaeta kitina* and *Conochilus unicornis*. Because it is so large, *Asplanchna* sp. often dominated rotifer biomass even when numerically uncommon. These taxa tend to be common throughout Lake Ontario (Makarewicz and Lewis 2015). Rotifer densities in Toronto Harbour averaged 334.5 animals L^{-1} in 2010 and 170.3 animals L^{-1} in 2013.

The highest rotifer biomass values were observed at stations 1364 and 431 in 2010, with values around 6 mg m^{-3} at each station). Rotifers comprised 11% and 43% of the total zooplankton + rotifer biomass at these two stations, respectively, but only 3% at the Humber Bay station 2047. In September 2013, rotifer biomass ranged between 1.6 mg m^{-3} at LO8 and 3.4 mg m^{-3} at 708 off Pickering, showing an increasing west to east gradient. Rotifers comprised the highest proportion of rotifer + zooplankton biomass at LO8 (17%) and the inner harbour station 1364 (15%), and <8% at the remaining stations. The percent contribution by rotifers tended to be higher in the Toronto Harbour area than in the more productive embayments of Lake Ontario, although the biomass values were in the same range. For example, seasonal mean rotifer biomass in the upper and middle reaches of the Bay of Quinte averaged 2.6 mg m^{-3} over the 2000 to 2008 period, representing only 2% to 4% of total zooplankton biomass (Bowen and Johannsson 2011).

Rotifers also show seasonal and inter-annual trends in biomass and species composition (Figure 2.10). At LO8 in July 2008, rotifer biomass was high (27.6 mg m^{-3} or 43% of total zooplankton + rotifer biomass), and was dominated by the large taxa *Synchaeta grandis* and *Asplanchna* sp. By September 2008, these two taxa had largely disappeared and biomass had declined to 6.0 mg m^{-3}. However, this still represented 25% of the total biomass. In 2013, rotifer biomass stayed below 1.7 mg m^{-3} on all four dates sampled between June and October (Figure 2.10), reaching its lowest levels in the late fall. Because zooplankton biomass was low in September, rotifers represented 27% of the total. Contribution by rotifers dropped to only 0.6%

on 24 August when zooplankton biomass was very high. *Synchaeta kitina* was the dominant taxon in June, although the community was more diverse on the other 2013 sampling dates.

Summary and Conclusions:

The limited zooplankton data available from inner Toronto Harbour have shown strong spatial and temporal variability over the last decade. Although more data are available for the nearshore zone of Lake Ontario adjacent to Toronto Harbour, it too shows seasonal variability associated with seasonal succession of zooplankton species, and longer term changes in zooplankton community structure in Lake Ontario (e.g., Rudstam et al. 2015, Johannsson 2003). These fluctuations are associated with changes in nutrients and phytoplankton, invasive species such as dreissenid mussels and predatory cladocerans, and changes in planktivorous fish populations (Sprules 2008). Although variable, zooplankton populations in the inner Toronto Harbour and adjacent nearshore tend to be lower than in other embayments in Lake Ontario such as the Bay of Quinte (Bowen and Johannsson 2011) or Hamilton Harbour (Dermott et al. 2007). Relatively low zooplankton populations in the Toronto Harbour area and Humber Bay may relate to high fish predation pressure, coupled with flushing from rivers and elevated water exchange with Lake Ontario. Upwelling events appear to be common phenomena in the Toronto area based on prevailing wind directions and basin morphology (Lee 1972), and may depress local zooplankton populations (Haffner et al. 1984a). Low zooplankton densities in the nearshore area of Ashbridges Bay have been noted on several occasions, and although reasons are uncertain, the role of the Ashbridges Sewage Treatment Plant should be investigated further. In conclusion, two late summer spatial surveys are not adequate to properly assess the zooplankton and phytoplankton degradation BUI in the Toronto AOC, and more intensive temporal sampling is required to address this issue. Although not conclusive, these results suggest that further examination of the effects of Toronto sewage discharge on zooplankton populations may be warranted.

Section 1.3:
Toronto Harbour Water Chemistry, Physical Conditions, Phytoplankton and Microbial Loop

H.A. Niblock

Background: Toronto and Region AOC

Toronto and Region is one of 43 locations across the Great Lakes designated as an Area of Concern (AOC) under the 1987 Great Lakes Water Quality Agreement (GLWQA) between Canada and the United States. An AOC is an area having experienced high levels of environmental harm due to human activities. Fourteen Beneficial Uses were evaluated in each AOC and if considered impaired a Remedial action plan was developed. The Greater Toronto Area (GTA) is the largest urban area in Canada, with a population of about 6 million people. Since the earliest settlements on Lake Ontario, agricultural and urban developments have dramatically reshaped the natural environment of the region. The shape of Toronto Harbour has changed dramatically with infill and river diversion altering the nearshore environment. Contaminants from stormwater runoff and melting snow have impacted the waters of Lake Ontario. Of the 14 potential Beneficial Use Impairments (BUIs) Toronto and Region, 8 BUIs were identified as 'impaired', five considered 'not impaired' and one 'requiring further assessment'. In Toronto and Region AOC the unknown BUI is degradation of phyto- and zooplankton populations. As in most of the Great Lakes AOCs, there was very little known about phytoplankton and zooplankton in the area and so evaluators were unable to say if their populations in the AOC were degraded relative to surrounding 'non AOC' areas. When the 2012 renewal of the GLWQA reaffirmed the commitment to restoring water quality and ecosystem health in the AOCs, an attempt to understand the phytoplankton and zooplankton populations in this AOC was initiated.

This report is an attempt to summarize the available historical data on phytoplankton and to present a snapshot of the phytoplankton community in and around the harbour in September 2013. This information is intended for publication. Do not distribute without permission.

Historical study of phytoplankton and microbial loop

Nalewajko (1966) published the earliest studies of the phytoplankton in the current Toronto and Region AOC. Surface samples were taken from a station 1km south of Gibraltar Point at 1-8 week intervals in 1964 and 1965. Unfortunately the nanoplankton was not enumerated and so seasonal trends are shown for the larger taxa only. Of 36 taxa with abundance reported; 17 were Diatoms, 15 were Chlorophyta, 1 was Chrysophyceae, 1 was Dinophyceae and 2 were Cyanophyta.

The most extensive studies on the phytoplankton of Toronto Harbour and surrounding area were by Haffner et al. (1982, 1984b). Samples were collected weekly from a mid Harbour station from May to October, 1977 and at 3 stations (5m, 12m & 30m depth) off of Scarborough and Clarkson in May to December, 1979. The inner harbour was found to have between 1-2 g m^{-3} with a maximum of 5 g m^{-3}, while the outer harbour, nearshore area was found to have a similar range of biomass. The outer harbour was found to be predominantly Diatomeae, Cryptophyceae and Chlorophyta, while in the inner harbour Diatomeae dominated in the spring and Cryptophyceae and Chlorophyta were dominant the rest of the season. Haffner et al. (1984a) concluded that the hydrology of the area is highly complex given upwelling, coastal jets, internal waves and thermal bar formation along with frequent meterorological changes, and that the coastal zone in this area is not a steady state environment.

In July 1985 Munawar et al. (1989a) conducted a study on the impacts of dredging and dumping dredged materials on the phytoplankton in Toronto Harbour. The natural phytoplankton communities reported in control measures (pre dredge or dump) show a biomass dominated by phytoflagellates, specifically *Cryptomonas erosa* Ehrenberg and *Uroglena Americana* (Calkins) Lemmerman. Unfortunately, total biomass was not reported. Bioassays conducted using natural phytoplankton populations showed that the rates of primary productivity of indigenous phytoplankton populations increased during and following dredging operations. At the time dredging was estimated to be ongoing for 270 hours a year in Keating Channel. Dredging also caused changes in nutrient and trace metal concentrations. Generally, a decrease in some nutrient concentrations was observed which is explained by enhanced productivity to biomass (P/B) quotients during dredging.

In 1986, Toronto Harbour sediments were used in a bioassay methods trial (Munawar et al. 1989b) and it was observed that exposure to increasingly higher sediment levels in the bioassay caused the phytoplankton community to have a significantly reduced rate of productivity.

In 1987 and 1988, bioassay work was conducted to test for the effects of a change in the Ashbridges Bay sewage treatment plant (STP) operations upgrades on the phytoplankton of Ashbridges Bay (Munawar et al. 1993). Rates of primary productivity were measured at the STP outflow, around the outflow area and along an offshore transect. Rates of productivity ranged from less than 1 to over 7 mg C m^{-3} hr^{-1} in November; from 15-80 mg C m^{-3} hr^{-1} in March; and, 9-80 mg C m^{-3} hr^{-1} in April. Rates less than 5 mg C m^{-3} hr^{-1} are consistent with oligotrophic conditions (Munawar et al. 2013), while rates over 50 mg C m^{-3} hr^{-1} are seen in the eutrophic embayments of Bay of Quinte and Hamilton Harbour (Munawar et al. 2012). The microbial loop was shown to have significantly less autotrophic picoplankton (APP) in the Bay compared to the offshore while bacteria and heterotrophic nanoflagellate (HNF) levels were similar. Cluster analysis of ciliate taxa data showed that the STP outflow station was different from the other stations in all samples. Sediment bioassays run using offshore phytoplankton showed that sediments from the STP outflow inhibited ultraplankton (>20 µm in size) productivity rate but this influence was restricted to the outflow station itself and effects were diluted in the immediate area.

The STP outflow station and stations along an offshore transect (southeast from Ashbridges Bay) had phytoplankton counts completed from July, August and October 1988 (Munawar unpublished data). In July and August, the STP outflow station has much more phytoplankton biomass than the other stations. In July peaks in Diatomeae (*Tabellaria fenestrata* (Lyngb.) Küetzing and *Melosira islandica* O. Muller) and the Euglenophyta genus *Colacium* accounted for 45% of the 16.5 g m^{-3} biomass. During the same survey, biomass ranged from 0.8-3.4 g m^{-3} at other stations. In August, 33% of the 9 g m^{-3} biomass found at the STP site was a *Euglenoid* spp. not seen at the other stations where biomass was much lower. At the other stations biomass ranged from 2.3 to 2.8 g m^{-3} and was a mix of Chlorophyta and Dinoflagellates. In October 1988 the biomass at the STP site was in line with the other stations measured (1.9 to 4.3 g m^{-3}) and was a similar mix of Chlorophyta, Dinophyceae and Cryptophyceae.

In October 1991 and September 1992 taxonomic data were collected on the phytoplankton, ciliates and microbial loop in the Inner Toronto Harbour, Ashbridges Bay and an offshore transect (Munawar et al. 2003). In October 1991, phytoplankton biomass in the Toronto region was one half of that of the offshore transect (although highly variable between stations). Inner harbour phytoplankton biomass ranged between 0.2 to 2.9 g m^{-3}, Ashbridges Bay phytoplankton biomass ranged from 0.4-2.6 g m^{-3} and offshore biomass ranged from 1.2-7 g m^{-3} (Munawar et al. 2003). Composition was a mix of Diatomeae and Cryptophyceae in all regions.

Ciliate biomass was also highly variable during the October 1991 survey. Average ciliate biomass in the inner harbour (20-1800 mg m^{-3}) was high compared to the outer harbour (50-550 mg m^{-3}) and offshore transect (20-70 mg m^{-3}, Munawar et al. 2003). Microbial loop biomass was similar in the nearshore and the offshore and the previously reported trend of low APP in the Toronto area was only seen at the STP outflow and the mouth of the Don River, the sites expected to be most impacted by urbanization. Bacteria and HNF values were similar among areas (Munawar et al. 2003).

MOE dataset

The Ontario Ministry of Environment and Climate Change collected phytoplankton samples from nearshore stations around the Great Lakes, in spring, summer and fall, approximately every three years as part of their Great Lakes Nearshore Index Station Network program. Samples were recently counted for phytoplankton biomass and composition and those collected from the inner Toronto Harbour and mid Humber Bay in the summers of 1994, 2003, 2006 and 2009 are presented in Fig. 3.1. Biomass was highly variable and ranged from 0.01 – 0.9 g m^{-3} in Humber Bay and from 0.01-2.2 g m^{-3} in the inner Toronto Harbour. Average summer biomass in Humber Bay was 0.54 g m^{-3} and the average biomass in the Inner Toronto Harbour was 0.68 g m^{-3}. Both of these are in the ultra- oligotrophic range of Munawar and Munawar (1982). The range of biomass values was extremely high and the greatest difference in biomass occurred between the two samples taken in 1994 only a month apart where they ranged from ultra-oligotrophic to mesotrophic. The highest biomass was found in August 1994 and this was primarily due to a peak in the large Dinophyceae taxa *Ceratium furcoides* and *C. hirundenella*. In recent samples the inner harbour appeared to be a mix of groups including Diatoms and Cryptophyceae. The Phytoplankton community in Humber Bay has been variable over time, but has had more Chrysophyceae in the most recent samples.

Current Study: Methods

A synoptic survey of the Toronto Harbour Area of Concern and nearby nearshore Lake Ontario was conducted the week of September 9, 2013 in conjunction with the spatial mapping described in Section 1.1. Traditional point sampling techniques were used to collect data comparable with previous sampling undertaken by DFO. Point sample parameters included profiles using an YSI EXO2 sonde (temperature, depth, dissolved oxygen, pH, conductivity, turbidity, salinity, chl a, phycocyanin and fDOM fluorescence sensors) and algal pigments using a FluoroProbe (bbe Moldaenke). Attenuation of photosynthetically active radiation (PAR) was measured with a Licor quantum sensor.

Temperature profiles were used to determine stratification and integrated sampling depth. Epilimnetic water samples were collected with a bottle integrator from the surface to a maximum of 8m or 1 m off bottom depending on stratification and bottom depth. The station was considered unstratified if the thermocline was less that 5m deep. Integrated water was stored in the dark and on ice and was pre-processed (filtered) the same day for water chemistry parameters, which were submitted to Environment Canada's National Laboratory for Environmental Testing. Analysis of total phosphorus (unfiltered), soluble reactive phosphorous, nitrite and nitrate, ammonia, total Kedjal nitrogen, dissolved organic and inorganic carbon, particulate organic carbon and nitrogen, silica, calcium, sodium, potassium and magnesium was undertaken. To determine chlorophyll *a*, water was filtered onto G/FC filters and frozen prior to acetone extraction and spectrophotometric reading (Strickland & Parsons 1968).

Subsamples of integrated water were preserved using acidified Lugol's iodine solution for phytoplankton and ciliate identification. Phytoplankton enumeration and measurement followed the HPMA (2-hydroxypropyl methacrylate) technique described by Crumpton (1987) and is

broadly compatible with the Utermöhl (1958) inverted microscope technique. Ciliate samples were post-fixed with Bouin's fluid and enumeration and identification followed the Quantitative Protargal Staining technique (Montagnes and Lynn, 1993). Microbial loop (bacteria, heterotrophic nanoflagellates and autotrophic picoplankton) samples were preserved in 1.6% formaldehyde and processed using DAPI staining and epifluorescent microscopy (Porter and Feig, 1980).

Size-fractionated primary productivity (Munawar et al. 1989c) was estimated using the 14C uptake technique (Vollenweider et al. 1974). Integrated water (as collected for water chemistry) was inoculated with $NaH_{14}CO_3$ and was divided into 100 ml portions and placed in four 200ml polycarbonate flasks. Each sample was then incubated for four hours at constant and optimal light levels of 238 $\mu E/m^2/s$ at 400-700 nm while being maintained at lake temperature. After the incubation period, the contents of each bottle were size-fractionated through 20 µm Nitex screen. The large material caught on the screen was back-washed onto a 0.45 µm Millipore membrane filter. This determined the netplankton productivity (>20µm). The portion of the sample that passed through the 20µm Nitex screen was filtered directly onto a 2µm Millipore membrane filter which determined nanoplankton (2-20µm) productivity. The left over sample was then filtered using 0.45µm Millipore membrane filters to determine the picoplankton productivity (<2µm). The membrane filters were then acidified with 10ml of 0.1 N HCl and kept in a Phase Combining System (PCS) for liquid scintillation counting (Lind & Campbell, 1969). Uptake rates of leucine from a whole water sample were used to determine the maximum potential bacterial carbon production following the procedure outlined by Jorgensen (1992). Bacteria are known to take up amino acids from their environment and amino acids are known to be present in modest amounts. Although some algae are heterotrophic, by far most of this heterotrophic activity is bacterial. The bacterial uptake constant Kt for leucine is generally about 10 nM, so they are not living in a "saturating quantity" of leucine and they are not taking it up at Vmax, the maximum rate. In this procedure we add sufficient leucine to bring the concentration to "saturation", and incubate for one hour at surface temperatures to measure Vmax. Therefore we measure "potential" production rather than actual production.

Sampling moved from west to east, starting with Humber Bay on Monday, inner and outer Harbour on Wednesday and Ashbridges Bay to Pickering on Friday. Due to time and monetary constraints a subset of the stations sampled for physical parameters were chosen for water chemistry and plankton parameters. Stations were picked to represent a nearshore to offshore transect in Humber and Ashbridges bays and wide spatial coverage in the inner harbour (Table 3.1).

As part of the Lake Ontario 2013 Cooperative Science and Monitoring Initiative (CSMI) program, comparative data were also collected from 2 stations on the Humber Bay transect (mid-shore LO8 and offshore LO9) in the late spring (June), once in summer (August) and in twice in the fall (October and November) of 2013. A wide swath of stations were also sampled in and around Toronto Harbour in August 2010 as part of a DFO Lake Ontario nearshore study (see table 2.1 in the zooplankton section 1.2 for coordinates and sampling details).

Results

Physical parameters: Thermal structure

September 2013

The thermal structure was assessed using an YSI EXO2 water profiler (or MK9 datalogger if the EXO2 profile was not available) and most stations were found to have complex stratification with a series of steps or stable temperature lenses lying over other layers and divided by transition zones. The transition zones often comprised a large portion of the water column. Howell et al.

(2012) documented these complex thermal profiles along the north shore of Lake Ontario and attributed them to strong onshore-offshore circulation. Fig. 3.2 shows there was more layering in the eastern and western gap areas, were water from the lake was able to intrude into the warmer harbour area, than in the mid-harbour or offshore. The mid-harbour and Don River stations were warmest overall and were fairly stable as the entire water column was over 15°C. Stations in the inner and outer harbour as well as the off shore stations in the west and far east (Pickering) had surface temperatures (ST) over 15°C (Table 3.1). The near and mid-shore stations off Pickering and off Port Credit showed the influence of a recent upwelling event which are common on the north shore of Lake Ontario (Miners et al. 2002).As a result, surface temperatures were cooler than expected (13-15°C) for late summer in Lake Ontario (Dobiesz and Lester 2009). Nearshore Ashbridges Bay stations were isothermal due to upwelling and were less than 11°C for the entire water column. The 3 deepest stations had large portions of the water column that were unstable temperature transition zones (35-45%) and were the only stations with hypolimnion temperatures below 5°C.

Aug 2010

The thermal structure in August 2010 was measured using the FluoroProbe and showed no complex stepping (Fig. 3.3) as was seen in the 2013 survey. The majority of stations were shallowly stratified (epilimnion less than 10m deep with temperature greater than 19°C) and had a large sloped metalimnion (zone of temperature change) that continued right to the bottom. This pattern applied to inner and outer Toronto Harbour. Overall the surface temperatures seen in August 2010 were higher and more uniform than in the 2013 survey.

Seasonal 2013

Typically LO8, the 14m mid-shore Humber Bay station, was not found to be stratified and showed only surface warming in mid-June (around 3.5m) and late August (complex stepped layering in top 8 m). Surface water temperature was warmest in August at 18°C and coolest in early November at 5.5°C. Station LO9, the 60m deep station, showed complicated stratification patterns. It was warming in the June cruise with a surface temperature of 12°C and 4 layers of water, by August these lenses were more pronounced and by early September the area was fully stratified (surface temperature =18°C). Offshore station LO12, at 100m, was distinctly stratified in June (ST=11°C), August (ST=18°C) and October (ST=10.7°C) and fully mixed in November (ST=4.6°C). Increased chlorophyll fluorescence was associated with each thermocline at the 60 and 100m stations.

Physical parameters: Light Attenuation

September 2013

The euphotic zone (Zeu1%) is defined as the photosynthetically active zone from the surface to where only 1% of incidental or surface light is available, and the depth of this zone decreases with increasing light attenuation (i.e., higher turbidity). Attenuation (E_{PAR}) of photosynthetically active radiation (PAR) was measured with a Licor quantum sensor (Table 3.1). Average attenuation was higher in the west (0.291 m^{-1} ±0.005) than in the east (0.222 m^{-1} ±0.004) and was highest in the inner harbour (0.431 m^{-1} ±0.091) mainly because of high attenuation rates (turbidity) at the Don River outflow site. Despite a slightly higher attenuation rate in the inner harbour, at all but the Don River outflow station the predicted euphotic zone was deeper than the station depth, allowing for photosynthesis to occur throughout the full water column. The euphotic zone also reached the bottom at the near and mid-shore stations to the west and east of Toronto Harbour where light attenuation was measured. At the deepest station measured (71m), the 1% euphotic zone reached to 20.5m or 29% of the water column.

Seasonal 2013
Light attenuation rates at LO8 increased from a low of 0.181 m^{-1} in June to a high of 0.286 m^{-1} in September. Average attenuation was higher at LO8 compared to LO9 (Table 3.2). At LO9 light attenuation was higher in June than in August. The euphotic zone (to 1% incidental light) reached to the bottom (14m) at LO8 on all dates, whereas at LO9 Zeu1% reached to 20 and 20.4m. LO9 is 59m deep and in late summer and early fall the full epilimnion was in the euphotic zone due to a deep mixed layer.

Water Chemistry and extracted chlorophyll
September 2013
As expected given the light attenuation rates, particulate organic nitrogen (PON), particulate organic carbon (POC) and total phosphorus were higher in the inner harbour than in the east or west (Table 3.2). The level of Kjeldhal nitrogen (organic + inorganic Ammonium) was also higher here. Ammonia (NH3) is the preferred form of Nitrogen selected by autotrophs (Neel 1979) and was lowest in the inner harbour. Not surprisingly acetone extracted Chlorophyll *a* was higher in the inner harbour (5.19 ±1.6 µg L^{-1}) than the west (2.917 ±0.5 µg L^{-1}) and both were higher than the east (1.82 ±0.2 µg L^{-1}) (Table 3.2).Some of the lowest densities of zooplankton were found in the inner harbour while higher densities were seen in the east (see Section 1.2: Zooplankton, and Section 1.1: Towed survey).

Dissolved organic Carbon (DOC) and soluble reactive phosphorus (SRP) were highest in the east and slightly higher in the inner harbour compared to the western station region. This is interpreted as being caused by outflow from one of Toronto's major sewage treatment plants at Ashbridges Bay. Higher DOC and SRP are generally associated with higher bioactivity in a region.

Seasonal 2013
Calcium, sodium and dissolved inorganic carbon were stable through the season and similar at the mid-shore (LO8, 14m) and offshore (LO9, 59m) stations (Table 3.2). There was a similar seasonal trend seen at LO8 and LO9 for silica, SRP and nitrate plus nitrite. They were found to be higher in June and October than in August and September. The opposite trend was seen in DOC. Winter et al. (2011) reported a similar seasonal trend in NO2 +NO3 and silicate in Lake Ontario waters collected at the water intake pipes in the Toronto Area.

These patterns are indicative of higher algal activity in the summer taking up the silica, SRP and inorganic nitrogen and producing organic carbons. Chlorophyll *a,* which is indicative of standing crop biomass, not production, only partially reflects this trend in our 2013 sampling, and showed slightly higher chlorophyll in summer (August 1.59 ± 0.12 µg L^{-1}, Sep 2.62 ± 0.68 µg L^{-1}) compared to spring (1.36 ± 0.26 µg L^{-1}). Fall chlorophyll *a* values were much lower than earlier in the season (0.335 ± 0.08 µg L^{-1}).

TP and NH3 showed irregular patterns and there was a slight downward trend in Kjedal nitrogen over the season.

FluoroProbe Chlorophyll and Pigment Groups
September 2013
The FluoroProbe measures fluorescence in the water column associated with algal pigment groups and converts it to chlorophyll *a* as a standard measure. The average whole water column (surface to bottom) chlorophyll *a* in the Toronto Harbour was 2.6 µg L^{-1} which is about double the average for the few main lake stations sampled (1.3 µg L^{-1}). The pigment groups are associated with traditional taxonomic groups and give a version of the phytoplankton

composition. When comparing whole water column average pigment groups the main pigment in the lake was the brown pigment (average 65%) which is associated with the Diatoms (Fig. 3.4). The inner Toronto Harbour also had a much higher proportion of green pigments (32%) compared with stations outside the harbour (9%). Green pigments are associated mainly with Chlorophyta but also occur in other algal groups.

Sub-surface maxima in total chlorophyll *a* were seen almost exclusively at the deep offshore stations. These layers are shown in Fig. 3.5 and they coincide nicely with the large temperature transitional layers shown in Fig. 3.2.

August 2010
Whole water column chlorophyll *a* averaged 3.1 µg L^{-1} at the Toronto Harbour stations and 1.3 µg L^{-1} at the main lake stations. As in the September 2013 survey, brown pigment was the predominant contributor in the lake as measured by FluoroProbe contributing on average 47% to total chlorophyll *a*. As in the 2013 survey, green pigments were more dominant in the inner Toronto Harbour (48%) compared to the lake overall (27%).

Biological Parameters: Phytoplankton Biomass and Composition
September 2013
Phytoplankton biomass was low overall, ranging from 0.294 g m^{-3} at the nearshore Ashbridges Bay station (an upwelling station) to 1.38 g m^{-3} at the western gap (Table 3.3, Fig. 3.6). These values are considered ultra-oligotrophic on the scale devised by Munawar and Munawar (1982) with the exception of the western gap station which is oligotrophic. Biomass was mainly Cryptophyceae (8-64%) or Diatomeae (4-75%) with the exception of a large amount of Dinophyceae at 2 stations (western gap =79% *Peridinium* sp. and mid depth Ashbridges Bay Transect 49% *Ceratium hirundinella* Dujardin*;* Fig. 3.6). *Chrysochromulina parva* Lackey was found at all 9 stations and often contributed over 5% of the biomass at the station (Table 3.3). *Cryptomonas erosa* Ehrenberg contributed from 6-57% of total biomass at 7 of 9 stations while *Rhodomonas minuta nannoplanctica* Skuja contributed from a minimum of 1.8% to over 24% at all stations sampled. There were a variety of Diatom taxa identified with no one taxa present at all stations. *Cocconeis pediculus* Ehrenberg contributed 3 to 30% at the 4 stations where it was found, and *Synedra filiformis* Grunow and *Cyclotella comensis* Grunow were found at most stations, often contributing over 1% of the total biomass.

Species richness was highest in the inner harbour and Humber Bay STP outflow station and was lowest at the nearshore Ashbridges Bay station (Table 3.4). Richness in the inner harbour averaged 36.6 ± 1.7 taxa (n=3), while the outer harbour shallow stations averaged 28.75 ± 3.5 taxa (n=4) and lake wide Ontario nearshore stations averaged 27.72 ± 2.61 taxa (n=11, August 2013 survey, Munawar unpublished data). Shannon diversity (Magurran 1988) was lower in the inner harbour (1.89 ± 0.52; n=3) compared to the outer harbour shallow stations (2.15 ± 0.03; n=4). The inner harbor values were also low compared to lake wide Ontario nearshore samples taken in August 2013 (2.28 ± 0.11 (n=11); Munawar unpublished data) but not statistically different. Alpha algal biomass (Magurran 1988) showed similar patterns to species richness and Shannon diversity (Table 3. 4).

The Palmer water quality index scores (Palmer 1969, Table 3.4) were low indicating little organic pollution at all stations, but had the highest scores in the eastern and western gaps. These stations were also in areas where there was a lot of temperature layering and these shifts in stability would have collected organic detritus (Fig. 3.2).

The majority of taxa identified in the Toronto area were undefined using the saprobien index Kolkwitz and Marsson (1909) as this index is mainly used for periphyton and not phytoplankton. None of the taxa identified were saprophobic (tolerating pristine conditions only) or saprophilic (usually in polluted waters). Stations in nearshore Ashbridges Bay, mid shore Humber Bay, Don Mouth and Eastern Gap each had a single taxon (*Nitzschia palea*) belonging to SI-S2, which indicates preference for living in areas with high levels of pollution and/or considerable organic material present. Five stations (inner harbour and nearshore Humber Bay) had taxa tolerant of pollution but not of high DO content (*Cyclotella meneghiniana*, *Cyclotella atomus* and *Cyclotella silesiaca*). Most 'categorized' biomass was found to be oligosaprobic (S5) or mesosaprobic beta (S4) which by definition prefer highly oxygenated aquatic environments with moderate or little organic material. This is consistent with well mixed and oligotrophic Lake Ontario waters.
Most taxa were not named in the nitrogen uptake metabolism scale of Van Dam et al. (1994, 2002) and of those listed most are nitrogen autotrophs requiring dissolved inorganic nitrogen for growth. There was one facultative nitrogen-heterotrophic taxon (*Cyclotella meneghiniana)*, that needed the periodically elevated concentrations of organically bound nitrogen found at the Humber nearshore, Don Mouth and Eastern Gap stations. Humber Bay nearshore was the only area with an obligate nitrogen-heterotrophic taxon (*Nitzschia acicularis*). This taxon requires continuously elevated concentrations of organically bound nitrogen, in this case likely provided by the outflow of the Humber STP.

Biological Parameters: Size Fractionated Primary Productivity

September 2013

Total productivity was higher in the inner harbour (average =11.95 ± 5.0 mg C m^{-3} hr^{-1}) than in the west (average =4.4 ± 0.9 mg C m^{-3} hr^{-1}) and east (average =3.3 ± 1.3 mg C m^{-3} hr^{-1}). This is mainly due to the influence of the Don River inflow station which had a total productivity of 26.8 mg C m^{-3} hr^{-1} (Fig. 3.7). Excluding the Don inflow, the inner harbour stations averaged 6.9 ± 0.7 mg C m^{-3} hr^{-1}, still higher than the outer harbour stations. At all stations nanoplankton (2-20 µm size) contributed the most to total productivity (47-55%) and the netplankton (greater than 20 µm) contributed the least (4-8.5%) to total productivity.

Seasonal 2013

Productivity was measured at LO8 and LO9 in June, September and October 2013 (Fig. 3.8). Total productivity averaged about the same but variability was much greater at the shallower station over the season (average 2.6 ± 1.42 mg C m^{-3} hr^{-1} at LO8 and 2.66 ± 0.34 mg C m^{-3} hr^{-1} at LO9). Variability is known to be great in the nearshore zone as it is more influenced by runoff from precipitation events, air temperatures and onshore offshore circulation. As in the September cruise, netplankton contributed the least to total productivity (3-30%) while the nanoplankton (39-55%) and picoplankton (26-55%) contributed substantially more.

Biological Parameters: Microbial Loop Biomass

September 2013

The biomass of microbial loop components (APP, HNF and bacteria) during the September 2013 survey are shown in Fig. 3.9. Total biomass ranged from a low of 203 mg m^{-3} at the Don River mouth (with very low APP and relatively high HNF indicating an impaired station) to a high of 770 mg m^{-3} at the Western Gap where high HNF biomass accounted for the increase. This was the biomass of phytoplankton in the Harbour at this time (200-1380 mg m^{-3}) and to biomass across the lake in late August 2013 (225-1177 mg m^{-3} Munawar unpublished data). As expected for Great Lakes samples, bacteria were the largest component of the biomass with between 44-80% of the total but this was a higher proportion than found in the lakewide survey. APP contributed between 18-33% of the biomass and HNF were more variable with 0-36% of the total.

Seasonal 2013
Microbial loop biomass was highly variable when measured at the Humber Bay transect stations in June, August, September and October. Total average biomass ranged from a low of 144 mg m^{-3} in September during the Toronto Harbour survey to a high of 309 mg m^{-3} during the August survey. Average biomass by station was lowest at the nearshore (170 mg m^{-3}) and highest in the offshore (298 mg m^{-3}). There is so much variability it is hard to see trends although bacteria did increase over the season at the 2 deepest stations (Fig. 3.10).

Biological Parameters: Bacterial growth rates
September 2013
The potential growth rate determined for bacteria was much lower than the growth rate of the phytoplankton but showed a similar trend with much higher rates in the inner harbour (3.08 ± 1.01 mg C m^{-3} hr^{-1}) compared to the west (0.75 ± 0.36 1.01 mg C m^{-3} hr^{-1}) and east (0.08 ± 0.05 mg C m^{-3} hr^{-1}). The highest rate was found in the western gap (5.93 mg C m^{-3} hr^{-1}) which was more than 7 times the average in the west and 65 times higher than the average in the east (Fig. 3.7). The next highest rate was found at the eastern gap which may be explained by the higher number of temperature transition zones found in the gaps. These layers could trap plankton cells and other detritus on which bacteria would feed. Following this line of thought the offshore of Ashbridges Bay was higher than the nearshore stations and it had the most layering seen in the sampled water zone. Unfortunately, temperature profiles collected at water collection points in Humber Bay show decreased bacterial production with increased layering, but it is more likely the increase growth in the nearshore is related to proximity to the Humber Bay STP.

Seasonal 2013
Rates of bacterial growth were much lower than that of the algae averaging 0.33 ± 0.26 mg C m^{-3} hr^{-1} at LO8 and 0.04 ± 0.01 mg C m^{-3} hr^{-1} at LO9 (Fig. 3.8). As with the algae the nearshore station was much more variable than the offshore mainly due to high rates in September as was also seen in the algal productivity.

Summary and Conclusions
This region of Lake Ontario is a highly dynamic physical system (internal oscillations, upwelling) which affects the response of phytoplankton to other stressors such as nutrients and toxins (Haffner et al. 1984a). There were several intensive studies of phytoplankton in Toronto Harbour and area (Nalewajko 1966; Haffner et al. 1982 and 1984b; Munawar et al. 1993, 2003) and these historical studies gives some evidence for an impaired phytoplankton community in the inner harbour. These lines of evidence included:

- Total biomass consistently > 3 g m^{-3} (i.e. eutrophic)(Haffner et al. 1984b, Munawar et al. 2003, Munawar 1988 unpublished data)
- Euglenophyta and other pollution-tolerant flagellated forms dominating biomass at times (sewage outflows, Haffner et al. 1982, 1984b; Munawar et al. 1989a; Munawar et al. 2003, Munawar 1988 unpublished data)

The survey undertaken by DFO in September 2013 was influenced by the highly variable physical structure in the lake as it was undertaken during one of the largest upwelling events seen in 2012 and 2013 (B. Hlevca, University of Toronto, personal communication, 2015) and this confounds the analysis. A storm also came through between the second and third day's sampling further affecting the results.

The shallow, enclosed harbour is distinct from the main lake even with its very high flushing rate. In September 2013, phytoplankton biomass was typically < 1 g m^{-3} in the ultra-oligotrophic range and was higher in the inner harbour as was TP. Phytoplankton composition was highly variable between stations although there were a preponderance of flagellated forms (79% in inner harbour) which are able to move up and down in the water column and have the ability to deal with the complex physical structure in the area.

Primary productivity was generally low (< 5 mg C m^{-3} h^{-1}) and comparable to the open lake, except at the Don River mouth where it was quite high. Productivity of algae and bacteria were higher in the inner harbour compared to other stations. Dissolved organic carbon of algal origin is usually considered to be of high quality for bacterial use, as suggested by the pattern of increased bacterial production with increased primary production (Cole et al. 1988), even without an increase in nutrient in the higher production areas.

Ammonia levels were lower in the inner harbour while there was no trend in NO_3 between regions. As ammonia is selected by autotrophs ahead of nitrate (Neel 1979) the increase in phytoplankton biomass and productivity in the harbour can help to explain the lower levels found there.

It was expected that the shallow inner harbour with sediment laden inflow from the Don River and higher productivity than the main lake would result in higher light attenuation rates than outside the harbour, but the upwelling event caused the eastern measures to be lower than expected given the inflow from the STP in Ashbridges Bay. The upwelling was not as evident in Humber Bay as it was in Ashbridges Bay, probably due to the bathymetry of the area.

The September 2013 survey provides only a snapshot of current conditions in Toronto Harbour and area. Given the scarcity of recent data, comprehensive spatial and temporal assessment is needed to more fully understand the current status of phytoplankton in Toronto Harbour and area.

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Table 1.1: Corresponding taxonomic groupings of zooplankton based on Equivalent Spherical Diameter (ESD) measures from the LOPC.

ESD bin range [µm]	Likely zooplankton composition	Major Group
75-150	Larger Dreissenid veligers	Mollusca
	Some large protists (e.g. *Ceratium*)	Protista
	Larger rotifers (*Keratella*, *Synchaeta*)	Rotifera
	Chydorus	Cladocera
	Harpactacoid copepods	Copepoda
	Larger copepod Nauplii	…
151-300	*Bosmina* sp.	Cladocera
	Eubosmina sp.	…
	Alona sp.	…
	Cyclopoid copepodids (juvenile)	Copepoda
301-405	*Ceriodaphnia* sp.	Cladocera
	Polyphemus sp.	…
	Holopedium sp.	…
	Diacyclops thomasi (adult)	Copepoda
	Calanoid copepodids	…
406-600	*Daphnia* sp.	Cladocera
	Diaphanosoma	…
	Leoptodiaptomis sp.	Copepoda
		…
600+	*Cercopagis*	Predatory Cladocera
	Bythotrephes	…
	Leptodora	…
	Limnocalanus	Copepoda

Table 2.1: Sampling information for stations in the Toronto area during the August 2010 western Lake Ontario nearshore survey. Mean values and standard errors are given for surface temperature, secchi disk depth and turbidity (in bold). Chlorophyll *a* was only measured at three stations.

Station	Date	Lat. (N)	Long (W)	Sounding (m)	Chlor *a* ug.L^{-1}	Surface Temp C	Secchi (m)	Turbidity (NTU)	Zoopl. analyzed	Rotifers analyzed
Humber						**19.3 ± 2.4**	**3.0 ± 1.0**	**1.4 ± 0.7**		
K22	09-Aug-10	43°37.6408	79°28.0034	7.4	-	16.9	2.0	2.1	Yes	No
2047	12-Aug-10	43°37.5677	79°26.9036	13.8	2.8	21.7	4.0	0.8	Yes	Yes
Inner Harbour						**20.3 ± 0.2**	**2.9 ± 0.4**	**1.5 ± 0.5**		
TH1	12-Aug-10	43°38.0693	79°23.4252	6.5	-	20.7	4.0	0.9	Yes	No
726	12-Aug-10	43°38.0340	79°22.8550	7.7	-	20.3	3.5	1.1	Yes	No
1364	11-Aug-10	43°38.1061	79°22.2479	8.4	7.0	19.5	1.5	3.1	Yes	Yes
725	12-Aug-10	43°38.4572	79°21.7926	9.7	-	20.6	2.6	2.1	Yes	No
TH2	11-Aug-10	43°37.9297	79°20.4435	11.3	5.3	20.5	3.0	0.5	Yes	No
Ashbridges						**19.8 ± 0.6**	**6.0**	**0.5 ± 0.1**		
431	11-Aug-10	43°39.0804	79°18.7469	6.1	-	19.2	6.0	0.5	Yes	Yes
909	11-Aug-10	43°38.1770	79°18.5072	13.8	-	20.4		0.6	Yes	No
Offshore						**20.8 ± 0.4**	**5.8 ± 1.1**	**0.7 ± 0.0**		
1323	12-Aug-10	43°36.4650	79°26.0350	27.2	-	20.9	10.0	0.8	Yes	No
K23	12-Aug-10	43°35.9738	79°26.2198	39.3	-	21.9	6.0	0.6	Yes	No
TH3	11-Aug-10	43°36.6457	79°21.8215	8.8	-	19.5	4.0	0.6	Yes	No
TH4	11-Aug-10	43°36.2424	79°21.8379	36.1	-	21.2	4.0	0.7	Yes	No
TH5	11-Aug-10	43°36.9223	79°18.2756	69.7	-	20.7	5.0	0.6	Yes	No

Table 2.2. Summary of 2013 sampling depths for zooplankton net hauls and epilimnetic rotifers. Samples shaded in grey were collected but not counted; the rest were analyzed. The individual depth stratum samples (Epi=epilimion, Meta = metalimnion and Hypo = hypolimnion) were collected using a 64 µm net, whereas the total nets (T) were collected using a 153 µm net. "E+M" indicates total water column samples were made by pooling the 64 µm epilimnetic and metalimnetic nets and counted. The "-" symbol indicates this net was not collected. Study area abbreviations are explained in Figure 2.6.

			Sounding	Total	Zoopl. Strata Depths (m)			Rotifer
Date	Station	Region	Depth (m)	Net	Epi	Meta	Hypo	Depth (m)
September 2013 AOC Survey								
11-Sep	IH1	IH	9.6	E+M	0-3.5	3.5-8	-	0-8
11-Sep	1364	IH	8.4	E+M	0-3.5	3.5-7.5	-	0-5
11-Sep	L12	IH	9.0	E+M	0-3	3-8	-	0-4
09-Sep	IH13	IH	8.6	E+M	0-3.5	3.5-8	-	0-6
09-Sep	HB3	NS	5.3	T	0-4.5	-	-	0-4.5
09-Sep	LO8	NS	15.4	T	0-5	5-14	-	0-5
11-Sep	ST1	NS	9.7	E+M	0-3	3-8	-	-
09-Sep	TH3	NS	8.6	T	0-4.5	4.5-7	-	-
11-Sep	OH1	NS	11.3	T	0-4	4-10	-	-
09-Sep	AB2	NS	8.7	T	0-7.5	-	-	0-7
09-Sep	3508	Off	20.6	T	0-4	4-19	-	-
09-Sep	LO9	Off	59.4	T	0-5.5	5.5-15	15-58	0-5
09-Sep	TH4	Off	44.0	T	-	-	-	-
09-Sep	AB3	Off	42.0	T	-	-	-	-
13-Sep	AB1	East	7.0	T	0-6.5	-	-	0-7
13-Sep	1325	East	17.5	T	0-12.5	12.5-16	-	0-8
13-Sep	1326	East	71.0	T	0-12	12-25	25-70	0-8
13-Sep	708	East	15.8	T	0-6	6-11	11-15	0-6
13-Sep	1329	East	29.0	T	0-5	5-15	15-29	-
2013 CSMI Surveys								
12-Jun	LO8	NS	15	T	0-13	-	-	0-14
12-Jun	LO9	Off	60.8	T	0-25	25-35	35-59	0-20
24-Aug	LO8	NS	14.6	T	0-13	-	-	0-7
24-Aug	LO9	Off	60	T	0-6	6-10	10-58	0-6
21-Oct	LO8	NS	15	T	0-13	-	-	0-10
21-Oct	LO9	Off	60	T	0-10	10-14.5	14.5-57	0-10

Table 2.3: Number of zooplankton samples analyzed, mean total water column density and biomass (including standard errors) for each of the areas sampled in August 2010, August 2012 and Sept. 2013. Study area abbreviations are explained in Figure 2.6. Percent composition by biomass for the dominant zooplankton groups and taxa are also given.

	Aug. 2010				Aug. 2012	Sept. 2013			
	HB	**IH**	**Off**	**Ash**	**IH**	**IH**	**NS**	**Off**	**East**
No. samples	2	5	5	2	2	4	6	4	5
total density (No.L^{-1})	**9.7**	**57.3**	**56.5**	**52.4**	**25.6**	12.1	9.7	37.4	103.5
SE of Density	*37.6*	*14.0*	*8.2*	*49.4*	*3.8*	*2.4*	*3.0*	*9.9*	*40.5*
Total biomass (mg.m^{-3})	**18.2**	**65.5**	**105.8**	**42.9**	**42.7**	**8.3**	**6.3**	**41.5**	**74.3**
SE of Biomass	10.4	5.5	14.4	34.6	5.1	*2.1*	*1.7*	*11.8*	*33.9*
% Composition by biomass									
Cladocera	**69.8**	**67.9**	**69.6**	**67.6**	**91.2**	**62.0**	**56.7**	**27.9**	**39.8**
Bosmina sp.	1.2	11.3	1.5	3.8	8.8	28.7	29.0	10.5	16.0
Cercopagis pengoi	2.2	1.1	0.2	2.7	2.0	1.1	3.3	1.4	0.8
Ceriodaphnia lacustris	0.0	0.9	0.6	0.0	2.2	3.5	2.9	0.2	0.1
Chydorus sphaericus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Daphnia galeata	23.7	14.2	40.7	20.7	10.8	6.4	5.2	2.6	4.3
Daphnia retrocurva	12.6	37.2	23.4	20.3	25.2	16.9	8.1	10.1	15.0
Diaphanosoma sp.	0.0	0.2	0.0	0.0	0.3	0.5	0.0	0.0	0.0
Eubosmina sp.	0.9	1.1	0.7	4.9	16.9	2.8	3.4	1.3	1.8
Holopedium gibberum	3.2	0.2	0.9	10.8	24.6	0.5	2.4	1.0	1.2
Leptodora kindtii	19.8	0.8	1.2	3.0	0.2	0.1	1.2	0.7	0.6
Cyclopoids	**6.0**	**2.6**	**2.8**	**3.0**	**2.4**	**18.1**	**26.3**	**61.3**	**42.4**
copepodites	5.6	1.4	0.9	1.5	1.4	7.3	12.8	23.7	12.2
nauplii	0.4	0.5	0.4	0.4	0.1	5.2	4.6	4.9	9.0
Diacyclops thomasi	0.0	0.7	1.5	1.1	0.9	5.6	8.9	32.7	21.1
Mesocyclops edax	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Calanoids	**10.1**	**1.5**	**9.5**	**3.9**	**1.4**	**2.7**	**5.7**	**3.4**	**8.3**
copepodites	2.4	0.6	4.8	1.0	0.4	1.4	0.5	1.9	1.4
nauplii	0.5	0.3	0.2	0.1	0.2	1.3	0.2	0.1	0.3
Epischura lacustris	1.5	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
Leptodiaptomus sicilis	0.0	0.2	3.1	1.4	0.0	0.0	0.4	0.8	2.2
Limnocalanus macrurus	0.0	0.0	0.8	0.0	0.0	0.0	2.6	0.0	1.5
Skistodiaptomus oregonensis	0.6	0.0	0.1	0.0	0.3	0.0	0.4	0.0	2.7
other / unknown diaptomids	5.1	0.4	0.5	0.4	0.5	0.0	1.7	0.6	0.2
Veligers	**14.0**	**28.0**	**18.2**	**25.6**	**4.9**	**17.2**	**11.2**	**7.5**	**9.5**

Table 3.1: Station location and light attenuation information September 2013 survey. Some light attenuation values are missing due to logger error or low light levels during sampling (night).

Location	Latitude (N)	Longitude (W)	Station Depth (m)	Surface Temperature (°C)	Secchi Depth (m)	Light Attenuation rate (m^{-1})
WEST OF TORONTO HARBOUR						
3508	43° 34.363	79° 30.95	20.6	14	7	na
HB3	43° 37.861	79° 28.179	5.3	15.6	2	0.297
LO8	43° 37.40	79° 27.2	15.4	13.9	4.25	0.286
LO9	43° 35.200	79° 23.700	59.4	15.9	5.5	na
TH3	43°36.6457	79°21.8215	8.6	13.6	3	0.332
TH4	43°36.2424	79°21.8379	44	n/a	5	na
TORONTO HARBOUR						
MOE1364	43° 38.106	79° 22.248	8.4	16.2	2.5	0.379
L12	43° 38.611	79° 21.843	9	17	2	0.675
IH1	43° 38.053	79° 23.728	9.6	16.5	5	0.252
IH13	43° 38.189	79° 21.216	8.6	17	5	0.232
L10	43° 38.226	79° 22.948	7.3	16.6	2.7	0.616
ST1	43° 37.685	79° 24.456	9.7	17.6	5	0.332
OH1	43° 37.560	79° 20.912	11.3	15.6	3.5	0.332
TH1	43° 37.930	79° 20.444	9	16	na	na
EAST OF TORONTO HARBOUR						
AB1	43° 39.489	79° 17.730	7	10.7	5.5	0.229
AB2	43° 38.466	79° 18.967	8.7	11.1	7	0.208
AB3	43° 37.401	79° 18.028	42	n/a	8	na
1325	43° 39.013	79° 15.786	17.5	12.2	4	0.227
1326	43° 38.185	79° 14.964	71	13	5	0.224
708	43° 47.617	79° 5.100	15.8	14	na	0.198
1329	43° 45.674	79° 5.837	29	13.3	na	na
1330	43° 44.322	79° 3.408	65	15.5	na	na
1328	43° 46.404	79° 6.787	12.5	13	na	na

Table 3.2: Water chemistry parameters (mean ± SE mg L^{-1} unless otherwise indicated) and light attenuation from Toronto Harbour area 2013. LO8 and LO9 are monthly samples June-October while the remaining represent a wider range of stations sampled in September 2013.

	LO8 Seasonal June-October	**LO9 Seasonal June-October**	**West Outer Harbour Sep 9, 2013**	**Inner Harbour Sep 11, 2013**	**East Outer Harbour Sep 13, 2013**	**Spatial Survey All Stations**
n	4	4	3	4	3	10
Chl *a* extracted ($\mu g\ L^{-1}$)	**1.533**±0.643	**1.422**±0.341	**2.917±**0.49	**5.19** ±1.570	**1.82**±0.168	**3.497**±0.761
TP-P-UF	**0.113±**0.094	**0.014±**0.003	**0.023**±0.003	**0.035±**0.008	**0.020±**0.001	**0.027±**0.004
SRP-P-F	**0.003±**0.001	**0.002±**0.000	**0.002±**0.001	**0.003±**0.001	**0.008±**0.002	**0.004±**0.001
NO_3NO_2-F	**0.386±**0.048	**0.339±**0.035	**0.385±**0.046	**0.358±**0.006	**0.368±**0.009	**0.369±**0.013
TKN-N-F	**0.239±**0.008	**0.236±**0.009	**0.243±**0.014	**0.275±**0.034	**0.248±**0.002	**0.257±**0.014
NH_3-N-F	**0.018±**0.007	**0.015±**0.003	**0.012±**0.005	**0.003±**0.000	**0.020±**0.001	**0.010±**0.003
DIC	**20.93±**0.189	**20.78±**0.189	**21.23±**0.433	**21.90±**0.091	**21.23±**0.491	**21.50±**0.204
DOC	**2.500±**0.196	**2.500±**0.191	**3.100±**0.208	**4.300±**0.799	**7.133±**3.362	**4.790±**1.063
POC	**0.401±**0.125	**0.291±**0.059	**0.375±**0.017	**0.650±**0.115	**0.267±**0.036	**0.453±**0.070
PON	**0.051±**0.013	**0.046±**0.011	**0.069±**0.003	**0.118±**0.022	**0.045±**0.005	**0.082±**0.013
CA-F	**34.15±**0.357	**34.18±**0.466	**34.73**±0.769	**36.83±**0.330	**35.07±**0.088	**35.67±**0.394
NA-F	**15.38±**0.61	**14.70±**0.29	**17.23±**1.30	**19.03±**1.22	**18.90±**3.90	**18.45±**1.18
MG-F	**8.893±**0.094	**8.905±**0.063	**9.063±**0.081	**8.970±**0.031	**8.867±**0.027	**8.967±**0.035
SIO2-F	**0.813±**0.178	**0.685±**0.160	**0.803±**0.179	**1.088±**0.076	**0.830±**0.010	**0.925±**0.070
K-F	**1.780±**0.045	**1.730±**0.039	**1.910±**0.051	**1.825±**0.033	**1.773±**0.009	**1.835±**0.025
E_{PAR} (m^{-1})	**0.225±**0.031	**0.223±**0.008	**0.292±**0.006	**0.385±**0.102	**0.227±**0.001	**0.311±**0.048

Table 3.3: Phytoplankton percent biomass Toronto area September 2013.

	HB3	LO8	LO9	IH1	IH13	L12	AB1	1325	1326
total biomass (g m^{-3})	0.57	0.54	0.40	1.38	0.55	0.96	0.29	0.43	0.32
Cyanophyta									
Anabaena circinalis Rabenhorst					1.23				
Aphanocapsa delicatissima West & West	0.73	0.69	2.11	0.17	0.40	0.03	1.88	1.00	2.14
Aphanocapsa elachista West & West	0.08								0.53
Aphanocapsa holsatica (Lemmermann) Cronberg et Komarek		2.85	3.27	0.13	1.55	1.74	2.72	2.49	6.77
Aphanothece nidulans P. Richter	1.19	0.38	0.71	0.44	0.23			0.46	
Cuspidothrix issatschenkoi					1.52				
Cyanogranis ferruginea Hindak	0.00								
Microcystis aeruginosa Kutzing					0.62	0.11			1.07
Oscillatoria sp.				0.14					
Pseudanabaena limnetica Lemmermann				0.45			0.67		
Pseudanabaena sp.					3.13			5.74	
Rhabdoderma lineare W. Schmidle and R. Lauterborn				0.02				0.33	
Synechococcus elongatus Nageli	0.01	0.10	0.28				0.12	0.02	0.03
Synechococcus sp.	0.15	0.65	1.77	0.06	0.07	0.08	0.07	0.62	0.38
Synechocystis sp.	0.04	0.05			0.03	0.38	0.25	0.05	0.27
unknown cyanophyte	0.44	0.43	2.73	0.13	0.37	0.57	2.51	1.91	2.01
Chlorophyta									
Chlamydomonas sp.	3.50	3.14	2.24	0.87	1.29	1.82	2.66	3.44	3.30
Chloromonas prona (Ettl H. et O) Silva									
Closterium sp.					1.10	0.26			
Coelastrum microporum Naeg		1.30				1.14			
Cosmarium sp.									1.20
Dictyosphaerium pulchellum Wood						0.27			
Monomastix astigmata Skuja					0.01				
Monomastix minuta	0.02		0.10			0.04		0.04	
Monoraphidium arcuatum (Corda) Ralfs		0.05		0.01	0.12				
Monoraphidium capricornutum (Printz) Nygaard			0.10						0.12
Oocystis parva West & West	0.15	0.14	0.44	0.28		0.24		6.38	
Pediastrum boryanum longicorne Raciborski					4.39				
Pediastrum duplex West and West			1.81	0.89					
Scenedesmus abundans (Kirchn.) Chodat		0.13							
Scenedesmus bijuga (Turpin) Lagerh.					0.03	0.09		0.06	0.22
Schroederia setigera (Schroeder) Lemmermann				0.02					
Selenastrum minutum (Naegeli) Collins					0.21				

Chlorophyta (continued)	HB3	LO8	LO9	IH1	IH13	L12	AB1	1325	1326
Spermatozopsis exsultans Korschikoff									
Sphaerocystis schroeteri Chodat	0.68								
Staurastrum sp.									1.23
Stichococcus bacillaris Nageli					0.04				0.11
Tetraedron minimum (Braun) Hansgirg						0.27			
Treubaria setigera (Archer) G. M. Smith						1.65			
unknown Chlorophyte	0.86	0.54	0.12	0.54	0.52	1.34	1.74	0.85	0.30
Zygnema sp.					7.56				
Chrysophyta									
Bitrichia phaseolus (Fott) Fott		3.80							
Chromulina sp.	0.32	0.45	0.30	0.04	1.32	0.05	0.15	0.27	1.04
Dinobryon crenulatum West and West	0.32								
Dinobryon divergens Imhof			0.42						
Dinobryon sociale americana (Brunnthaler) Bachmann					1.34				
Dinobryon sp.	7.33		0.42	0.69	7.44	2.05	4.01		
Kephyrion sp.					0.20	0.14			
Mallomonas sp.	3.22	2.92	3.18	0.30	5.47	3.56			
Ochromonas sp.						0.27			
unknown Chrysophyte	0.29								
Haptophyta									
Chrysochromulina parva Lackey	3.09	9.43	5.82	0.59	5.07	3.00	3.90	5.36	9.76
Bacillariophyta									
Achnanthes minutissima Kutzing				0.07	0.15				
Asterionella formosa Hass.		0.11			0.23	0.09	0.10	2.47	2.29
Aulacoseira ambigua (Grunow) Simonsen		12.86							
Aulacoseira granulata (Ehrenb.) Simonsen	0.74								
Cocconeis pediculus Ehrenb.			7.57		3.09		30.09		6.39
Cyclostephanos invisitatus (M. H. Hohn & Hellerm.) Theriot, Stoermer & Hakansson		0.97		0.30					
Cyclotella atomus Hust.	0.15	0.17		0.03					
Cyclotella comensis Grunow	0.15	0.24	2.74	0.21		0.25	1.19	0.52	2.74
Cyclotella distinguenda unipunctata (Hust.)									0.69
Cyclotella meneghiniana Kutzing	7.45				3.06	2.38			
Cyclotella ocellata Pant.		0.24	0.81			0.17			
Cyclotella pseudostelligera Hust.		0.08			0.23	0.68			0.40
Cymbella sp.	0.18								
Cymbella silesiaca Bleisch						0.37			
Fragilaria capucina mesolepta Rabenh.				2.46					
Fragilaria capucina vaucheriae (Kutzing) Lange-Bertalot					2.62				

Bacillariophyta (continued)	HB3	LO8	LO9	IH1	IH13	L12	AB1	1325	1326
Fragilaria crotonensis Kitton			3.41				9.42	7.91	
Navicula salinarum Grunow	0.08								
Nitzschia acicularis (Kutzing) W. Smith	0.73								
Nitzschia fruticosa Hassall	0.36								
Nitzschia gracilis Hantzsch									
Nitzschia linearis (C. Agardh) W. Sm.				0.08					
Nitzschia palea (Kutz.) W. Sm.		0.18			0.25	0.46	0.35		
Skeletonema potamos (Weber) Hasle in Hasle & Evensen	0.85			0.09					
Stephanodiscus binderanus (Kutzing) Kreiger	1.20								
Stephanodiscus niagarae Ehrenberg									28.75
Stephanodiscus parvus Stoermer & Hak.	1.20								
Synedra filiformis Grunow	1.55	0.62		3.09	2.90		3.60	3.84	2.25
Tabellaria flocculosa (Roth) Kutz.									0.53
Cryptophyta									
Chroomonas sp.				0.14					
Cryptomonas erosa Ehrenberg.	49.65	41.01	30.53	6.45	27.58	57.73			7.96
Rhodomonas minuta Skuja		2.67	1.22		2.86	1.88		1.12	1.50
Rhodomonas minuta nannoplanctica Skuja	4.43	6.34	2.60	1.79	5.90	5.12	24.38	5.98	12.83
Pyrrhophyta									
Ceratium hirundinella Dujardin			25.29		3.48		3.48	42.71	
Gymnodinium helveticum		7.47					6.70	5.18	
Gymnodinium sp.				0.22	2.35	1.33		1.24	3.19
Peridinium sp.				79.21					
Peridinium umbonatum Stein	8.06					9.98			
Rhodophyta									
Bitrichia ochridana (Fott) Bourrelly	0.39			0.06					
Miscellaneous									
unknown	0.36			0.05		0.43			

Table 3.4: Phytoplankton diversity indices based on biomass. Toronto Harbour survey September, 2013.

	HB3	LO8	LO9	IH1	IH13	L12	AB1	1325	1326
Species richness	38	30	26	34	40	36	22	25	30
Palmer water quality index	10	10	4	12	12	9	7	4	4
Shannon diversity (biomass)	2.087	2.1482	2.2645	1.0211	2.818	1.8535	2.1857	2.2057	2.5449
Evenness based on Shannon (biomass)	0.4819	0.5247	0.5731	0.242	0.6431	0.4334	0.5776	0.5638	0.6216
Alpha algal biomass	3.14	2.4375	2.1445	2.5774	3.3288	2.8268	1.8355	2.0398	2.556

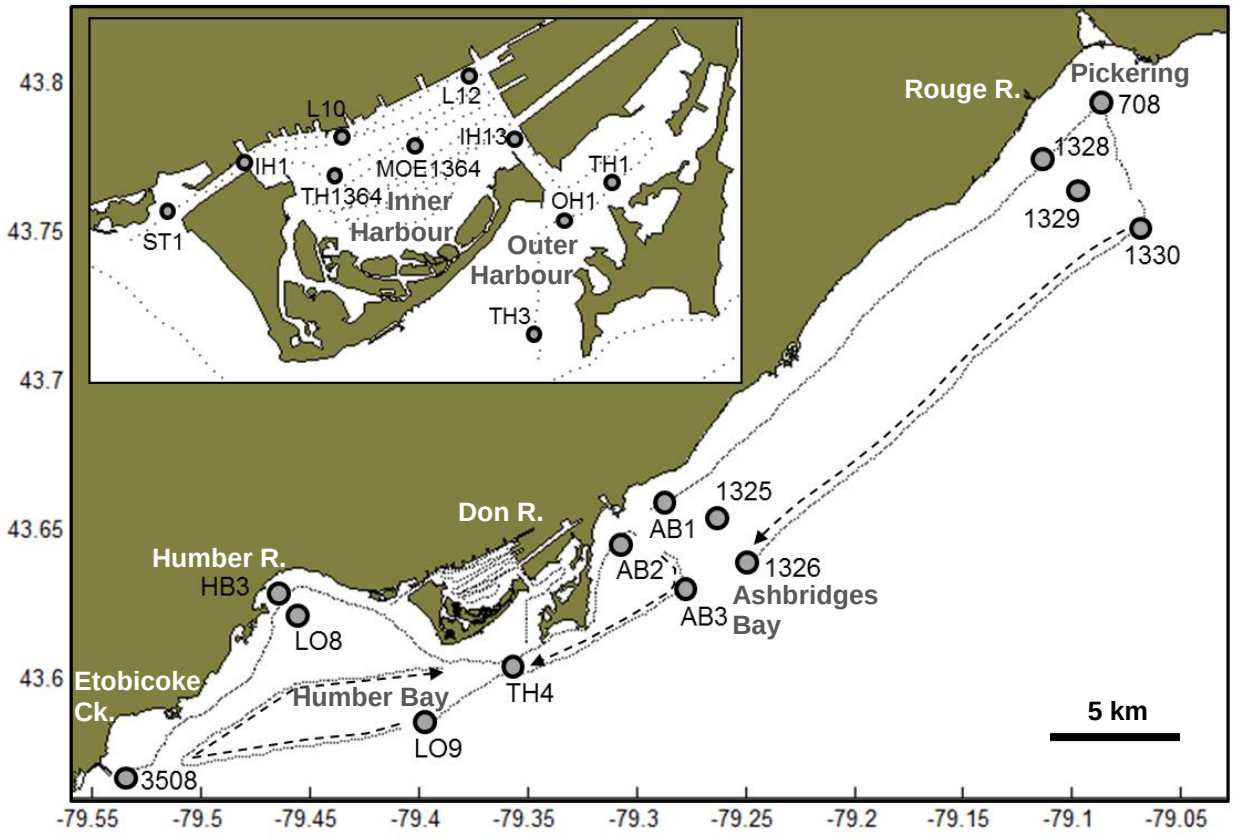

Figure 1.1: Map of Toronto Region Area of Concern towed plankton survey. Inset shows a magnified view of the Inner Toronto stations. Filled circles indicate stations locations of whole water column vertical profiles. The dotted line indicates the towed epilimnetic survey at 3m depth. The dashed line indicates the tow-yo transects from the surface-25m depth.

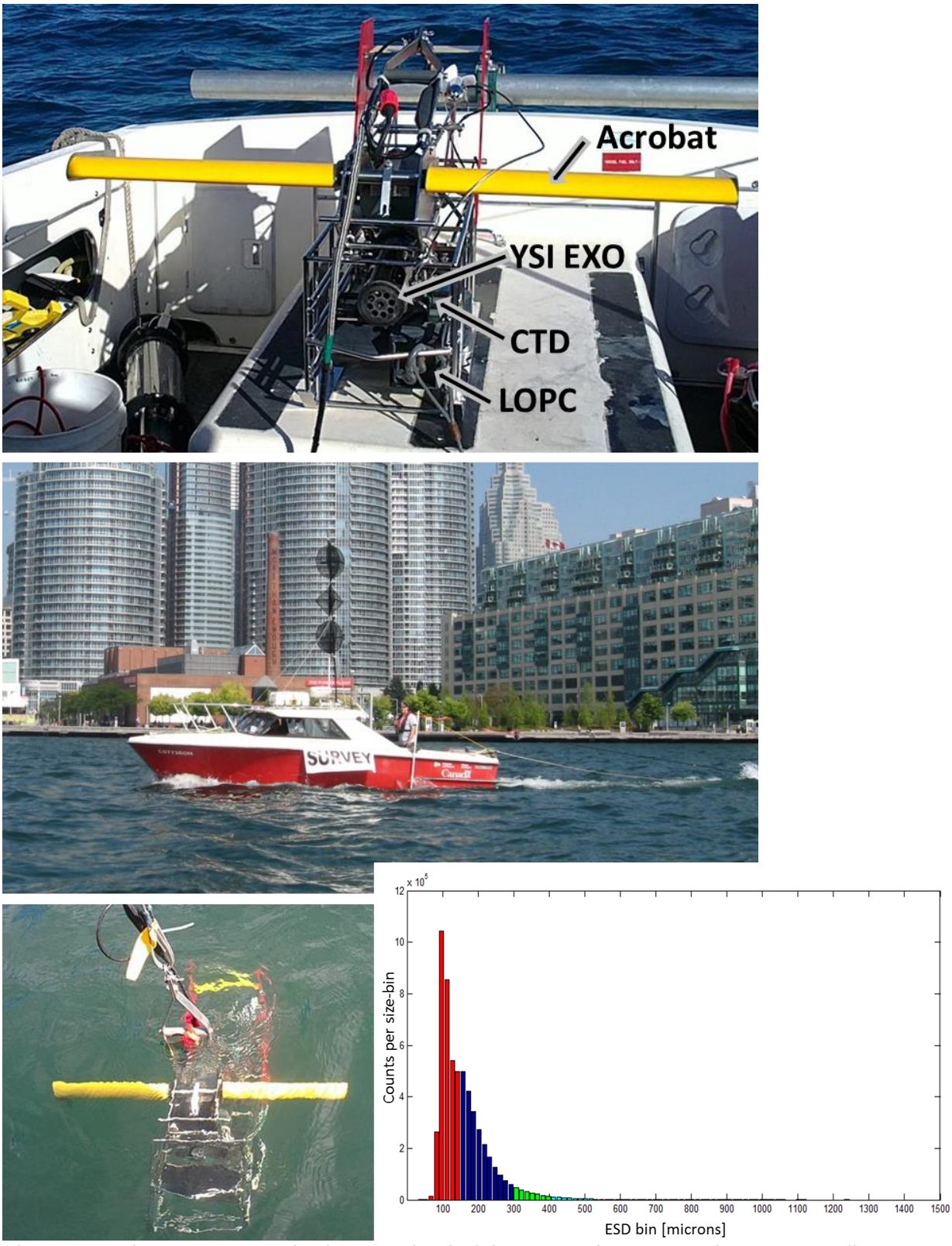

Figure 1.2: The SHRIMP towbody comprised of the Sea Sciences Acrobat, CTD, Rolls Royce HR-LOPC, and YSI EXO2 sonde towed from DFO's Leslie J. Inset graph shows a particle size-distribution with largest counts in the 91-105 µm Equivalent Spherical Diameter bin (see text).

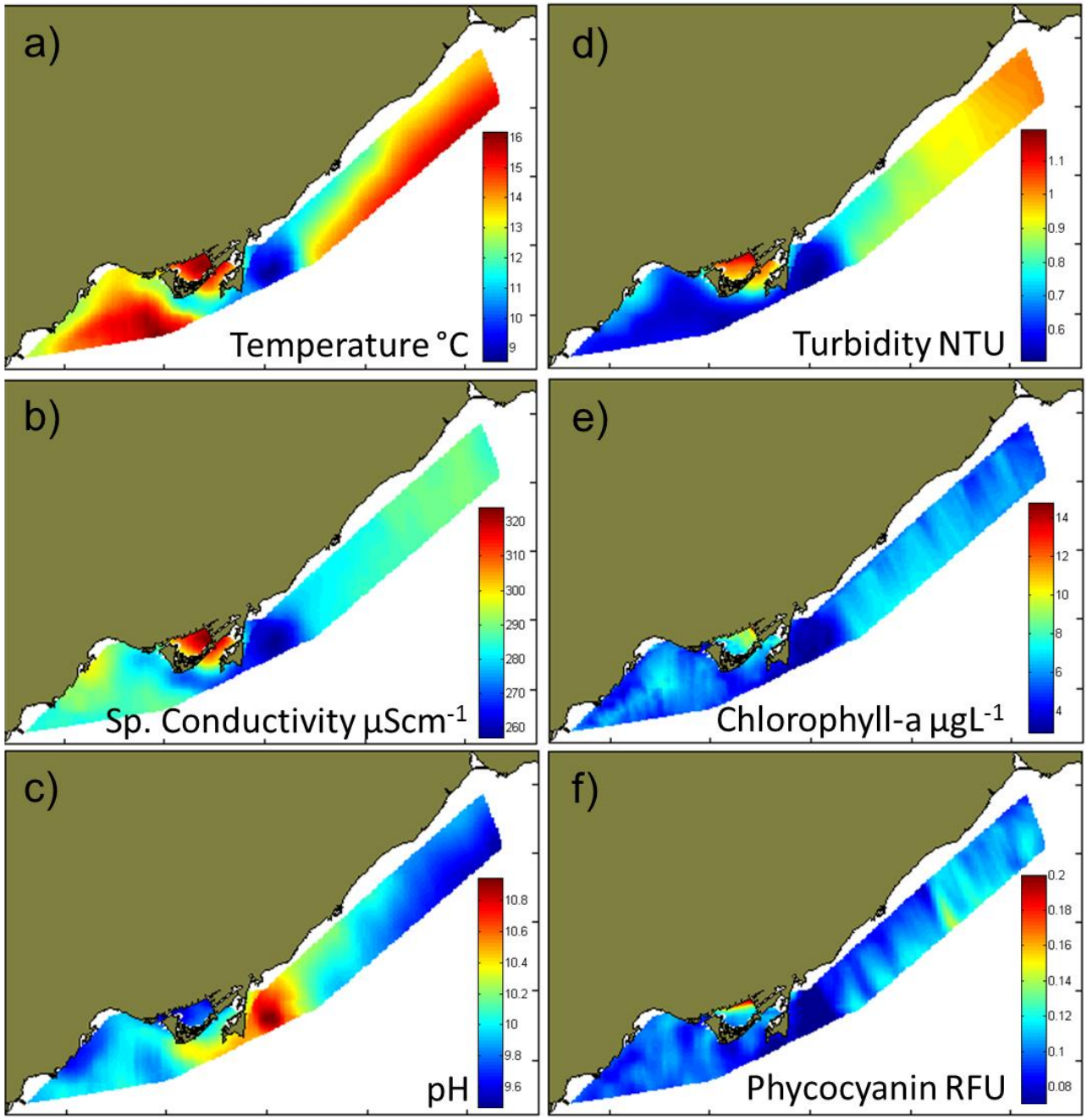

Figure 1.3: Maps of epilimnetic tows of the Toronto Region AOC for physical-chemical properties: Temperature, Specific Conductivity, pH, Turbidity, Chlorophyll-a and Phycocyanin. Interpolations between the tow tracks are done using MatLab's griddata function. The upwelling is clearly visible to the east and around Toronto Harbour.

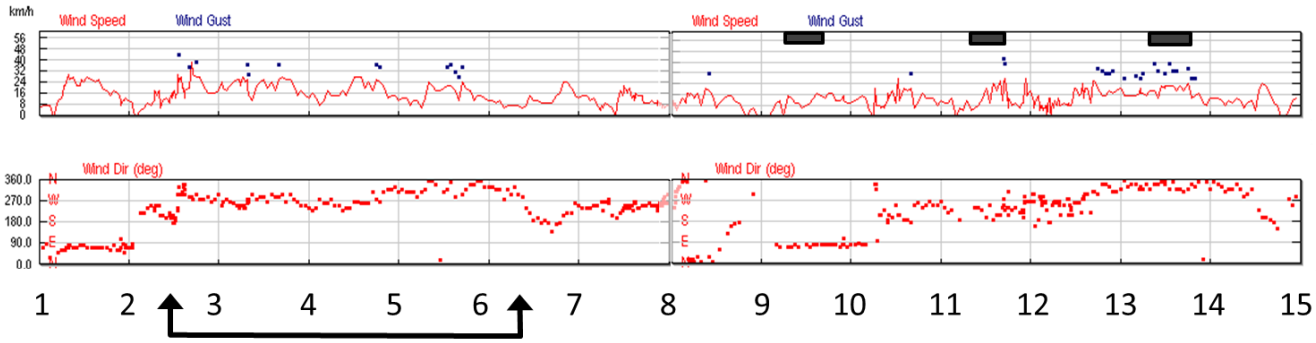

Figure 1.4: Wind speed (km/h) and direction (degrees) at Toronto Pearson Airport for Aug 1-15, 2013 (from WeatherUnderground.com). The period of persistent westerly winds (270°) is given by the bold arrows below the graphs. Times when transects were being undertaken is given by the black bars above the graphs.

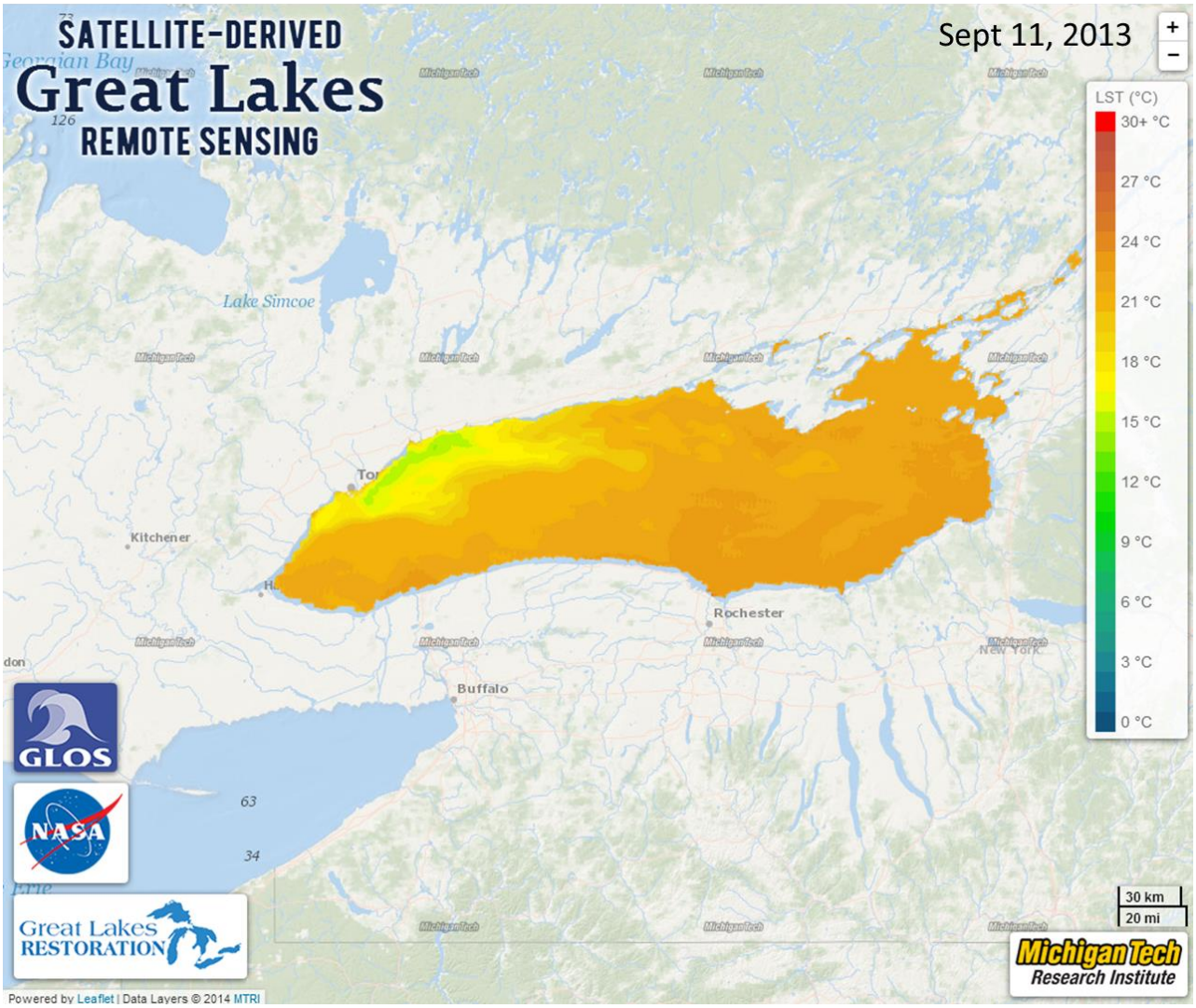

Figure 1.5: Screenshot of remotely sensed lake temperature from the MODIS satellite taken from Michigan Tech Research Institute portal (www.greatlakesremotesensing.org) for Sept. 11, 2013 clearly showing a widespread coastal upwelling to the east of Toronto.

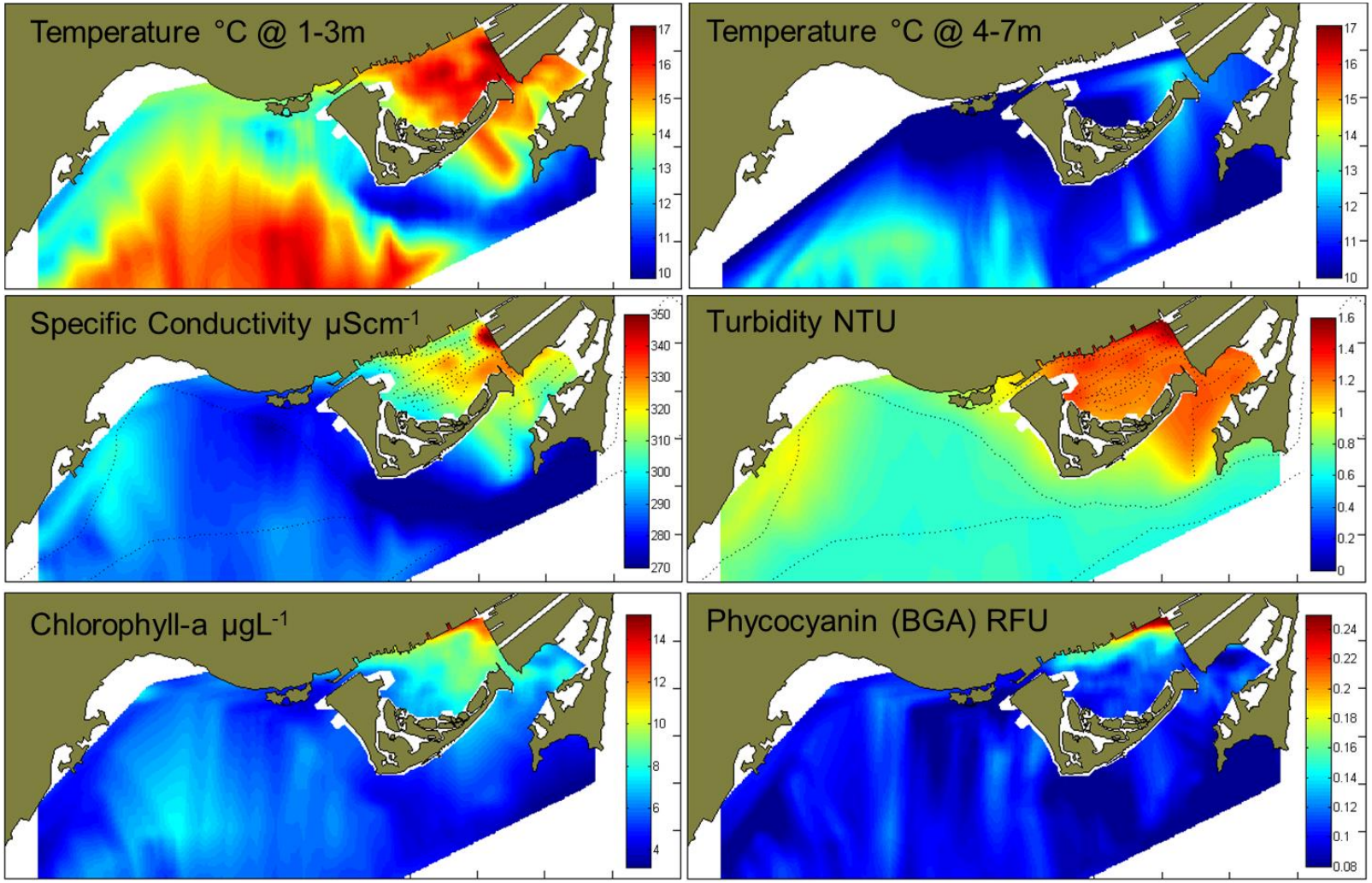

Figure 1.6: Magnified maps of interpolated epilimnetic tows surrounding Inner Toronto Harbour for physical-chemical properties: Epilimnetic Temperature (1-3 m depth), Hypolimnetic temperature (4-7 m depth), Specific Conductivity, Turbidity, Chlorophyll-a and Phycocyanin. The upwelling is clearly visible around Toronto Harbour, intruding into the nearshore of Humber Bay near the western gap of the inner harbour. Cold hypolimnetic water coming in from the west can be seen in western portion the inner harbour along the islands and also along the inner southern coast of the Leslie spit. Both chlorophyll-a and phycocyanin values are highest nearest the Don River extending along the Toronto waterfront.

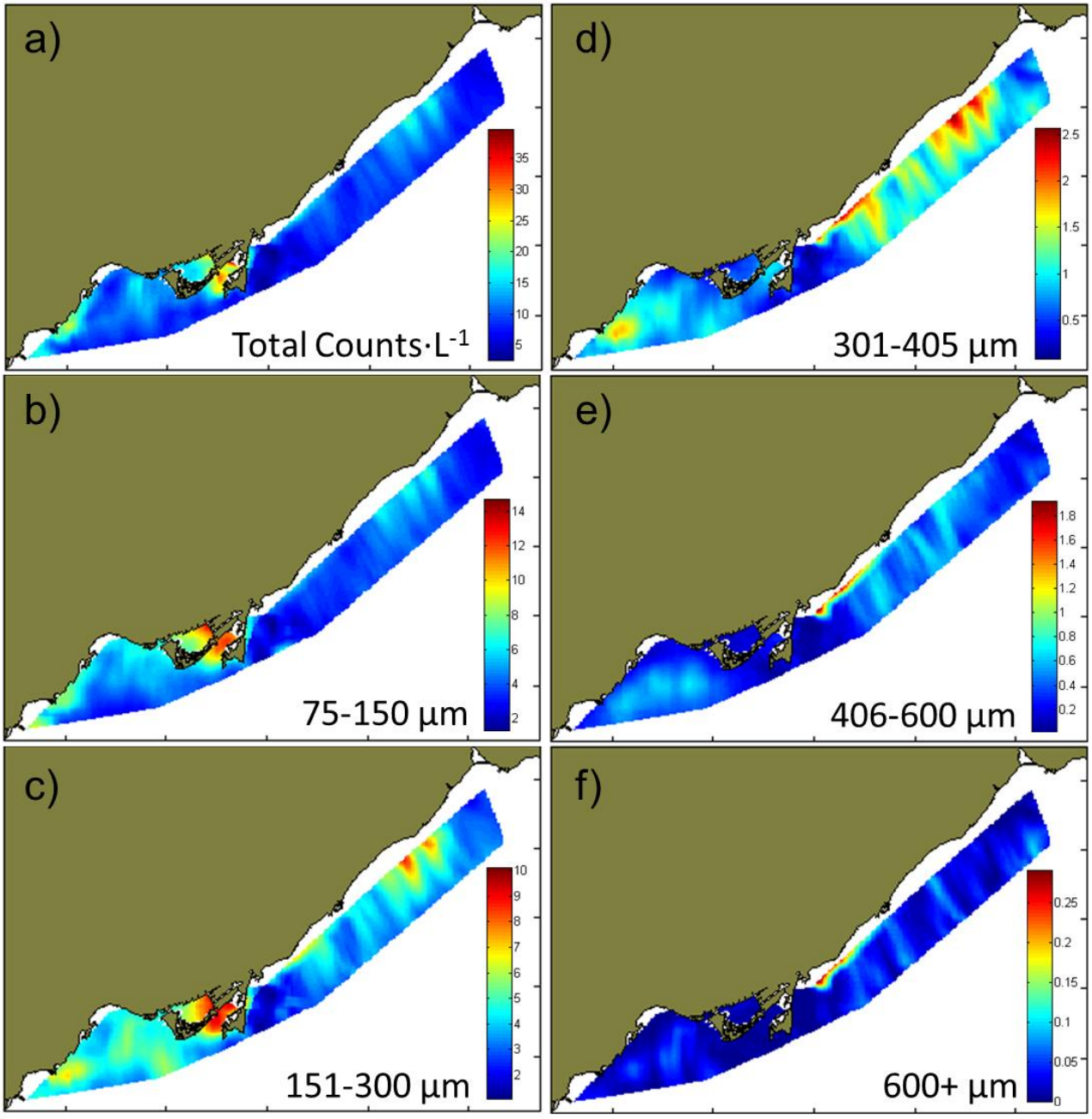

Figure 1.7: Maps of interpolated epilimnetic zooplankton counts·L^{-1} by size-bin from the High Resolution Laser Optical Plankton Counter (HR-LOPC) for the Toronto Region AOC out to the 60m isobath. Total counts and bin sizes are given on the panels. Smallest particles account for the highest percentage of the total counts with increasing size bins being successively rarer. Smallest particle sizes are higher in the inner harbour and outer harbour whereas larger-sized zooplankton are very rare in these areas and only found within the lake.

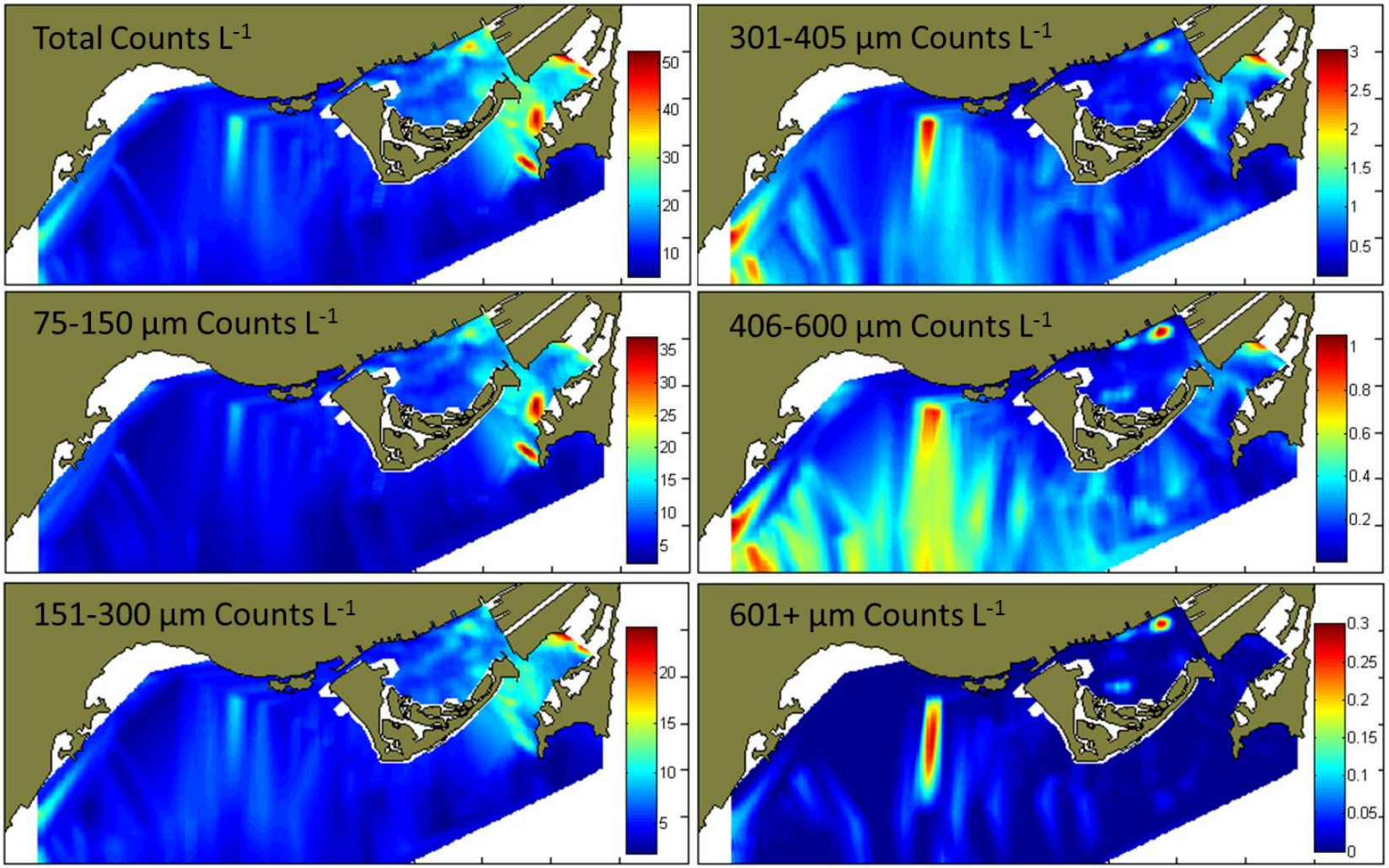

Figure 1.8: Magnified maps of interpolated epilimnetic zooplankton counts·L^{-1} by size-bin from the High Resolution Laser Optical Plankton Counter (HR-LOPC) for the area surrounding Toronto Harbour (see Fig. 1.7). Total counts and bin sizes are given on the panels. Counts of larger zooplankton size categories are only found within the inner harbour at one location along the waterfront near the entry of the Don River. A number of patches of smaller-sized zooplankton particles are found within in the inner and outer harbour, but not within the lake. Streaking of the patches outside of the harbour are due interpolation of the distances between the tow tracks (see Fig. 1.1).

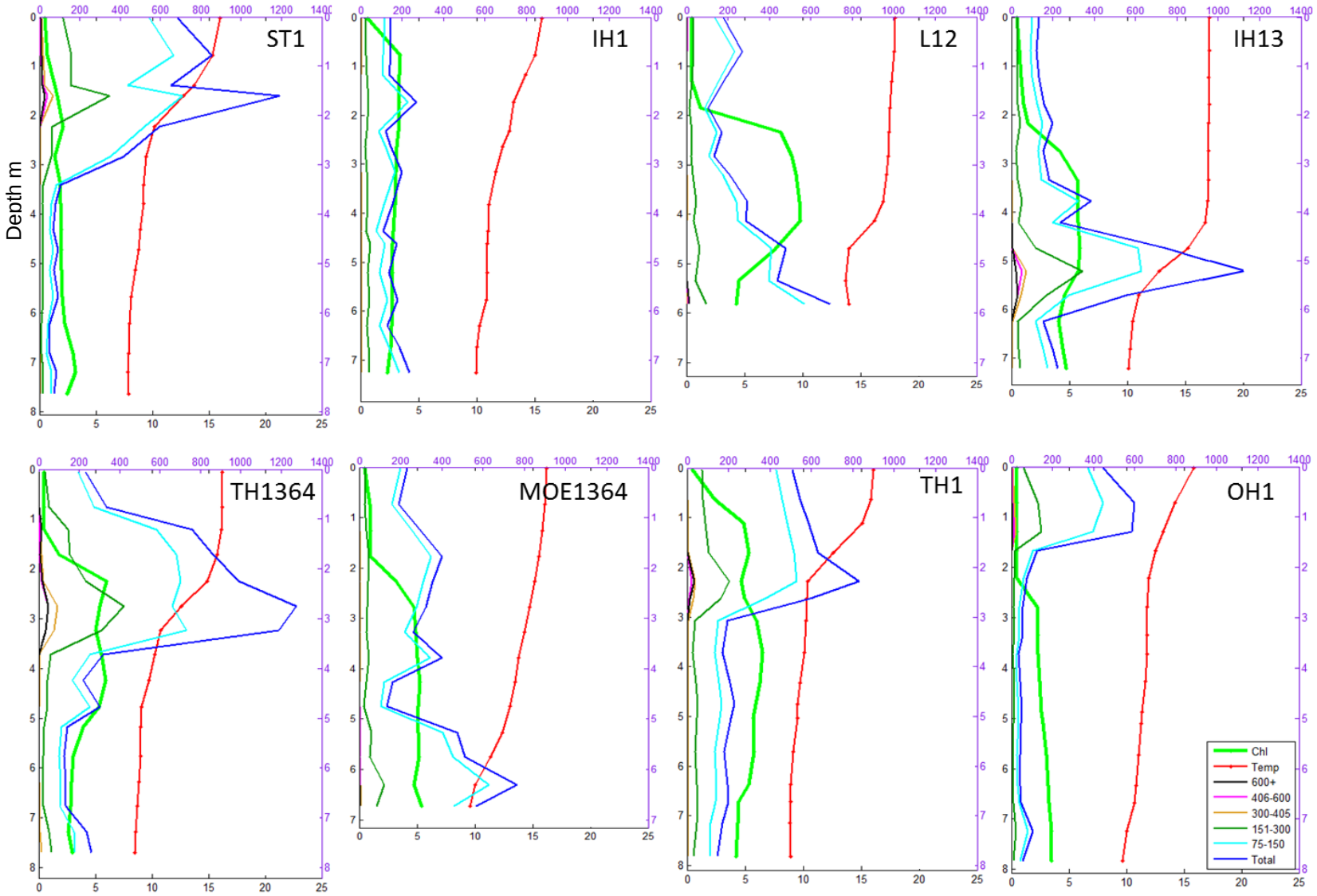

Figure 1.9: Vertical profiles at stations (Fig. 1.1) using of the HR-LOPC within and around Toronto Harbour for temperature (red), chlorophyll-a (green), total counts·L^{-1}, and counts per size-bin. Stations are arranged from west (on left) to east (on right). Profiles on the western side of the Inner Harbour and in Outer Harbour have shallower mixed depths and reduced temperatures.

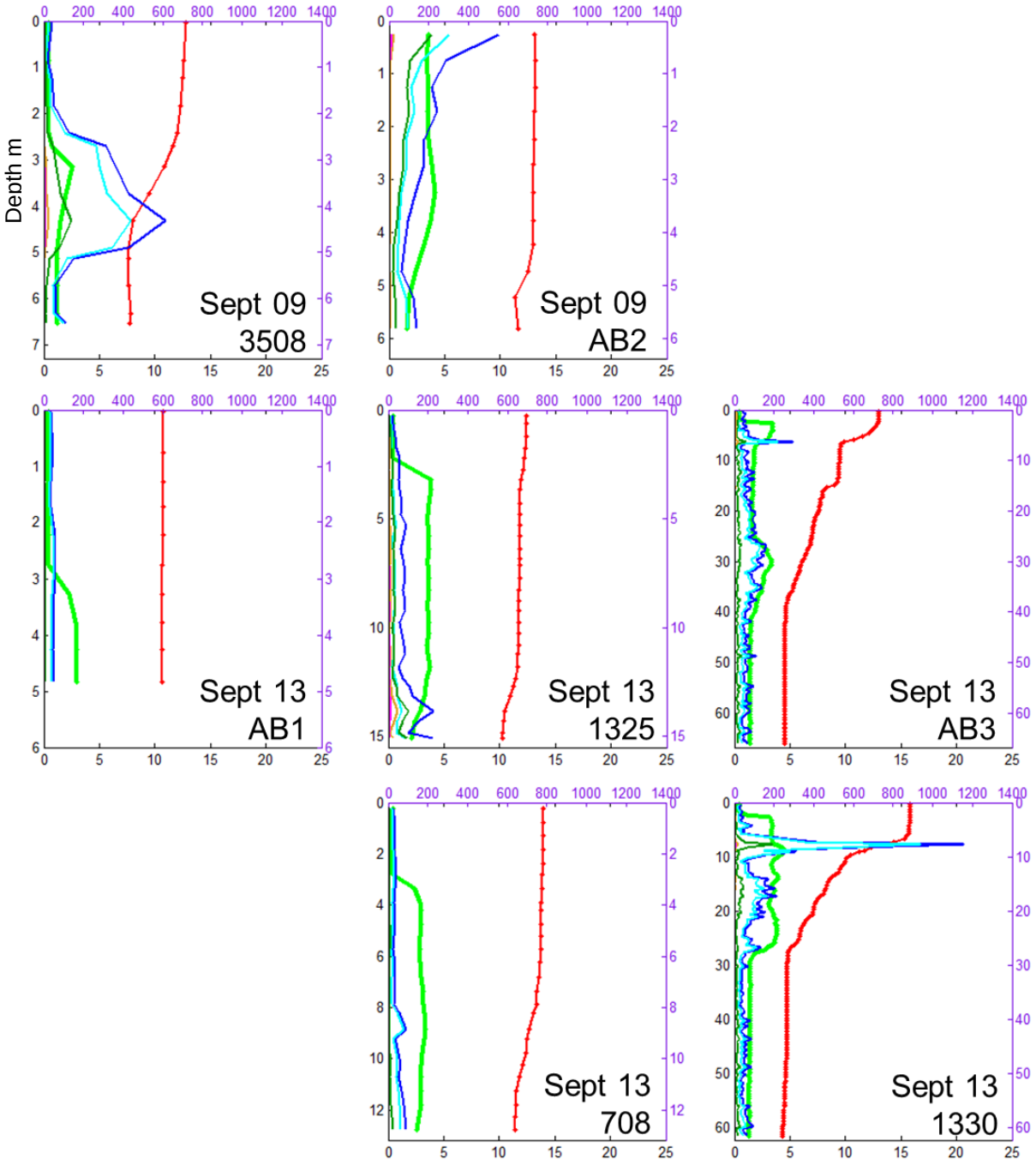

Figure 1.10: Vertical profiles at stations (Fig. 1.1) using of the HR-LOPC to the west (top) and east (middle and bottom) of Toronto Harbour for temperature (red), chlorophyll-a (green), total counts·L^{-1}, and counts per size-bin. Profiles are arranged from nearshore (left) to offshore (right) Profile dates are indicated on each panel.

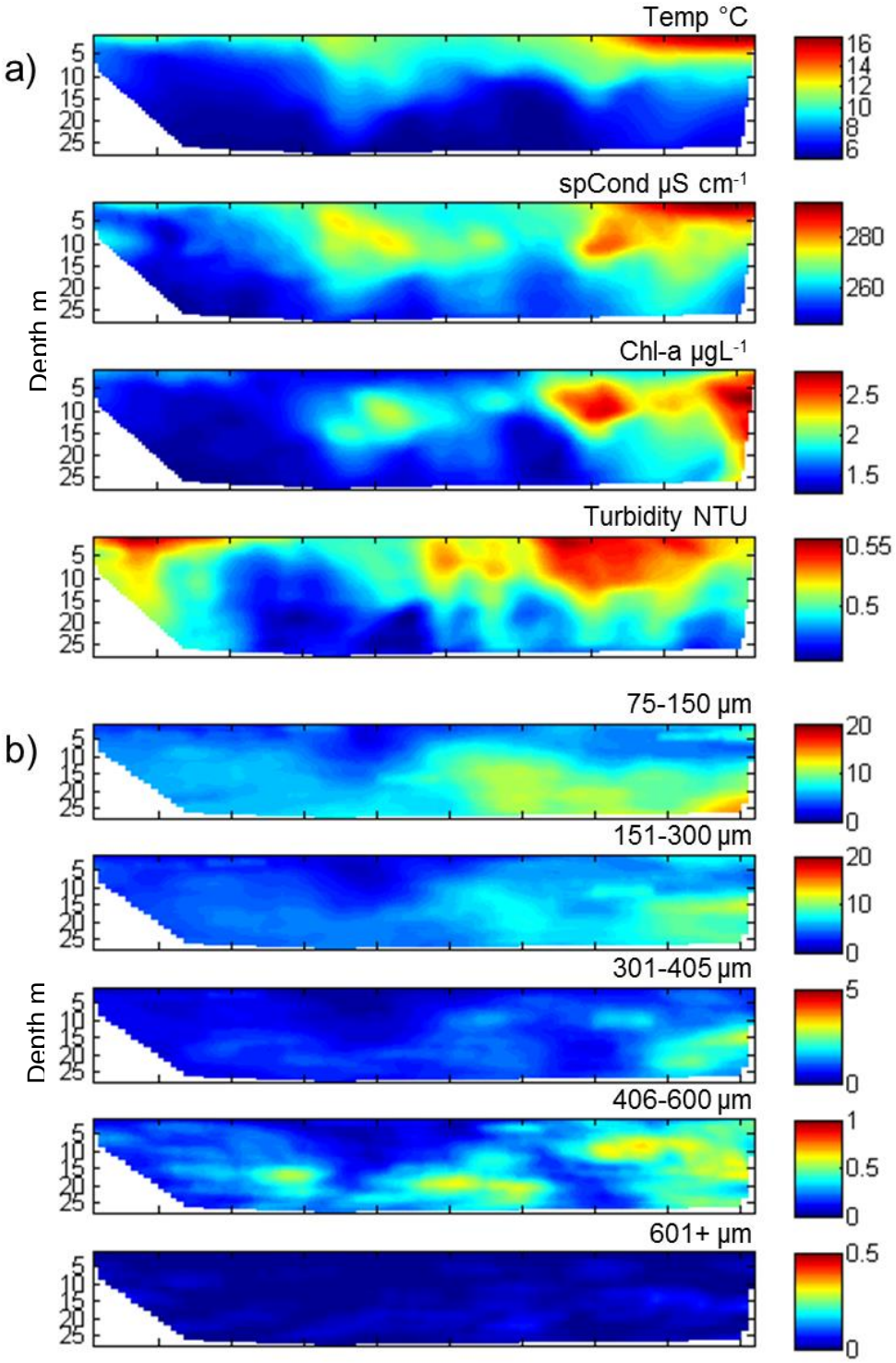

Figure 1.11: Tow-yo of surface-25m or 2m above bottom on Sept. 9 from nearshore AB2 to TH4 (see dashed line Fig. 1.1) using griddata interpolation in MatLab with 0.25m vertical bins for (a) temperature, specific conductivity chlorophyll-a, turbidity and (b) zooplankton particle size-bin counts·L^{-1}. Transect begins in the cold upwelling region with extremely low zooplankton counts and ends near the entry to Outer Harbour with surface temperatures >10 °C than the start of the transect and increased zooplankton counts especially in the larger size categories.

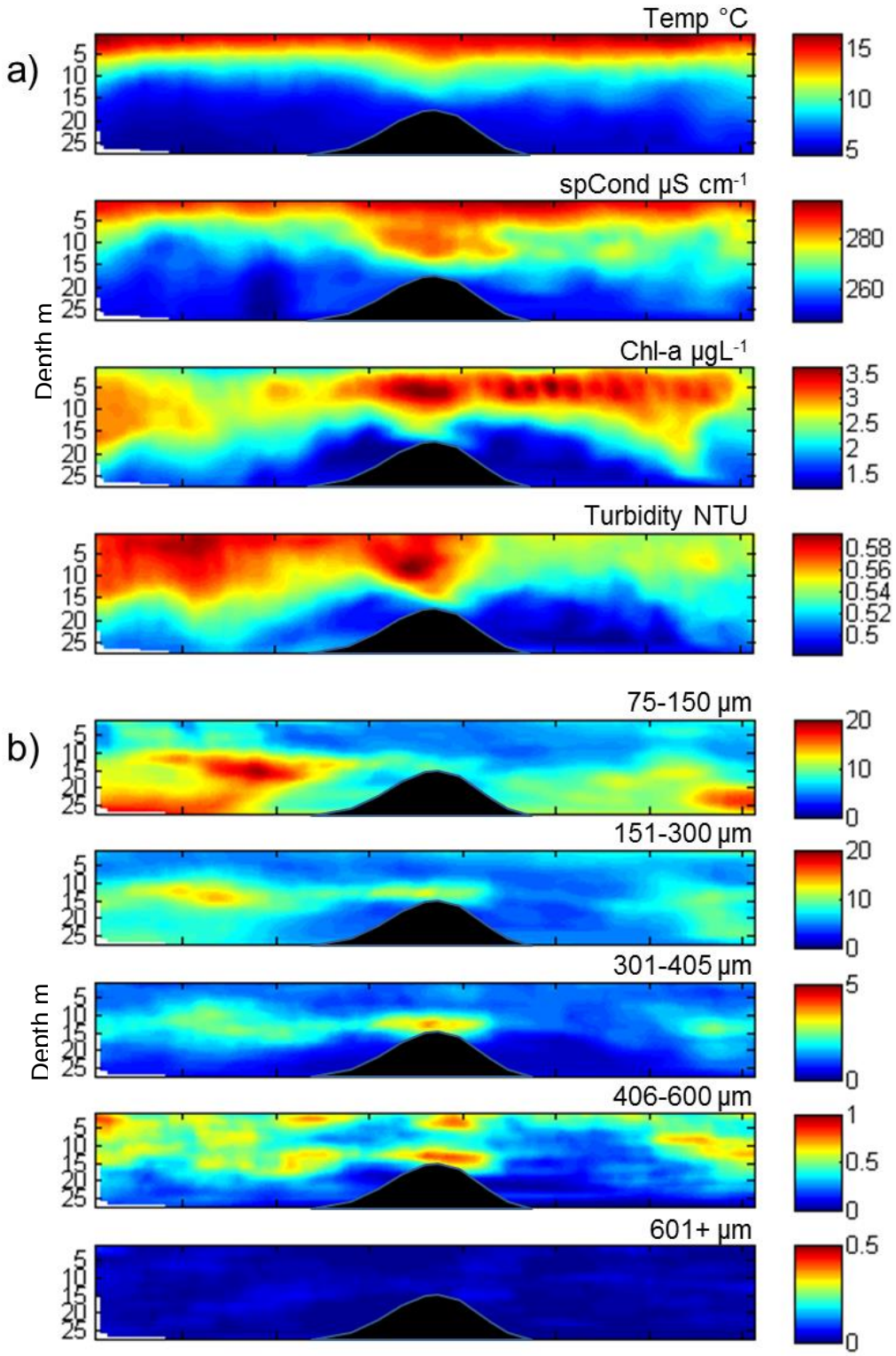

Figure 1.12: Tow-yo of surface-25m or 2m above bottom on Sept 9 from offshore L09 to nearshore 3508 and back across Humber Bay (see dashed line Fig. 1.1) with similar output to Fig. 1.11. The water column is consistently stratified along the transect but deeper chlorophyll-a and zooplankton counts are found on the first half (offshore leg). Two layers of large-size counts are seen ~5m and ~15m which are likely to be different zooplankton groups.

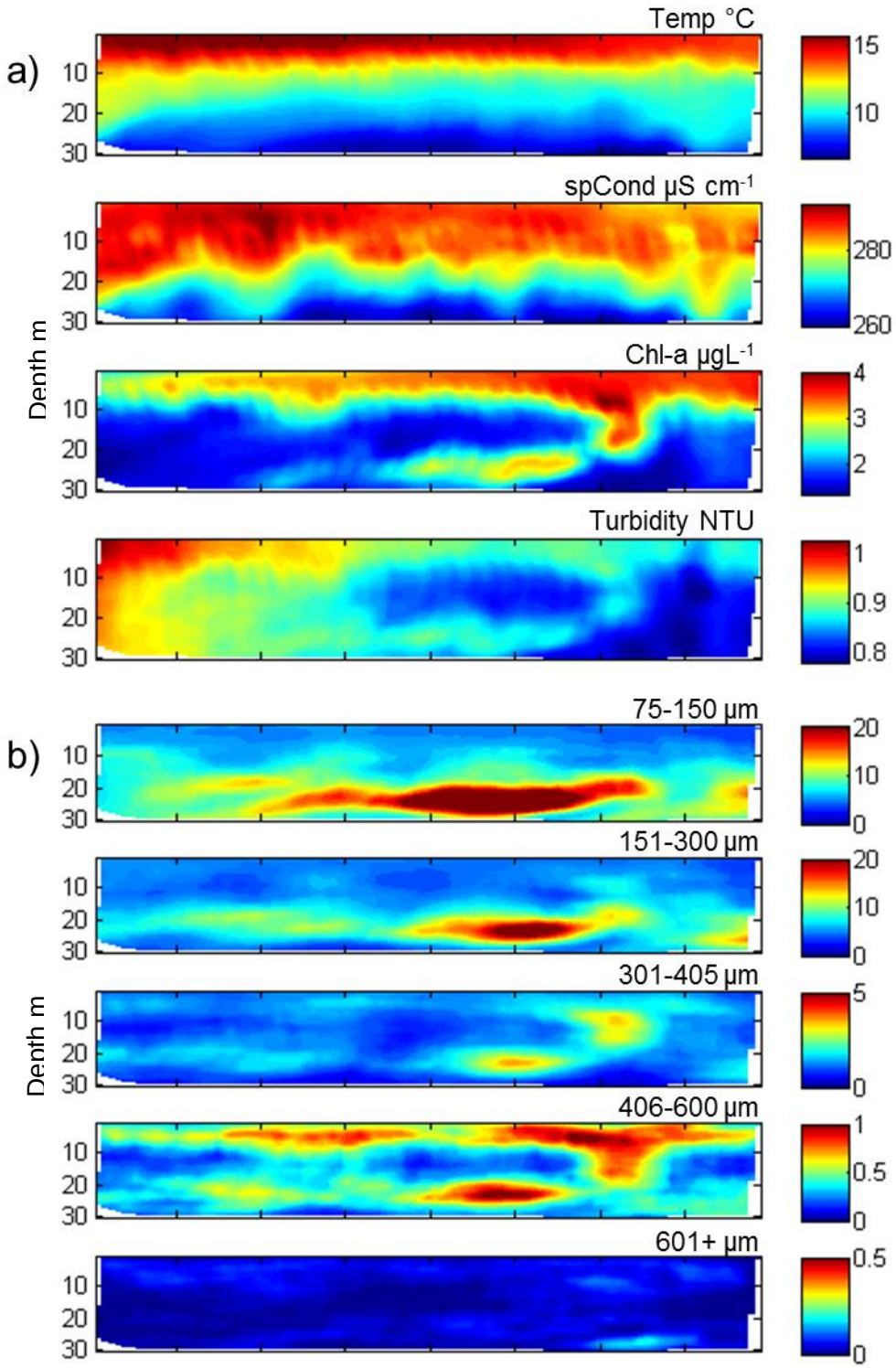

Figure 1.13: Tow-yo of surface-30m on Sept 13 from offshore Pickering 1330 to 1326 offshore Ashbridge's Bay (see dashed line Fig. 1.1) with similar output to Fig. 1.11. The water column is more deeply stratified near the beginning of the transect. The chlorophyll-a and turbidity signal suggest a downwelling near the end of the transect (vertical plume) which may be associated with the edge of the upwelling. Two layers of zooplankton counts are seen ~5m and ~25m which are likely to be different groups, but smaller size bins are only seen at depth.

Figure 1.14: Photo of the Lake Ontario whiting event on Aug 24, 2013 from the International Space Station (courtesy Karen Nyberg) with stations for DFO's Western Basin Transect for the 2013 CSMI year. The northern two stations marked in yellow are L09 and L08 (see Fig. 1.1). Note that the whiting event, shown by the bright blue colour is absent around Toronto Harbour along the northwestern coast of Lake Ontario. The whiting becomes more prominent near the eastern end of the transect at Pickering (given by dashed box) and offshore at this location.

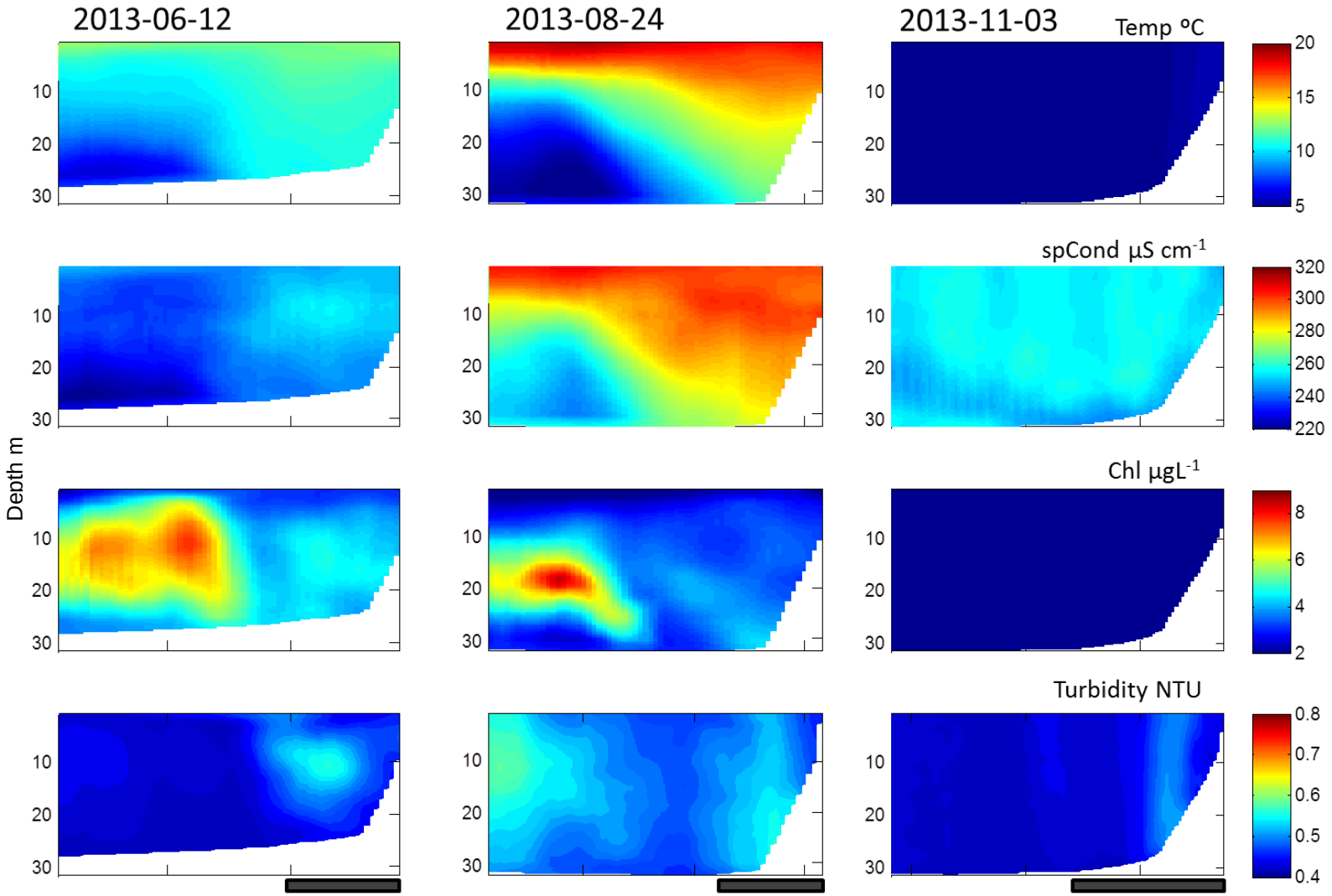

Figure 1.15: Tow-yo of surface-30m from DFO's CSMI 2013 Western Basin Transect for the northern half of Lake Ontario (see Fig 1.14) for physical-chemical values of temperature, specific conductivity, chlorophyll-a and turbidity. Surveys took place in June, August and November. The black bar at the bottom represents the section from LO9-LO8 in Humber Bay. Humber Bay is deeply mixed compared to the offshore and lacks the deep chlorophyll maximum (DCM) found in the offshore.

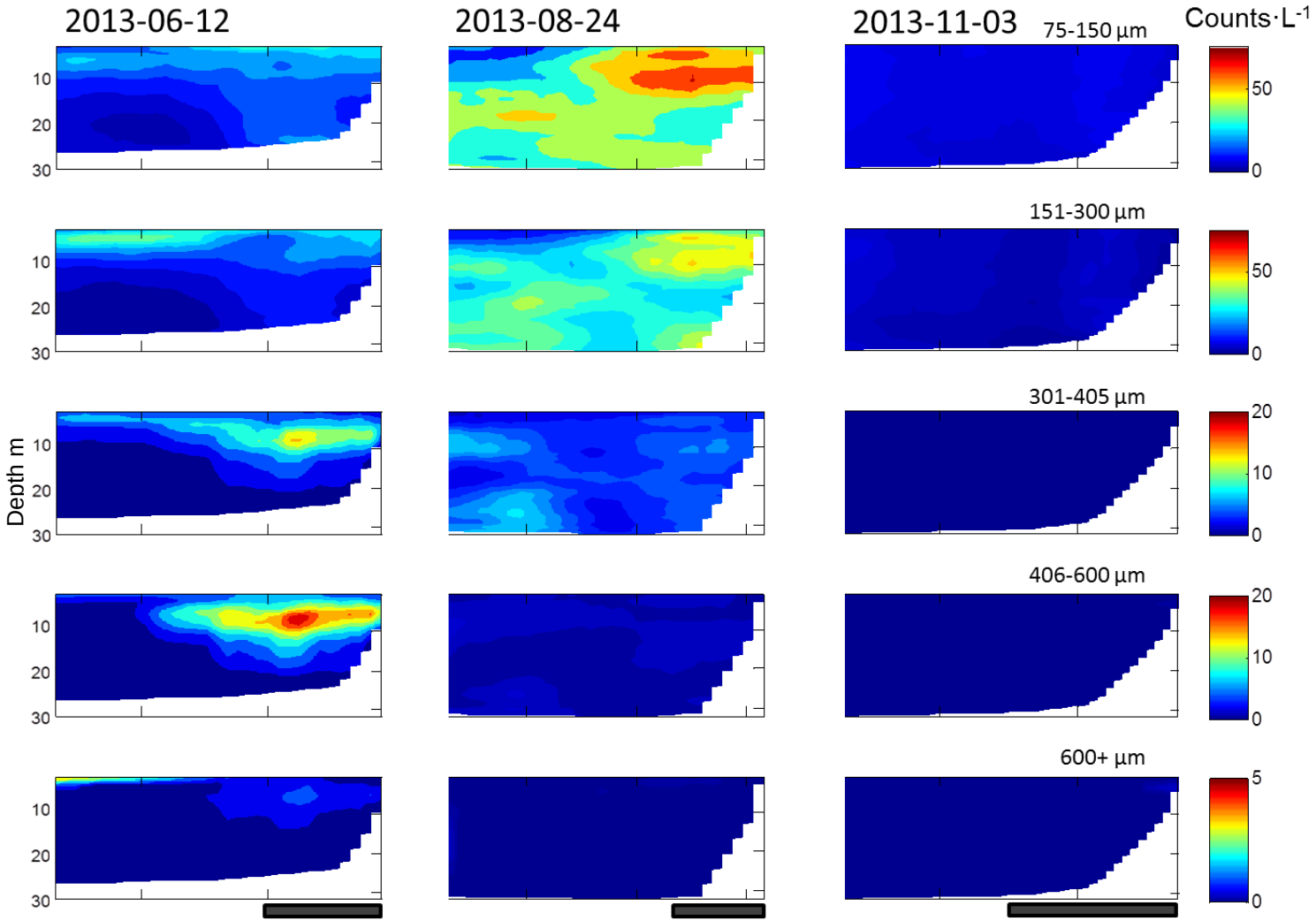

Figure 1.16: Tow-yo of surface-30m from DFO's CSMI 2013 Western Basin Transect for the northern half of Lake Ontario (see Fig 1.14) for zooplankton particle counts·L^{-1} by size-bin from the High Resolution Laser Optical Plankton Counter (HR-LOPC). The black bar at the bottom represents the section from LO9-LO8 in Humber Bay. Counts of larger zooplankton are found inside Humber Bay are seen in June (likely copepods) in a thin-layer at depth, but only very small sized zooplankton are found near surface during the summer. Extremely low counts of all size categories are found during November just after lake turnover.

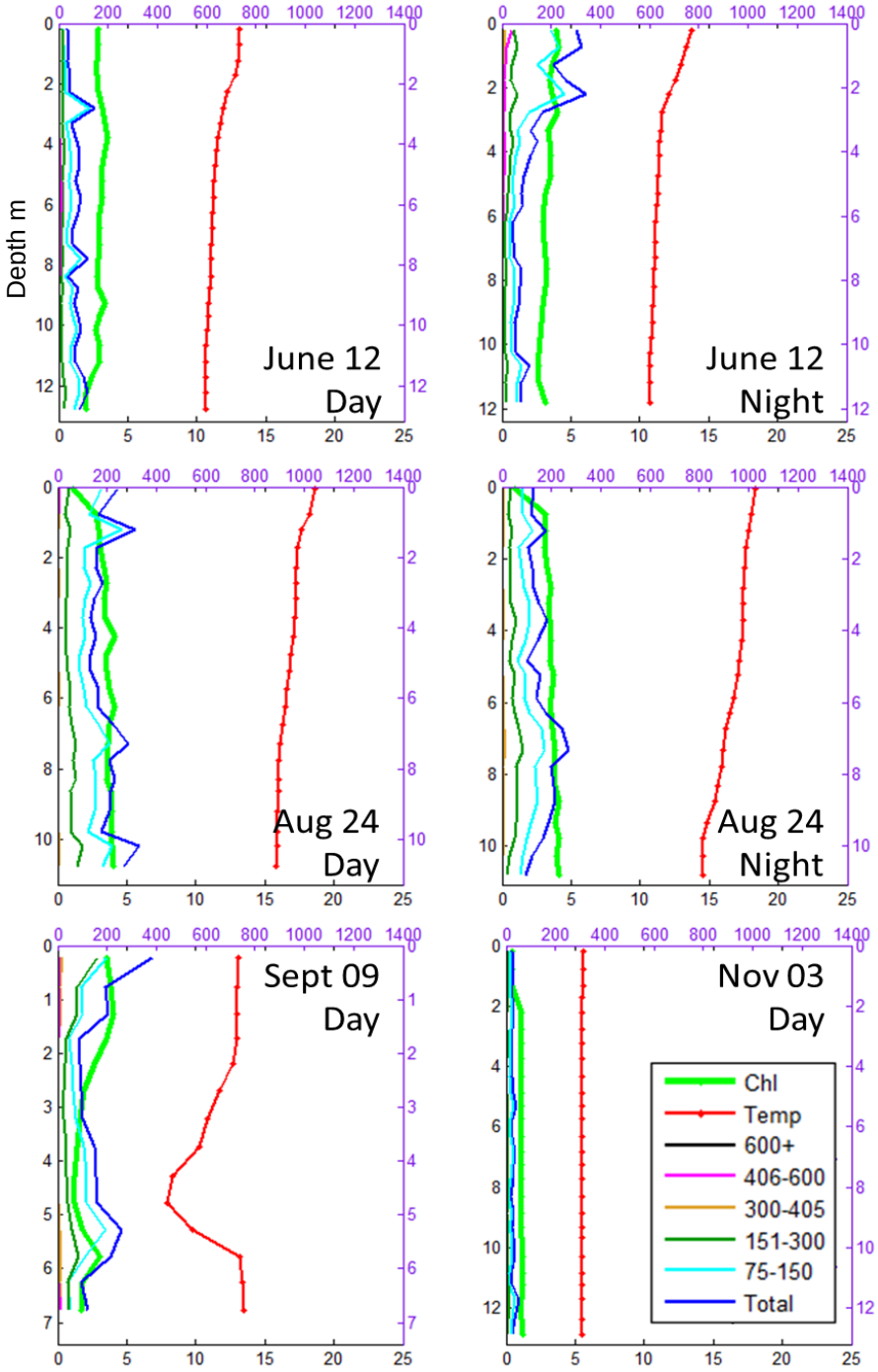

Figure 1.17: Vertical profiles at the inner Humber Bay station (LO8) as part of the CSMI 2013 survey using of the HR-LOPC for temperature (red), chlorophyll-a (green), total counts·L^{-1}, and counts per size-bin. Surveys took place in June, August, September (this survey) and November with day and night profiles taken in June and August. A midwater intrusion of cold water can been seen in the Sept. profile as a result of the upwelling. Very low counts of all size categories of zooplankton are found at this station with little vertical structure in total counts or chlorophyll-a. Higher zooplankton counts are found in the surface in June (night) and in Sept (day) with some indication from the day-night samples that there is overall slightly elevated counts (but still very low) of larger zooplankton during night samples.

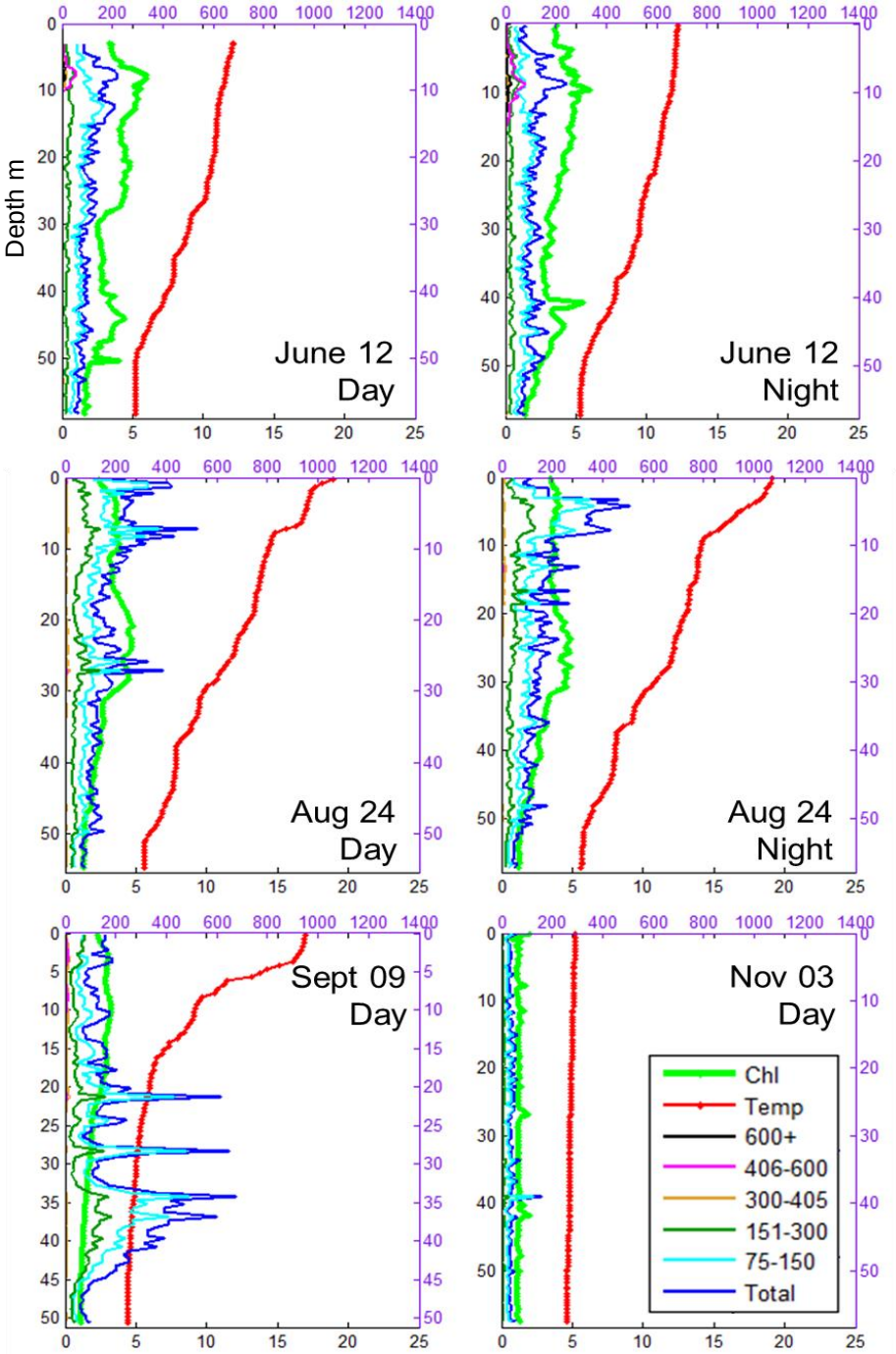

Figure 1.18: Vertical profiles at the outer Humber Bay station (LO9) as part of the CSMI 2013 survey using of the HR-LOPC for temperature (red), chlorophyll-a (green), total counts·L^{-1}, and counts per size-bin. Surveys took place in June, August, September (this survey) and November with day and night profiles taken in June and August. This station exhibits complex temperature stratification except in November when it was well mixed. Chlorophyll-a is elevated from the surface down into the metalimnion suggesting regular deep mixing and weak stratification. Peaks in zooplankton counts can be seen in thin layers and concentration of larger zooplankton (>300 µm) in the epilimnion especially during the night samples. During the upwelling in Sept, stratification is intensified as the hypolimnion is pushed up to a much shallower depth (~15m).

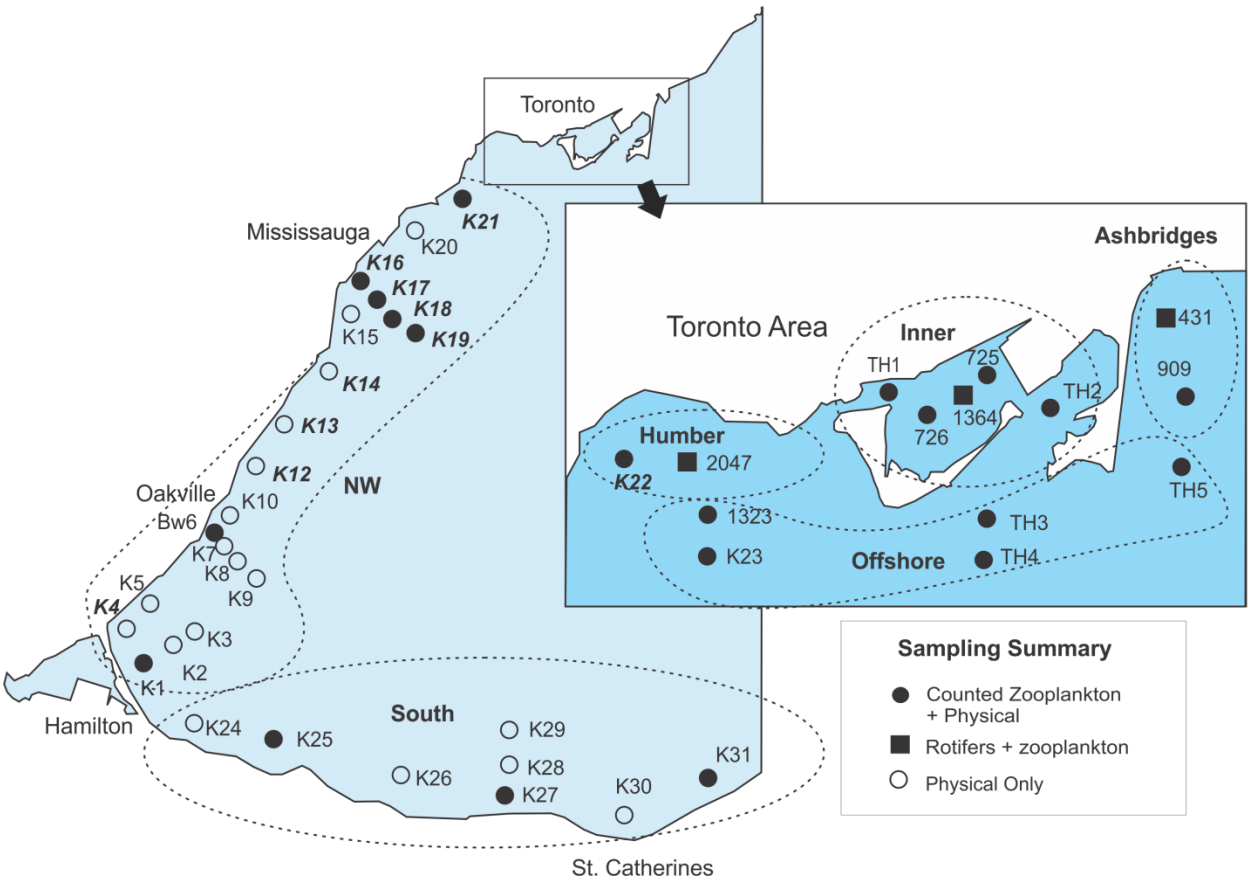

Figure 2.1: Location of sampling stations in western Lake Ontario during the August 2010 plankton nearshore survey undertaken by DFO. Physical parameters include station depth, secchi depth, surface temperature, pH and algal pigments measured using a fluoroprobe. Zooplankton samples have been analyzed from the stations indicated by the solid symbols, and rotifers were analyzed from stations indicated by square symbols. Stations in bold and italics were experiencing an upwelling event.

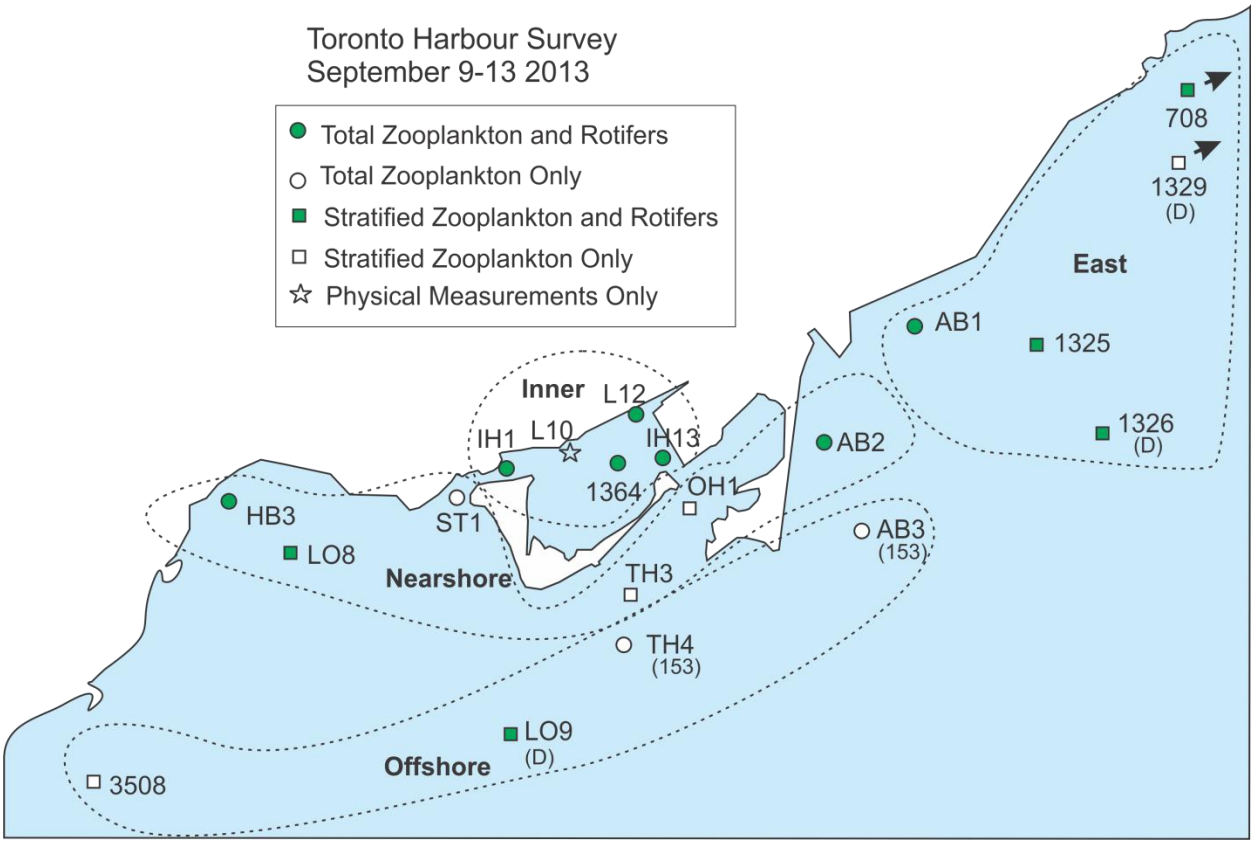

Figure 2.2: Location of sampling stations in the Toronto Area of Concern during the September 2013 plankton survey undertaken by DFO. Total water column (64 um) zooplankton samples have been analyzed from stations indicated by circles. Epilimnion and metalimnion zooplankton samples were counted separately at stations indicated by the square symbols. Additional hypolimnetic samples were counted at deep stations, indicated by (D). Although AB3 and TH4 were deep enough to be stratified, only total water column (153 um) samples were collected due to time constraints. Zooplankton was not counted at the station indicated by the star. The two Pickering area stations 708 and 1329 were located farther east than is indicated on this figure, as demonstrated by the arrows.

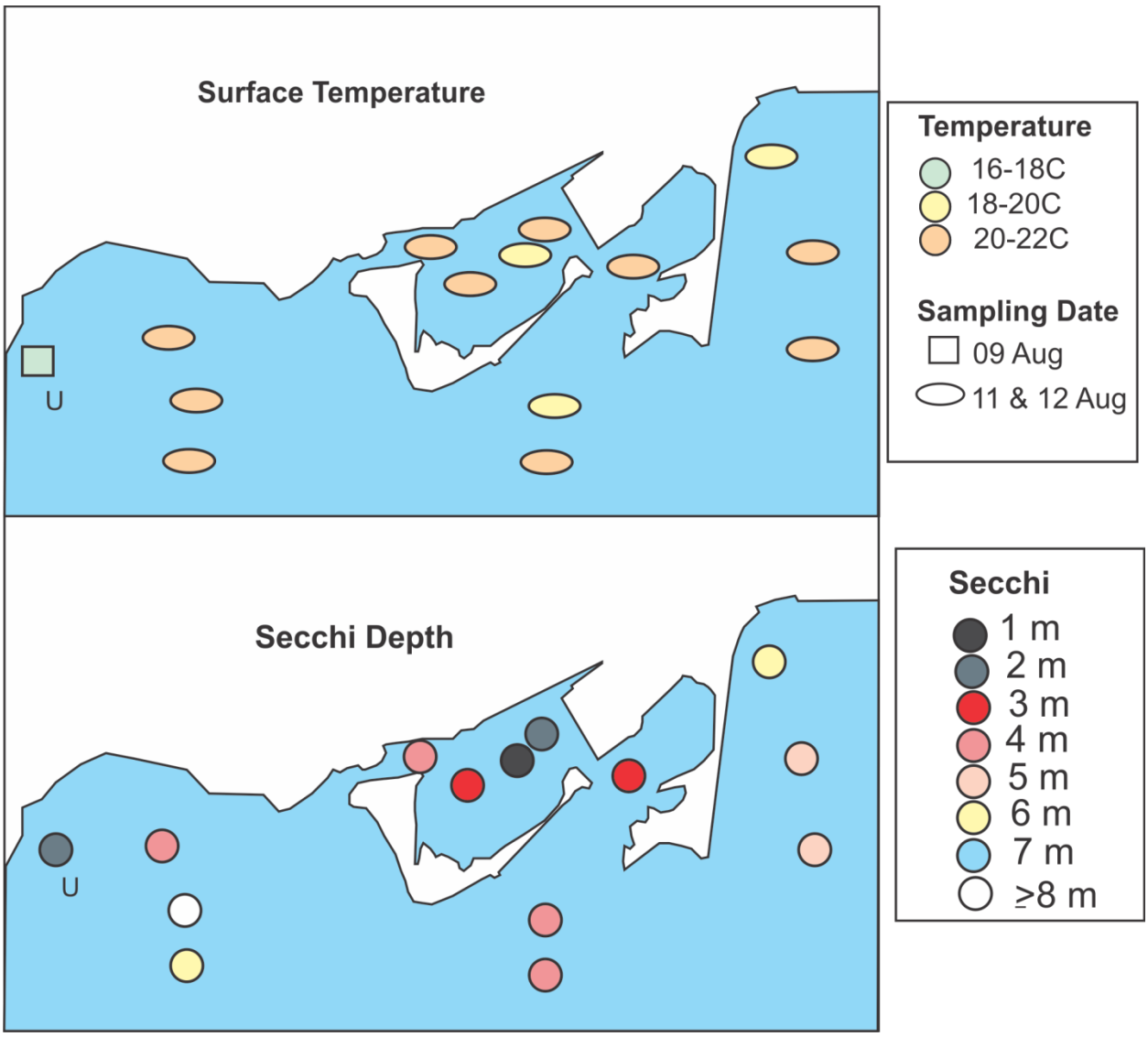

Figure 2.3: Surface temperatures (top) and secchi depth (bottom) recorded during the August 2010 survey. Stations with a U indicate the occurrence of an upwelling event on 09 August.

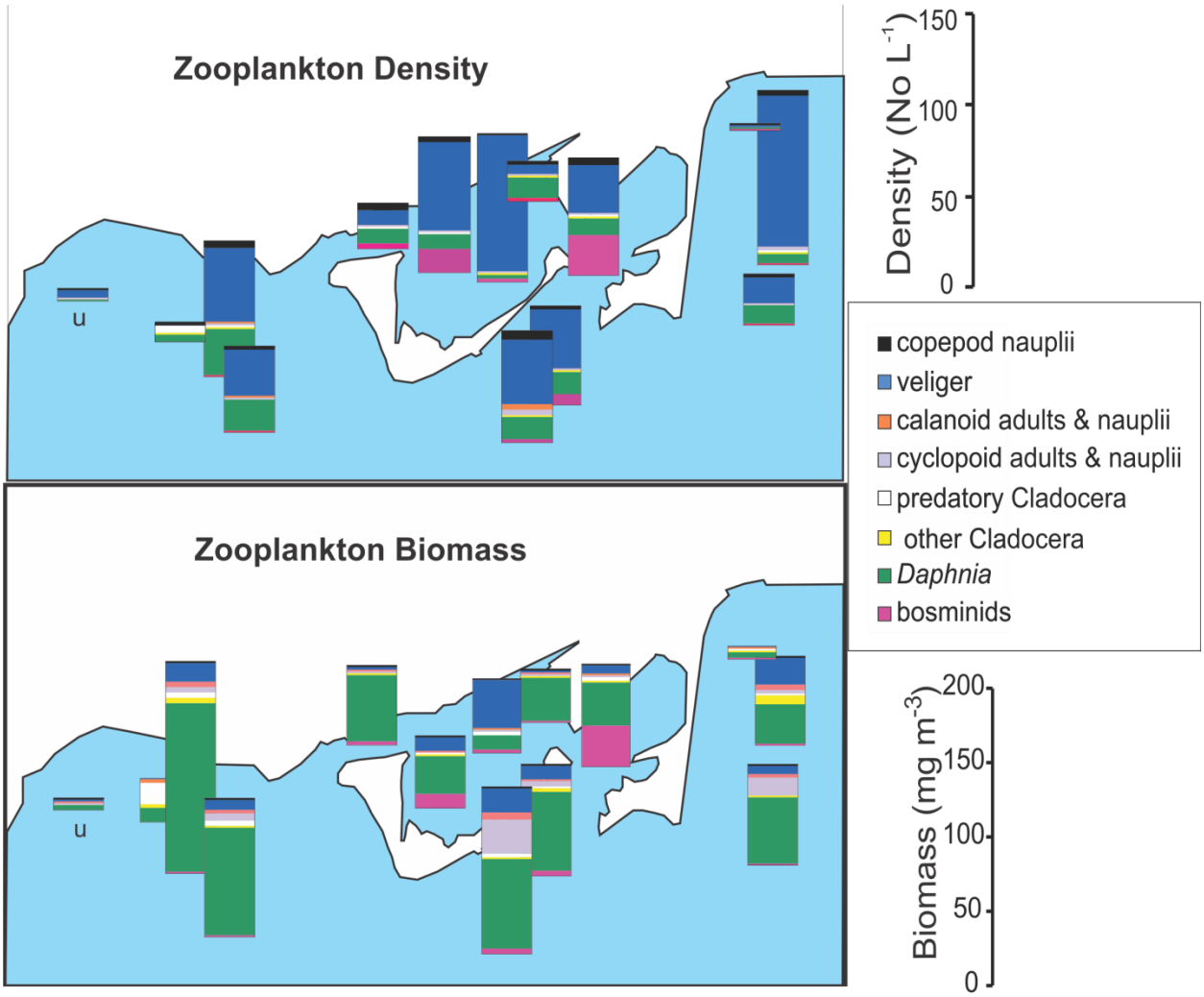

Figure 2.4: Density (top) and dry biomass (bottom) of dominant zooplankton groups in the Toronto Harbour area in August 2010. These were 64 µm total water column samples. Upwelling stations are indicated by a u. Veligers dominate numerically but *Daphnia* sp. dominate the biomass.

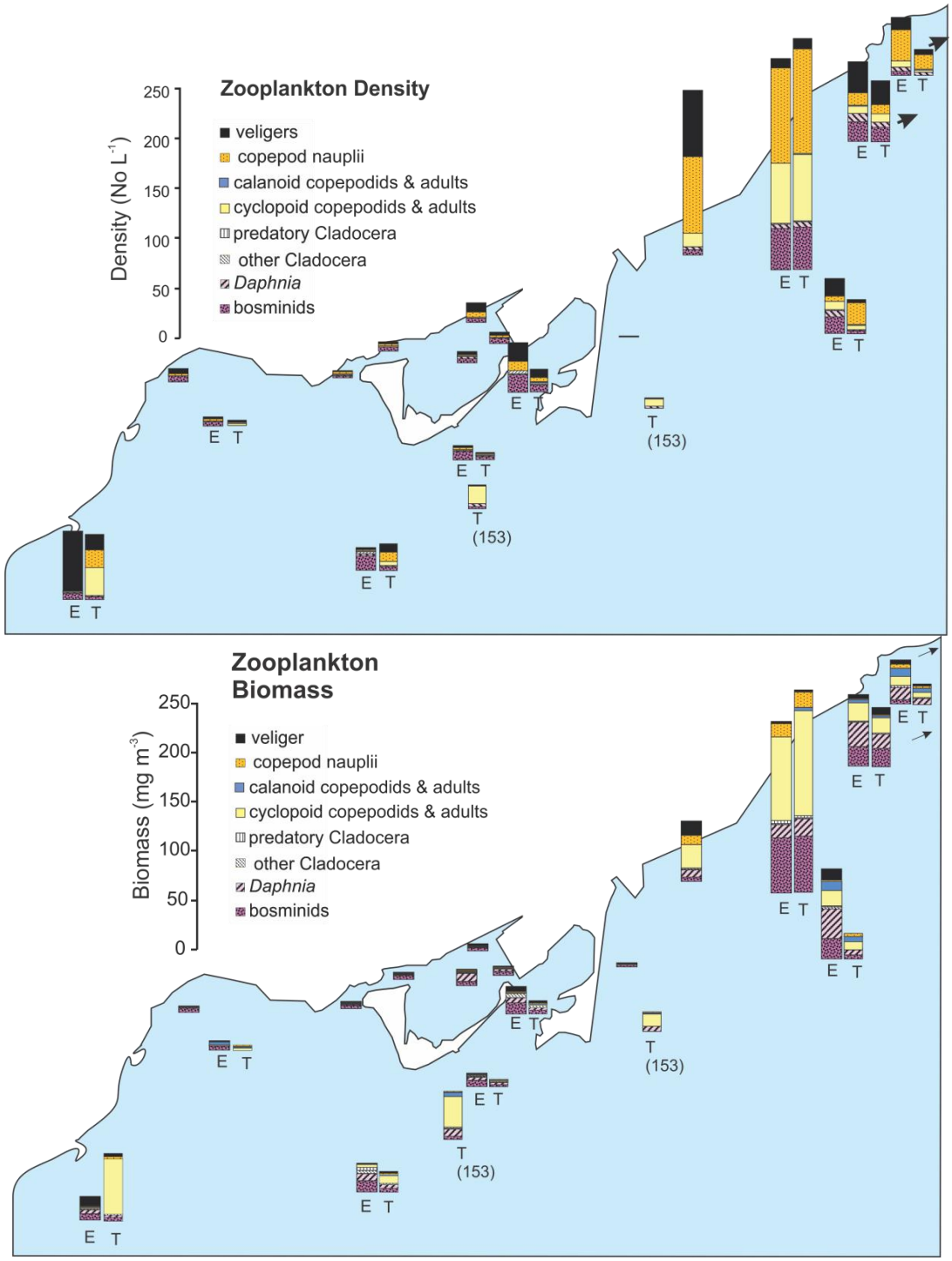

Figure 2.5: Density (top) and dry biomass (bottom) of dominant zooplankton groups in the Toronto Harbour area in September 2013. An E and T underneath the bar indicate epilimnetic and total water column values, respectively. At the stations indicated by (153), a 153 µm mesh net was used. A 64 µm mesh net was used at the remaining stations.

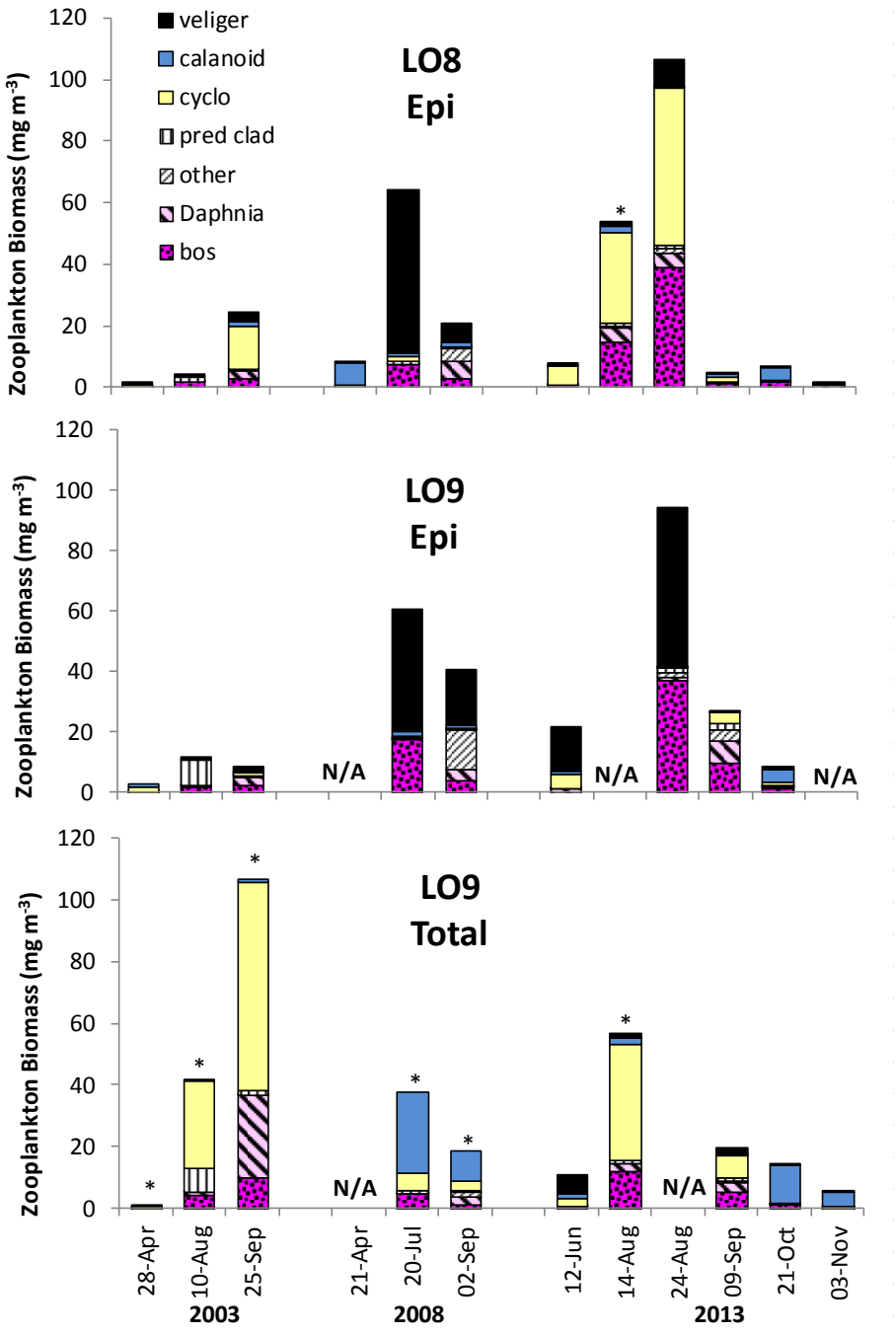

Figure 2.6: Epilimnetic (epi) zooplankton biomass at LO8 (top) and LO9 (middle) and total water column (TWC) zooplankton biomass at LO9 (bottom). These stations were sampled seasonally as part of the CSMI program in 2003, 2008 and 2013. For bars marked with a * veligers were not included or were under-represented in these samples as they were taken with a 153 µm net that did not adequately retain veligers. Only TWC nets were taken at LO9 on 14 Aug. and 03 Nov. 2013. The hypo sample was lost at LO9 on 24-Aug-2013, so the TWC biomass could not be calculated.

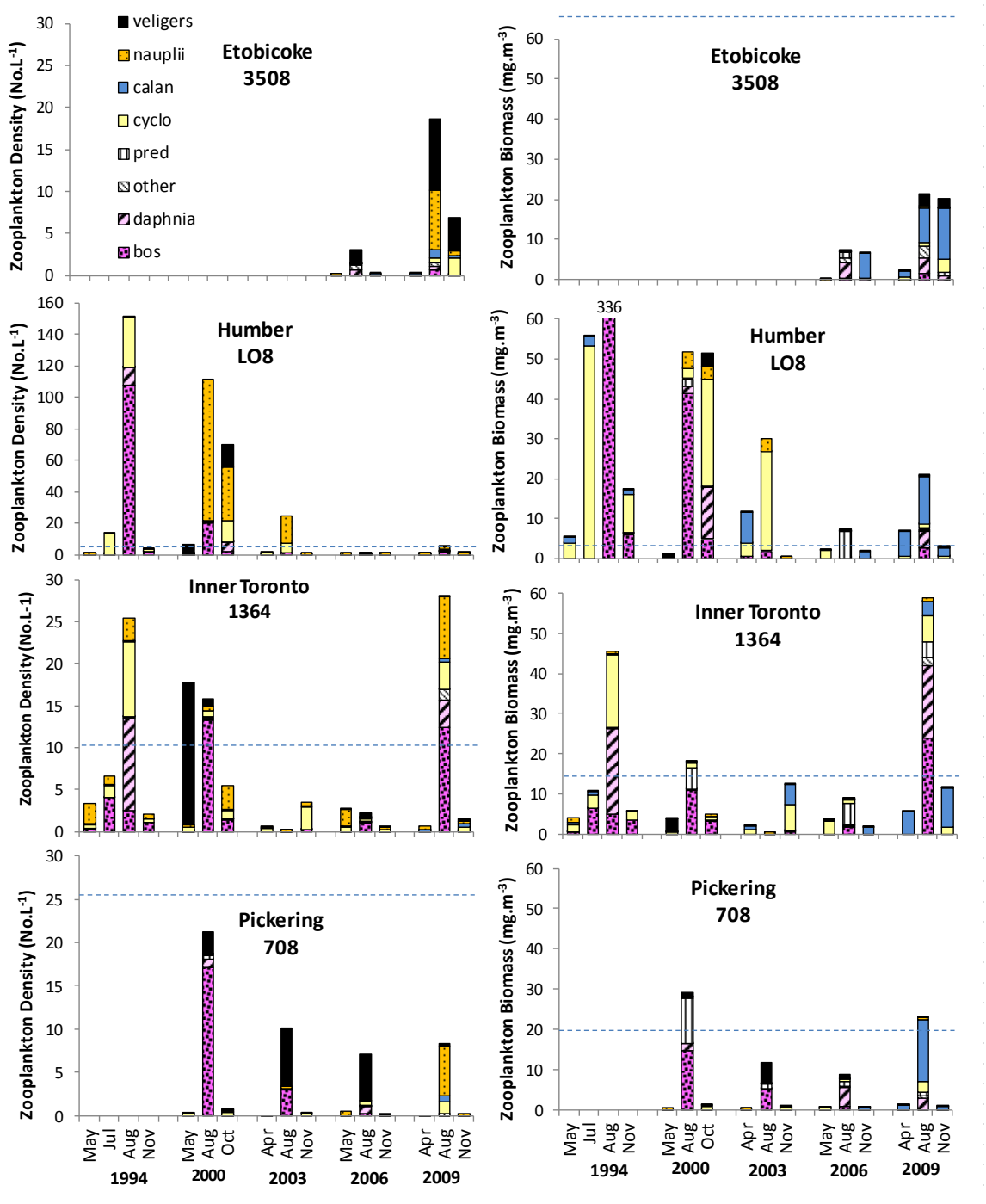

Figure 2.7. Zooplankton density (left) and biomass (right) at nearshore Lake Ontario index stations in the Toronto area. These were sampled by the OMOE sporadically between 1994 and 2009. Note that density at LO8 has a different scale than the other stations. Biomass at LO8 in August 1994 was off the scale at 336 mg m^{-3} (primarily bosminids, cyclopoids and *Daphnia*). The total water column value at each station during the September 2013 spatial survey is shown as a broken line. The density value at Etobicoke on this date was off the scale at 65.6 animals L^{-1}.

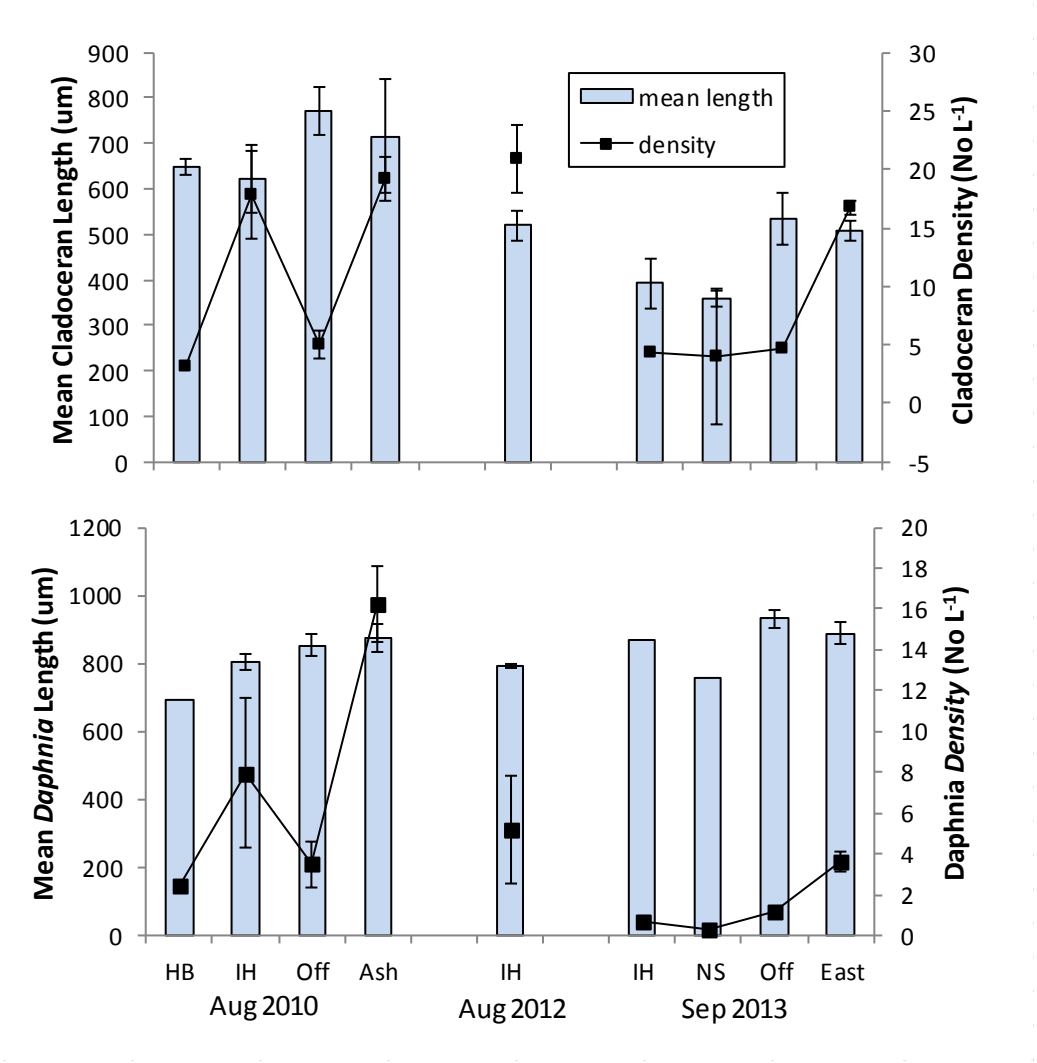

Figure 2.8: Mean herbivorous cladoceran length and densities (top) and mean *Daphnia* length and densities (bottom) in Aug. 2010, Aug. 2012 and Sep. 2013. Study areas are: HB = Humber Bay, IH = Inner Toronto Harbour, Off= offshore adjancent to Toronto, Ash = Ashbridges Bay, NS = nearshore adjacent to Toronto, East = east of Toronto.

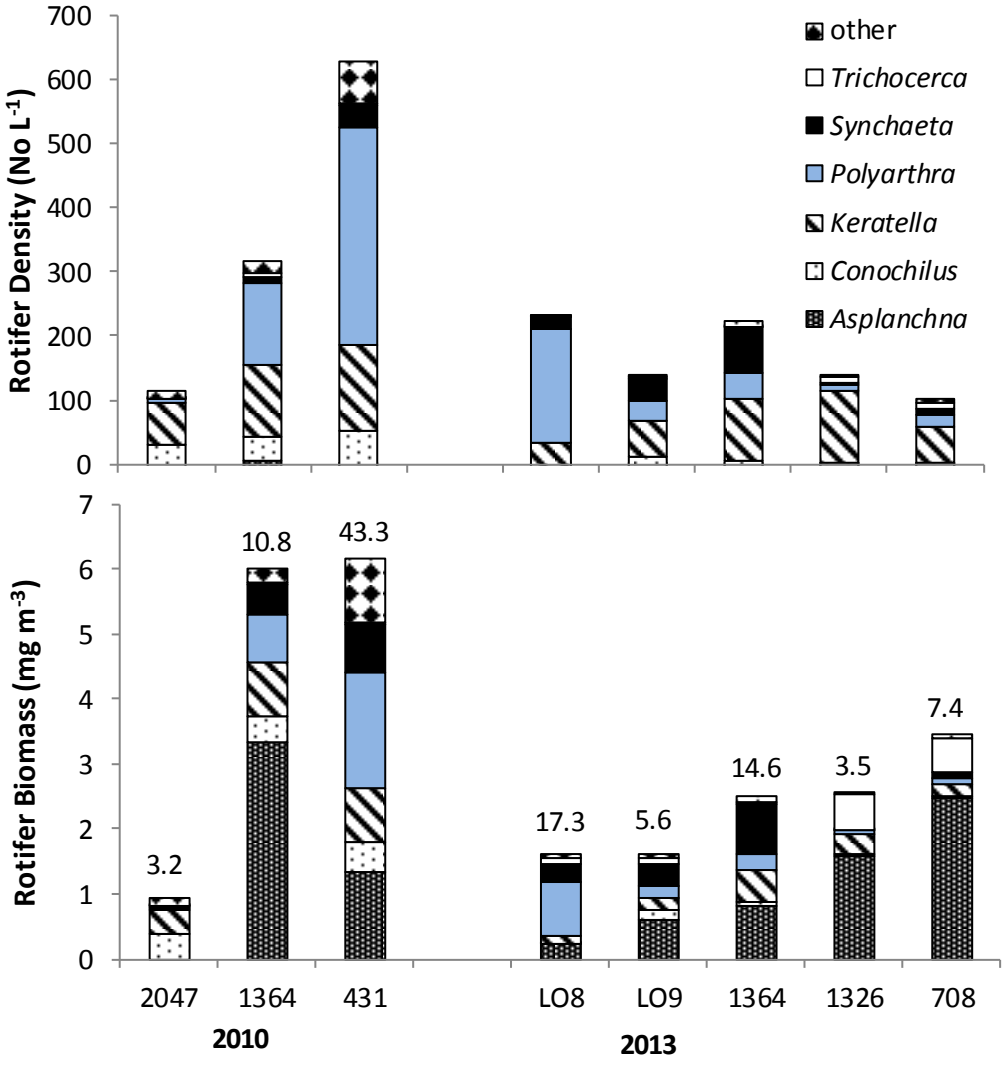

Figure 2.9: Epilimnetic density (top) and biomass (bottom) of dominant rotifer groups in Aug. 2010 and Sep. 2013 at selected stations. The numbers above the bars represent the percent of total epilimnetic biomass (rotifers plus zooplankton) comprised by rotifers.

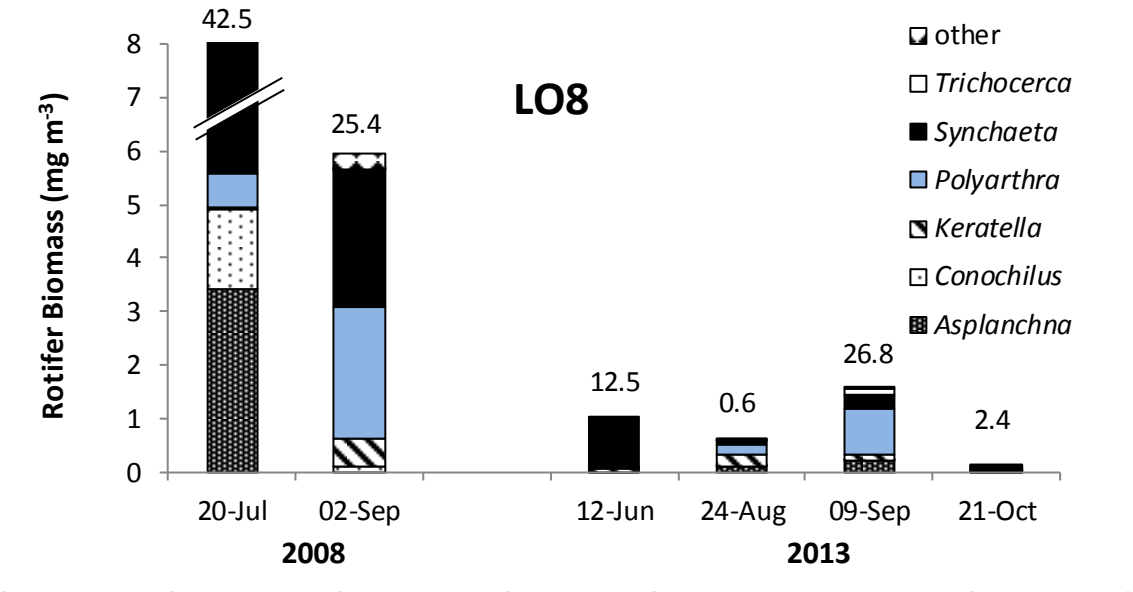

Figure 2.10: Total water column rotifer biomass at LO8 across the season in 2008 and 2013 as part of the CSMI program. Rotifers were not sampled on 14 Aug. or 03 Nov 2013. The numbers above the bars represent the percent of total epilimnetic biomass (rotifers plus zooplankton) comprised by rotifers. On 20 July 2008 rotifer biomass was off the scale, with a value of 27.6 mg m^{-3}.

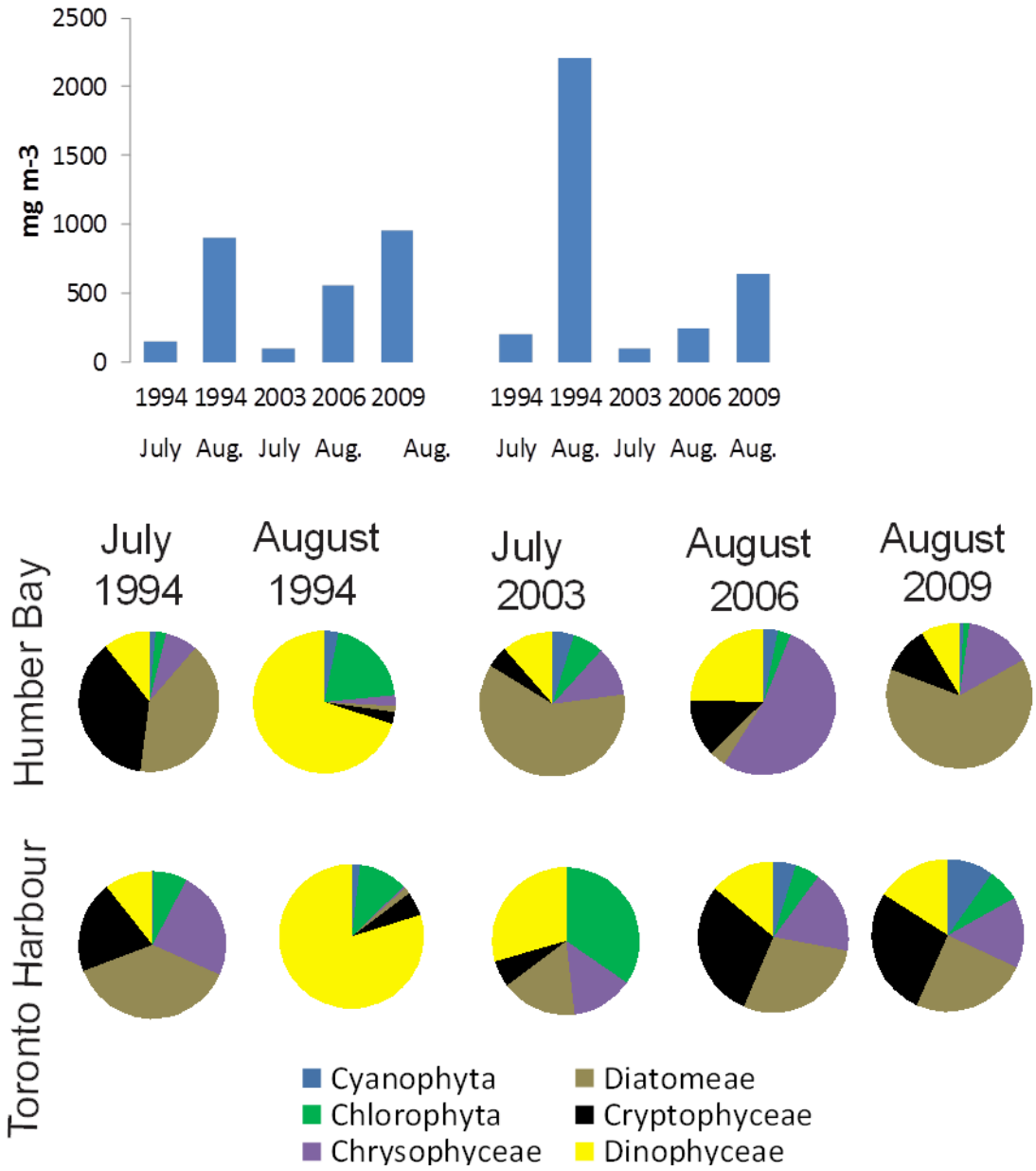

Figure 3.1: Phytoplankton biomass in g m^{-3} (top) and percent composition (bottom) at a single station in Humber Bay and Toronto Harbour. MOE Great Lakes Nearshore Index Station program.

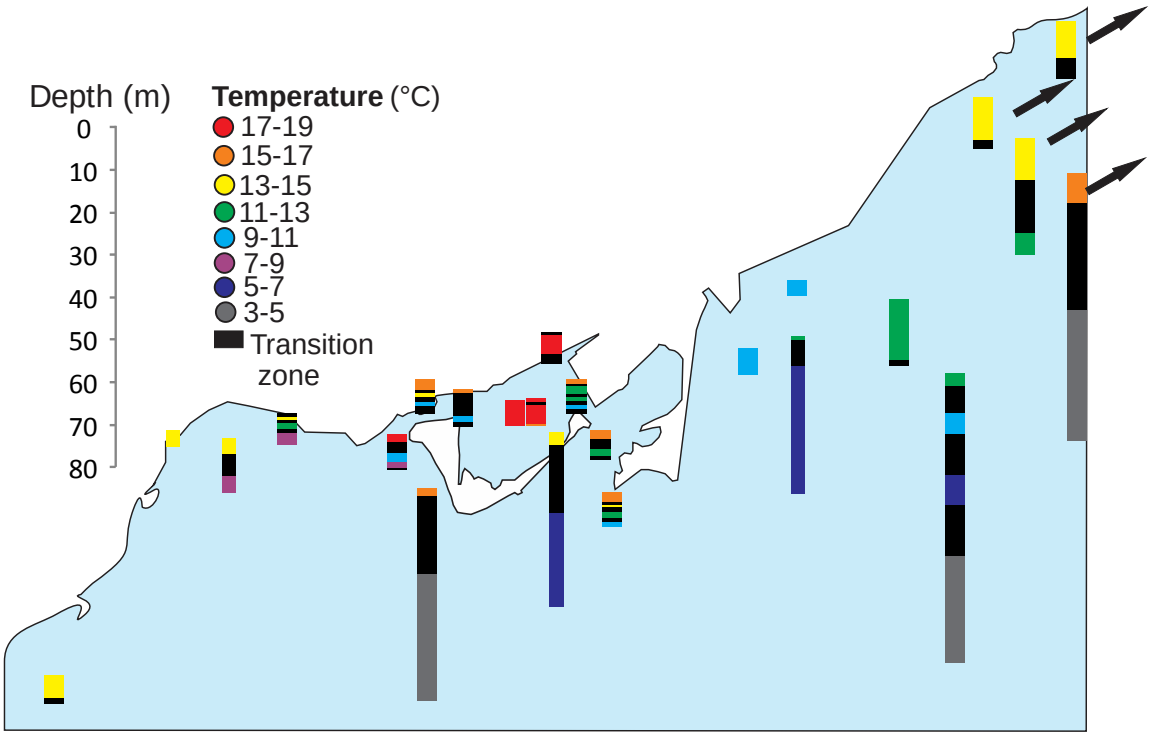

Figure 3.2: Water temperature profiles indicating layers of stable temperature and temperature transition zones. Measured with an EXO2 sonde or MK9 logger September 9-13, 2013. Length of bar indicates depth in metres. Bottom of bar on station location.

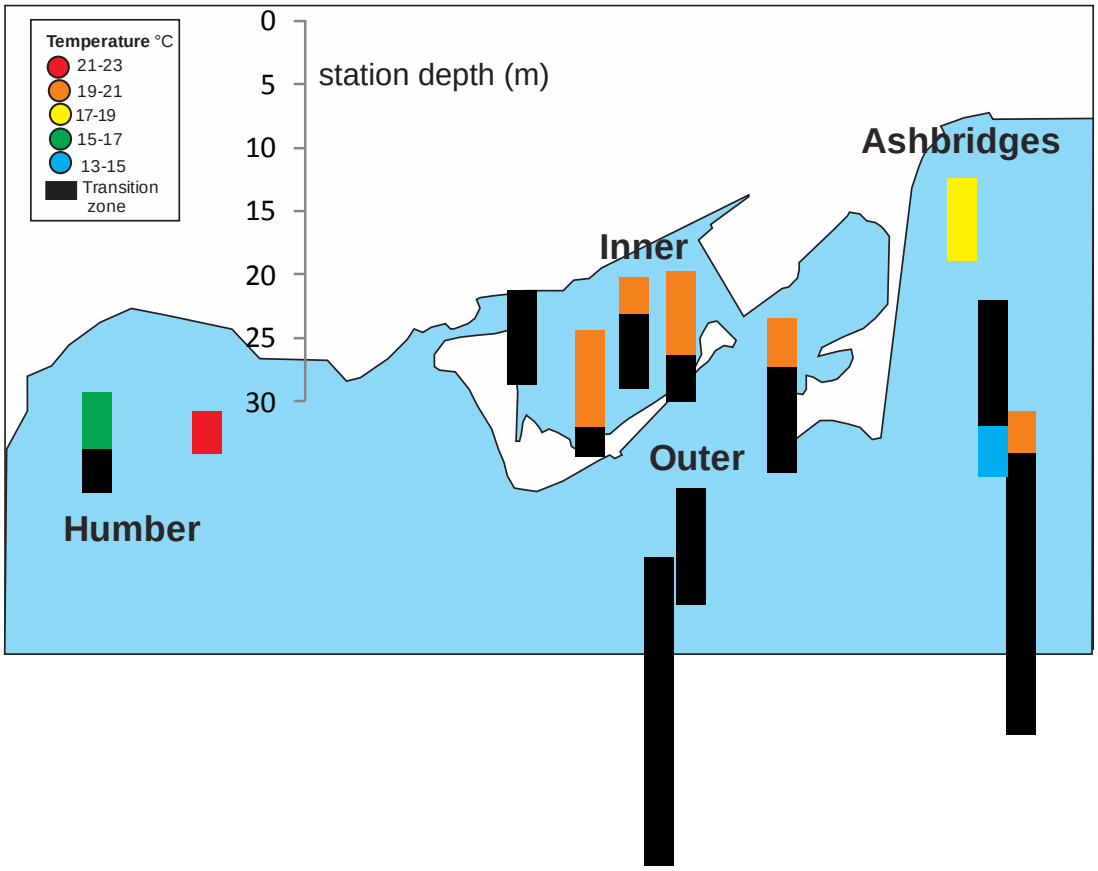

Figure 3.3: Water temperature profiles indicating layers of stable temperature and temperature transition zones. Measured with a FluoroProbe August, 2010. Length of bar indicates depth in metres. Top of bar on station location.

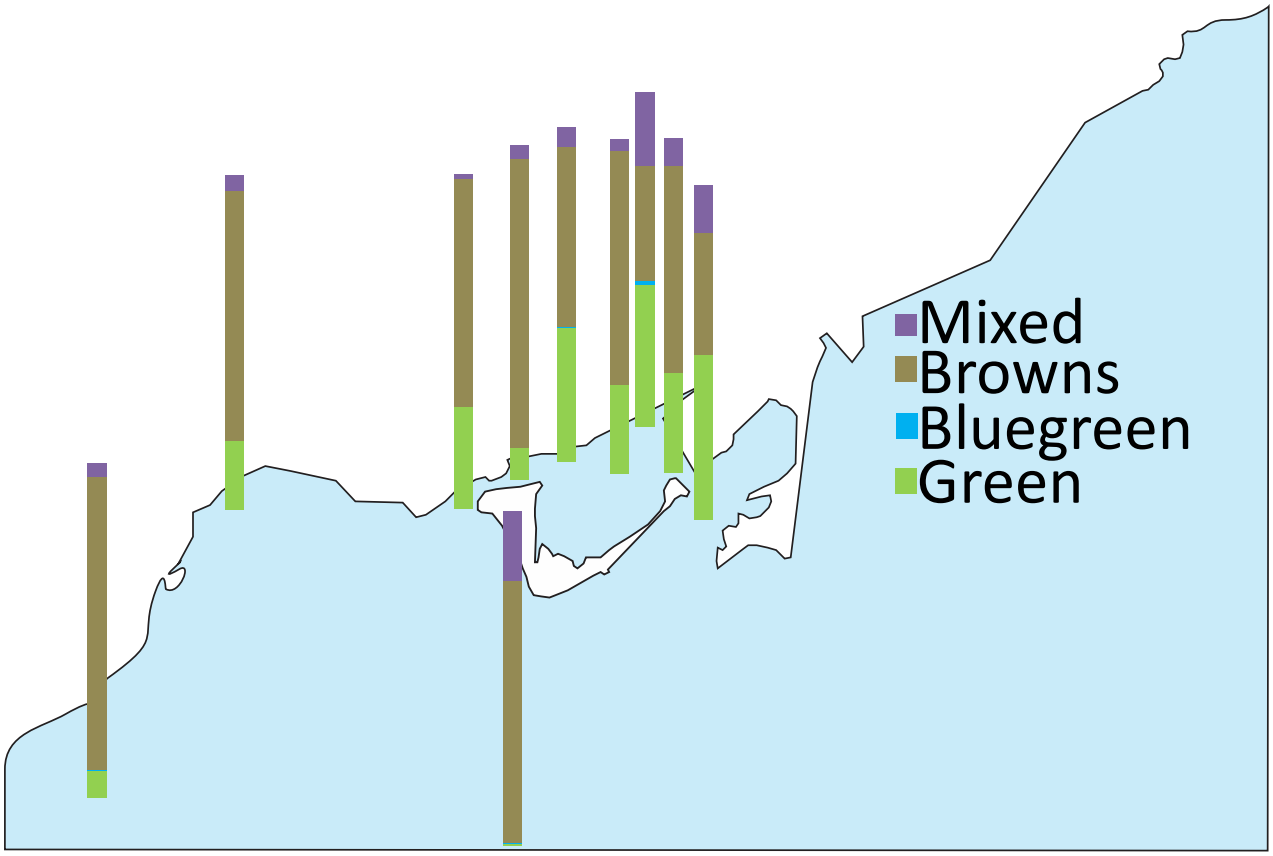

Figure 3.4: Whole water column average chlorophyll percent composition by pigment colour group as measured by FluoroProbe, September 2013. Bottom of bar on station location.

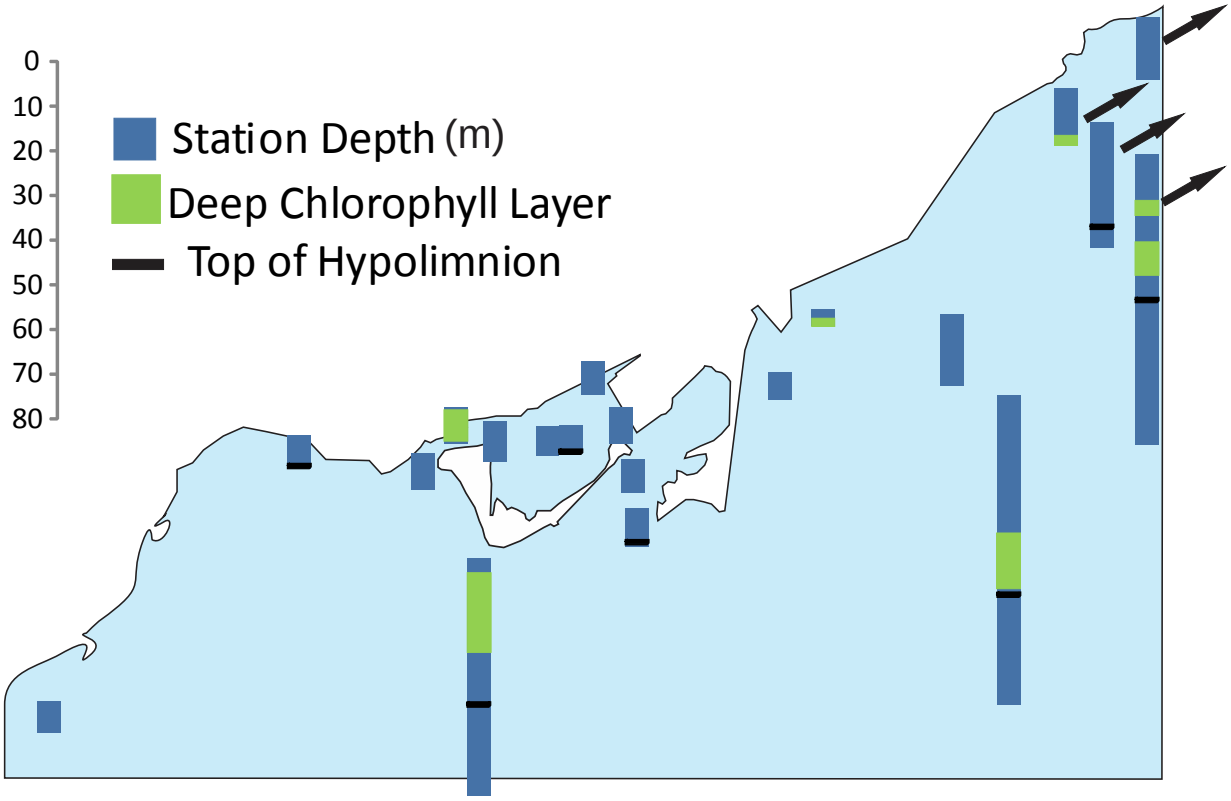

Figure 3.5. Region of increased chlorophyll within the water column as measured by FluoroProbe September 2013. Length of bar indicates total station depth in metres. Bottom of bar on station location.

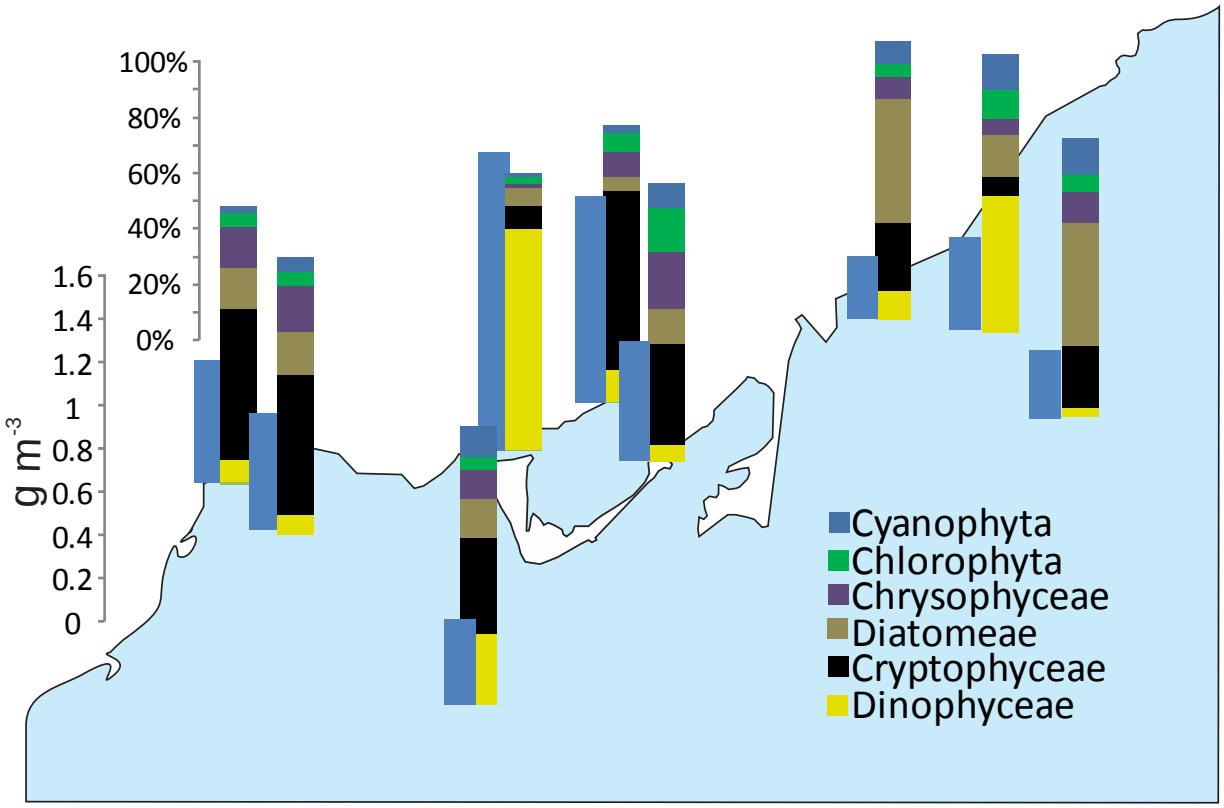

Figure 3.6: Phytoplankton biomass (g m^{-3}) and percent composition by biomass, September 2013. Bottom of bar on station location.

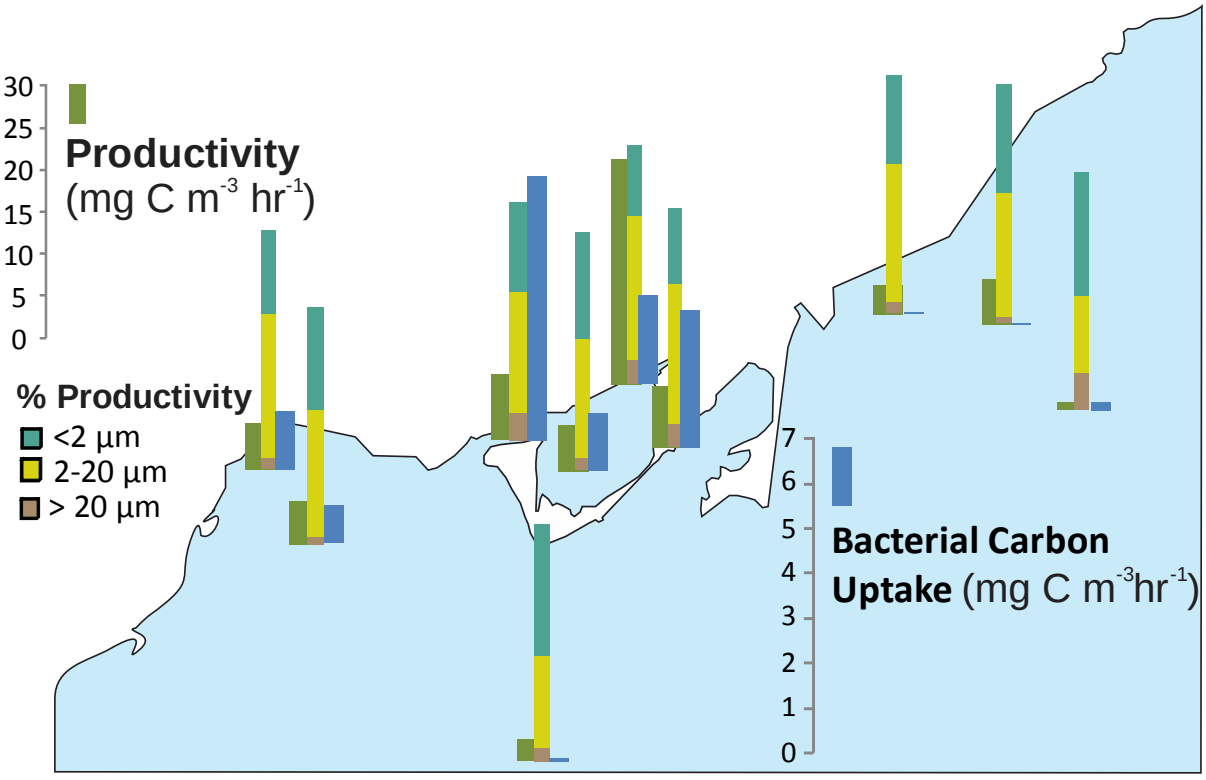

Figure 3.7: Phytoplankton and bacterial carbon uptake rates, Sep 2013. Total phytoplankton productivity (mg C m^{-3} hr^{-1}) shown in olive green, and then shown as a % contribution by size fraction. Picoplankton (<2 µm) is green, nanoplankton (2-20 µm) is yellow and netplankton (>20µm) is brown. Total bacterial carbon uptake is shown in blue. Bottom of bar on station location.

Figure 3.8: Seasonal measures of algal productivity (mg C m^{-3} hr^{-1}) at the mid shore (LO8 - 14m depth top panel) and offshore (LO9 - 59m mid panel) stations in Humber Bay. Bacterial Productivity is shown in the bottom panel.

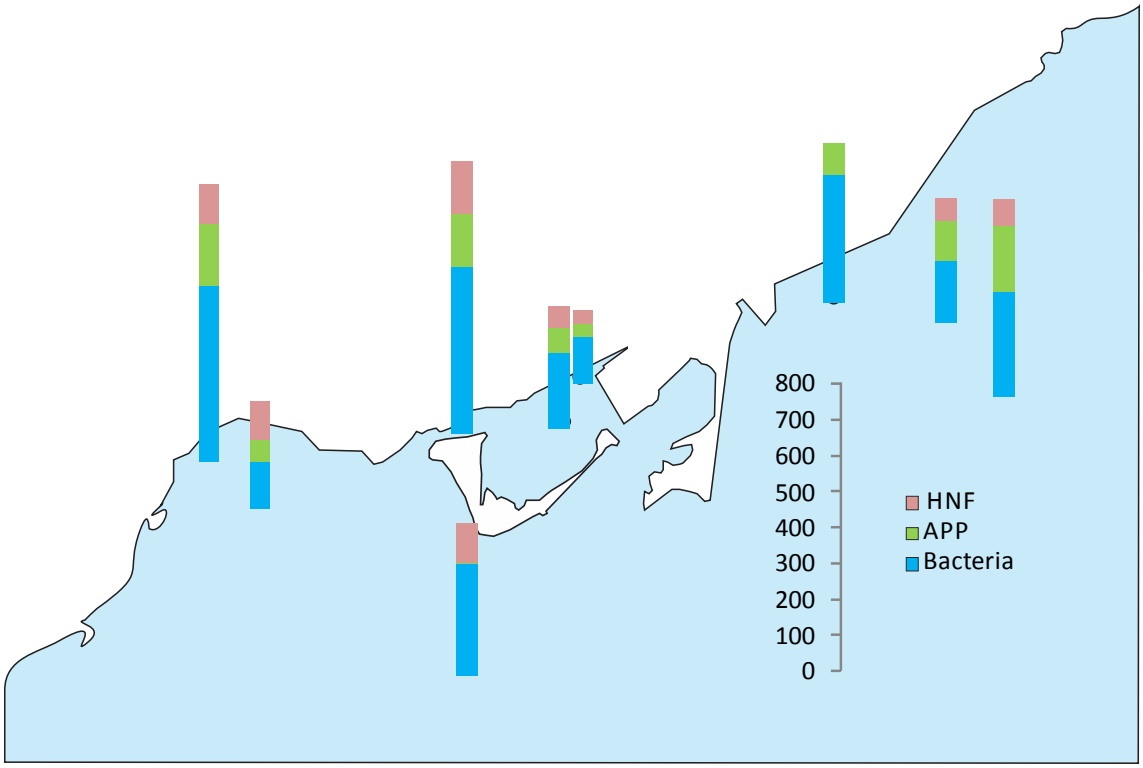

Figure 3.9: Microbial loop biomass (g m^{-3}) and breakdown by category: Heterotrophic Nanoflagellates (HNF), Autotrophic Picoplankton (APP) and Bacteria, September 2013.

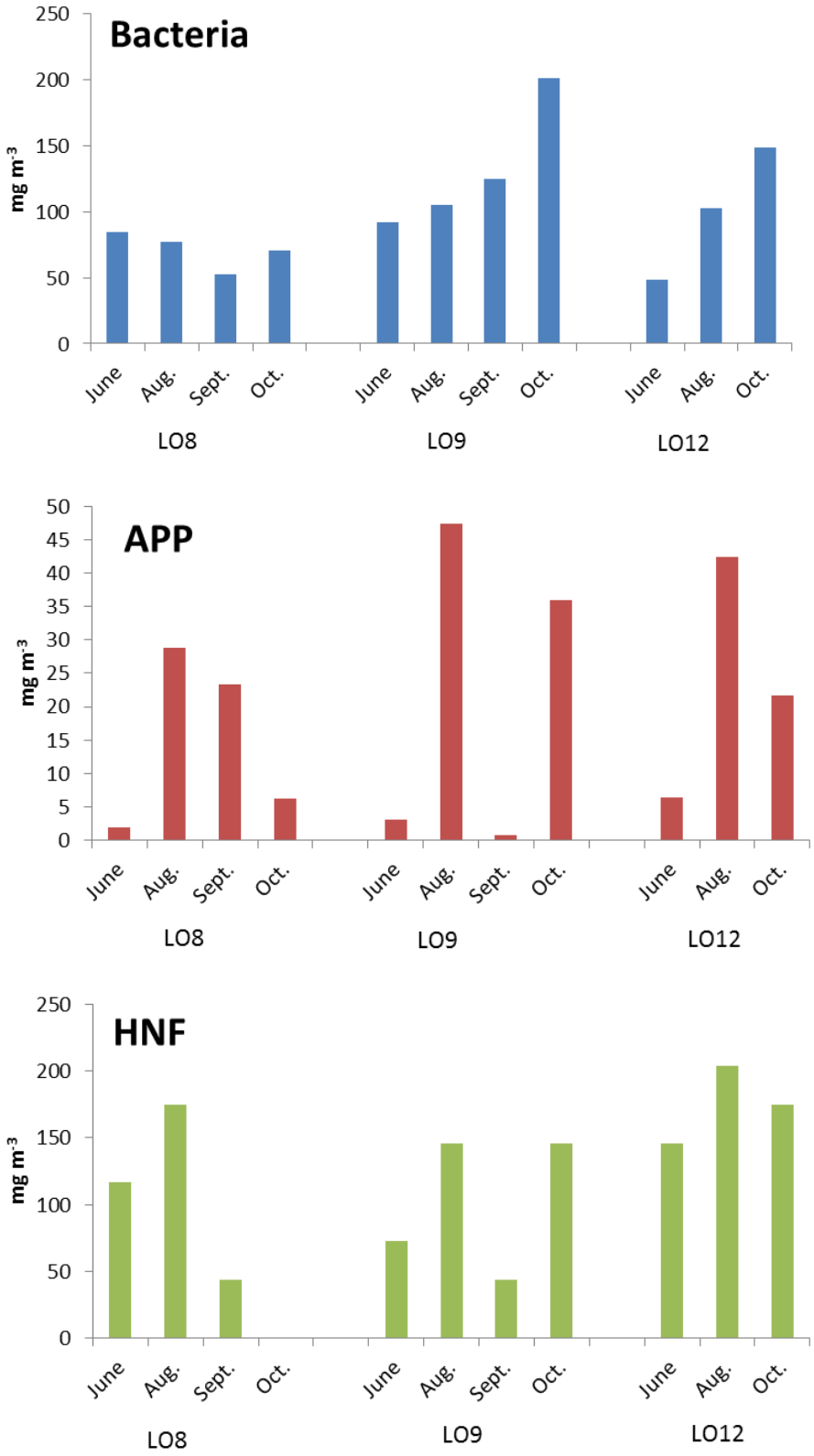

Figure 3.10: Microbial loop biomass as observed in 2013 at the Humber Bay mid-shore (LO8) offshore (LO9) and an deep offshore station (LO12). Bacteria, autotrophic picoplankton (APP) and heterotrophic nanoflagellate (HNF) biomass is given.

SECTION 2: REPORT ON THE VIABILITY OF USING MOE INDEX PLANKTON SAMPLES TO EVALUATE BUI 13: DEGRADATION OF PHYTOPLANKTON AND ZOOPLANKTON POPULATIONS FOR TORONTO REGION AREA OF CONCERN

W.J.S. Currie and M.A. Koops

Background

In 2011, the Great Lakes Laboratory for Fisheries and Aquatic Sciences scientists was asked to comment on the viability of using plankton samples collected as part of the Ontario Ministry of the Environment (now MOECC, hereafter MOE) *Great Lakes Nearshore Monitoring and Assessment* (hereby "Index") program to evaluate BUI 13: Degradation of Phytoplankton and Zooplankton Populations for the Toronto Harbour Area of Concern (hereby "TH-AOC"), which has only a few historical plankton surveys (Patalas 1969, Haffner et al. 1982, Munawar et al. 1993). The concern at the time was that there would be too few samples to indicate any trends since plankton are notoriously variable. It was decided by Environment Canada that the archived plankton samples should be analyzed to determine if they were sufficient to permit an analysis on the state of plankton populations in the AOC.

The intent of the Index network of stations is to provide a baseline time-series for determination of trends in compounds of concern in the nearshore. Though each site is not sampled frequently, the strength of the program is in the widespread spatial extent of stations which cover the entire Ontario Great Lakes shoreline from Lake Superior to the St. Lawrence River.

The Index program has two objectives and three indicators:

Objectives

1) *Identify temporal trends in sediment and water quality in the nearshore Great Lakes and to use these findings to support Ministry and inter-agency efforts to identify lake-wide or regional changes in environmental conditions, and,*
2) *Establish sites in each of the Great lakes removed from major point-source influences such that the data collected at the sites may be used as a reference when assessing environmental conditions at physically similar sites.*

Indicators:

1. *Concentrations of persistent contaminants in surficial sediment and in suspended particulate material*
2. *Composition of benthic invertebrates*
3. *Physical measurements including profiles of the water column and bottom characteristics*

Great Lakes Nearshore Monitoring and Assessment (GLWQM) Draft Project Description, Feb 3, 2009. (Todd Howell, personal communication, 2014)

In the lower Canadian Great Lakes, each Index (GLWQM) site is sampled 3 times (early spring, summer and late fall) every 3 years. While the Index program is focused on chemical constituents and uses only benthic organisms as indicators, MOE does collect plankton at each Index station as part of the protocol. For phytoplankton density and taxonomy, a single depth-integrated sample of the euphotic zone (to 2x Secchi disc depth or top of metalimnion) by lowering a "glug-glug" sampler of two, 1 L glass bottles and stored in a 500ml PET bottle with 2ml of Lugol's Iodine as preservative. The sample was ultimately concentrated in the lab and stored in the MOE archive facility. Zooplankton was collected using a Schindler-Patalas plankton trap with 64 µm mesh at 3 depths (2m from the surface, mid-depth and 2m above the

bottom) which are pooled together and preserved using 4% sugared-formalin and 2 drops of glycerin and archived.

This report summarizes the plankton data collected from the Index sites surrounding Toronto Harbour AOC, statistically analyzes the distributions and composition of plankton from these sites and makes recommendations on whether they can be used, in and of themselves, to evaluate the status of the Biological Use Impairment (BUI) 13: degradation of phytoplankton and zooplankton populations.

Methods and Results

The Index sites used for this analysis encompassed the boundary of the Toronto Harbour AOC: Etobicoke (outside Western boundary), Humber Bay, Toronto Harbour (within the AOC) and Pickering (outside Eastern boundary). Samples from Hamilton Harbour were also used to compare with more temporally intensively sampled stations by GLLFAS Freshwater Ecosystem Research program in 2006 and 2009.

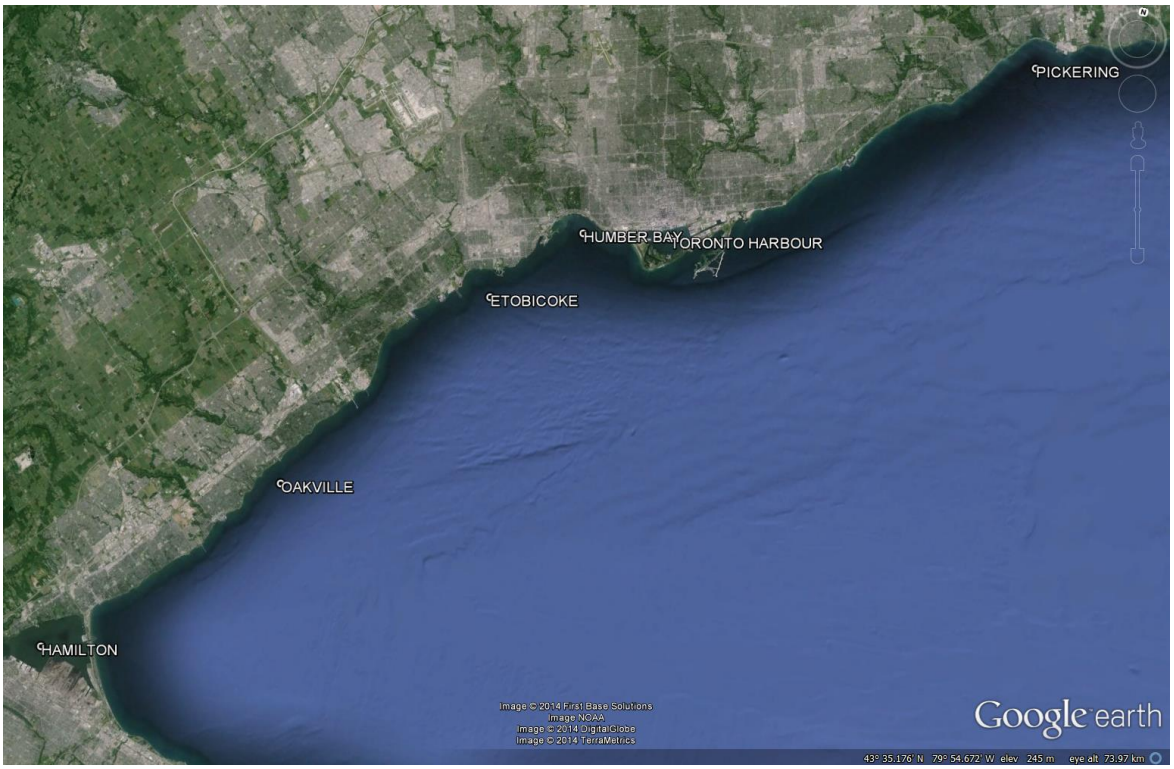

Figure 1: Google Earth image of Index Sites used for this analysis.

The plankton samples were counted to species by experienced taxomists with a long history of working with Great Lakes samples: Claudiu Tudorancea (Aquatic Bioservices) for zooplankton and Hedy Kling (Algal Taxonomy and Ecology Inc.) for phytoplankton. The output of density and composition was sent to Environment Canada and shared with this report's authors who QA/QC the data to assess any outliers. Summary spreadsheets were prepared that organized the plankton composition into standardized dominant groups for comparison to other site data collected by the GLLFAS Freshwater Ecosystem Research section. Analysis was done using R v3.0.1 (R Core Team 2012), JMP® and Microsoft Excel 2010.

Zooplankton

The Index zooplankton samples were identified to species except for juvenile stages of copepods which were identified to order. Rotifers are mentioned in notes but are not quantified. Comments regarding sample composition and preservation can be found in Appendix 1. To simplify the display and analysis of the zooplankton taxonomy data, major ecological groupings of zooplankton were used in this analysis. The groupings include: cladocerans: *Bosmina*, *Eubosmina*, *Daphnia*, Predaceous Cladocera (*Bythotrephes*, *Cercopagis*, *Leptodora*), and other Cladocera (e.g. *Holopedium*, *Diaphanosoma* etc.), for copepods: Calanoida, Cyclopoida, Harpacticoida, and Nauplii (initial larval stage), and Dreissenid mussel veligers (see Figs. 2-3).

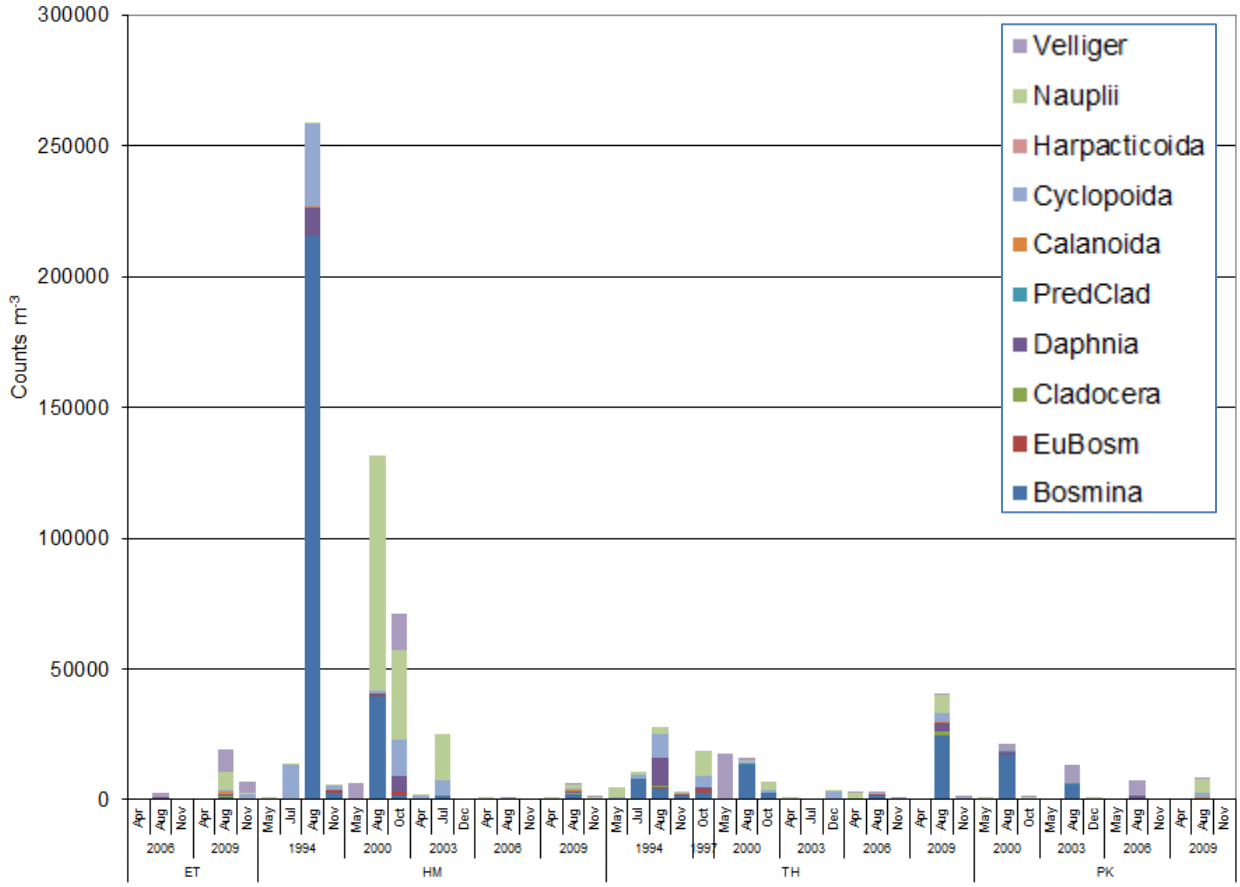

Figure 2: Zooplankton densities (ind m^{-3}). All samples analyzed for zooplankton composition from sites surrounding Toronto Harbour AOC. ET=Etobicoke, HM=Humber Bay, TH=Toronto Harbour, PK=Pickering. Major groupings are explained in more detail in the text.

The overall densities and biomass indicate very high variability (Figs. 2-3) but generally very low densities as noted in comments by the taxonomist (Appendix 1). Humber Bay had the highest counts prior to 2003, but now is comparable to most of the other sites. The very large spike at Humber Bay in 1994 is due to high densities of the common cladoceran *Bosmina*. The most complete data series from Toronto Harbour demonstrates this variability among years clearly when comparing relatively higher counts (Fig. 2) from 2000 to extremely low counts in 2003 and 2006. The variability over the year can be seen in 2009 where the counts are extremely low in the spring and fall and very high during the August sample. Timing can be extremely important for zooplankton sampling since they show very high temporal variability where densities can double in successive measurements (Mackas et al.1985).

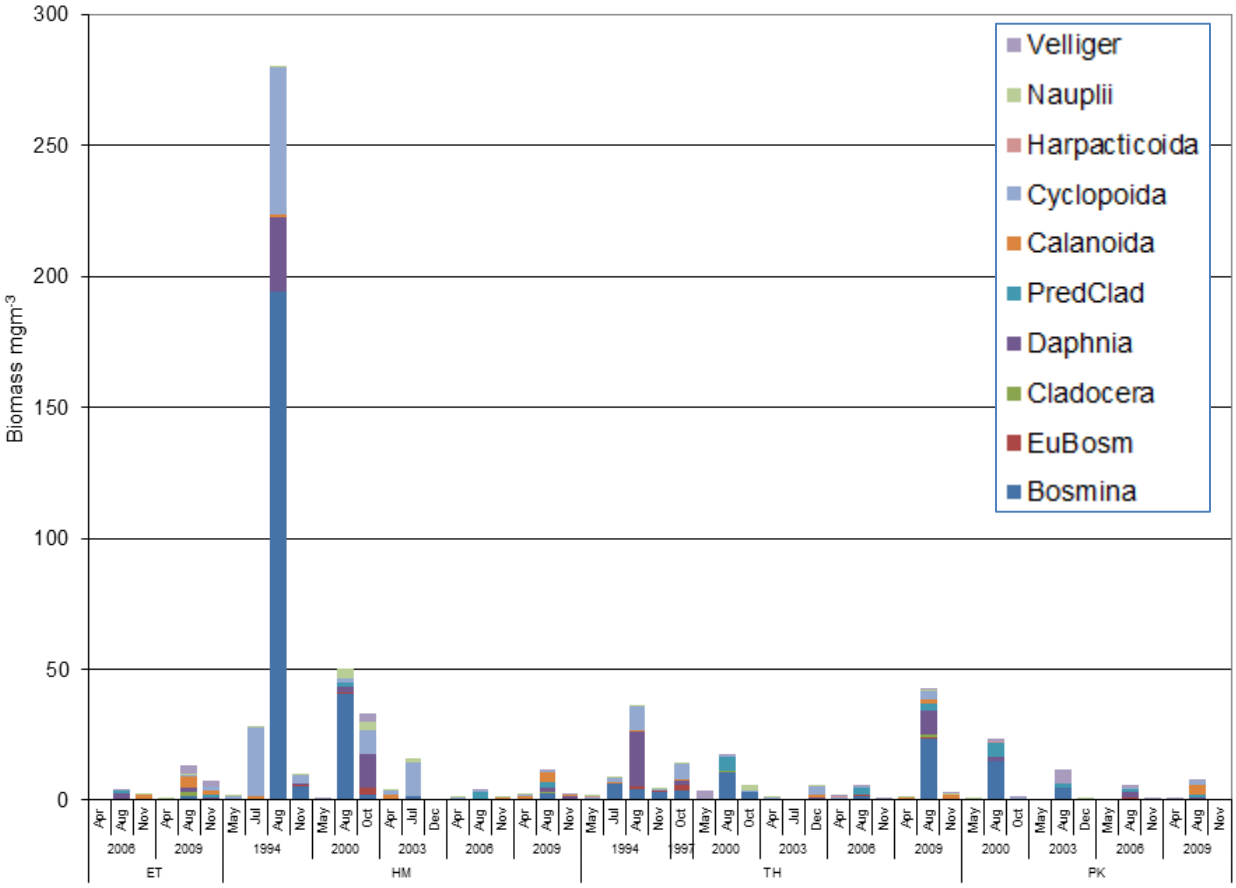

Figure 3: Zooplankton biomass (mg m^{-3}). All samples analyzed for zooplankton composition from sites surrounding Toronto Harbour AOC. ET=Etobicoke, HM=Humber Bay, TH=Toronto Harbour, PK=Pickering. Major groupings are explained in more detail in the text.

Species composition also indicated high variability (Fig. 4). After 1994, the spring samples are dominated by Dreissenid mussel veligers and some copepod nauplii, but biomass is extremely low. The summer samples have the most consistency from year to year, but even in this sampling group, the composition can change rapidly in subsequent samples (3 years later). The late fall samples have the highest variability in species composition with no consistency by year of a dominant species.

Yearly species richness (number of species encountered) and diversity (index of proportion of species found) ranges considerably since 1994 (Fig. 5). Richness and diversity can be highest in either the summer or fall samples. Species richness was at a low in the sites from 2000 – 2003 but has increased to similar levels found in 1994 in the two sites sampled then. The Shannon-Weiner diversity index has been relatively similar since 1994, though Toronto Harbour had the lowest value in its series in 2009 while the neighbouring sites increased. There is no significance to the trends (Student-t, $p>0.05$).

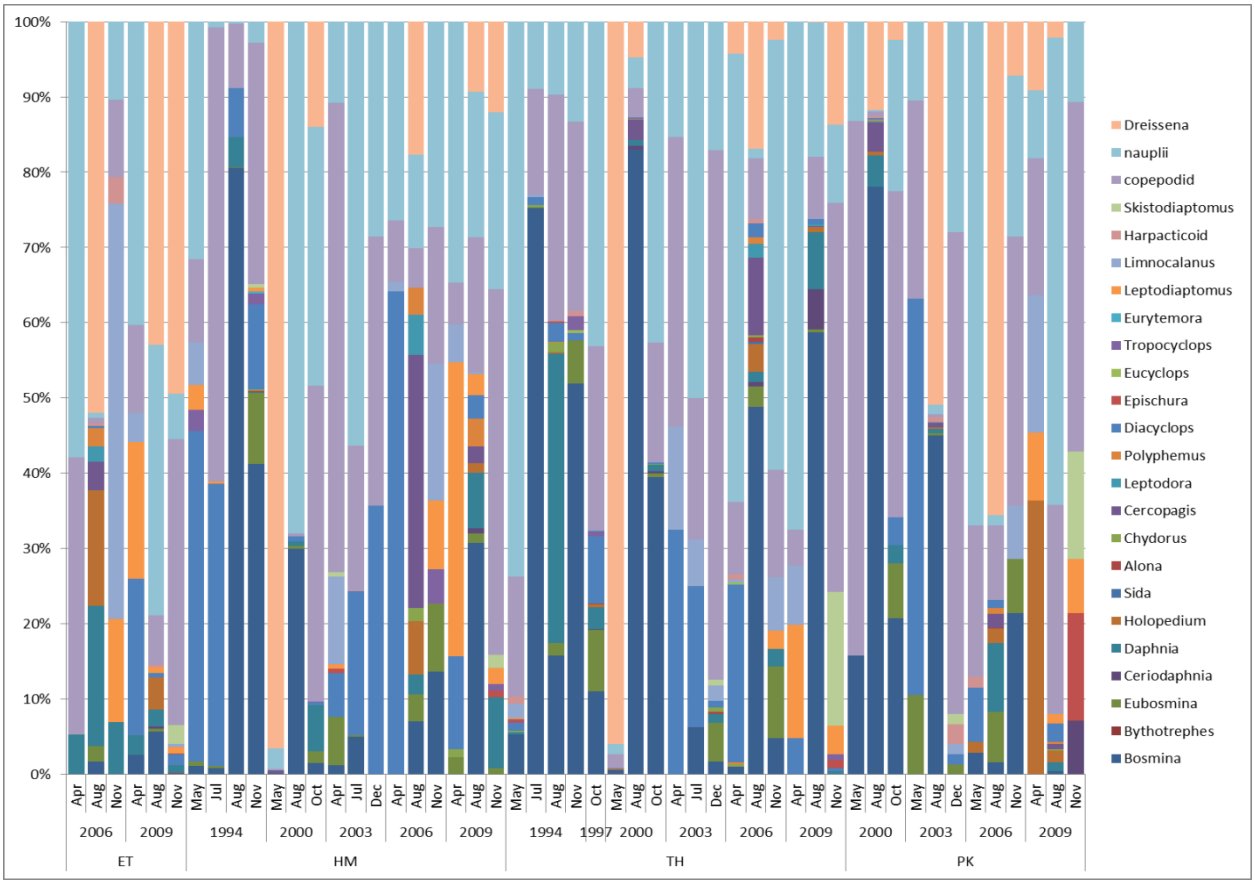

Figure 4: Percent composition of density by genus or group. All samples analyzed for zooplankton composition from sites surrounding Toronto Harbour AOC. ET=Etobicoke, HM=Humber Bay, TH=Toronto Harbour, PK=Pickering.

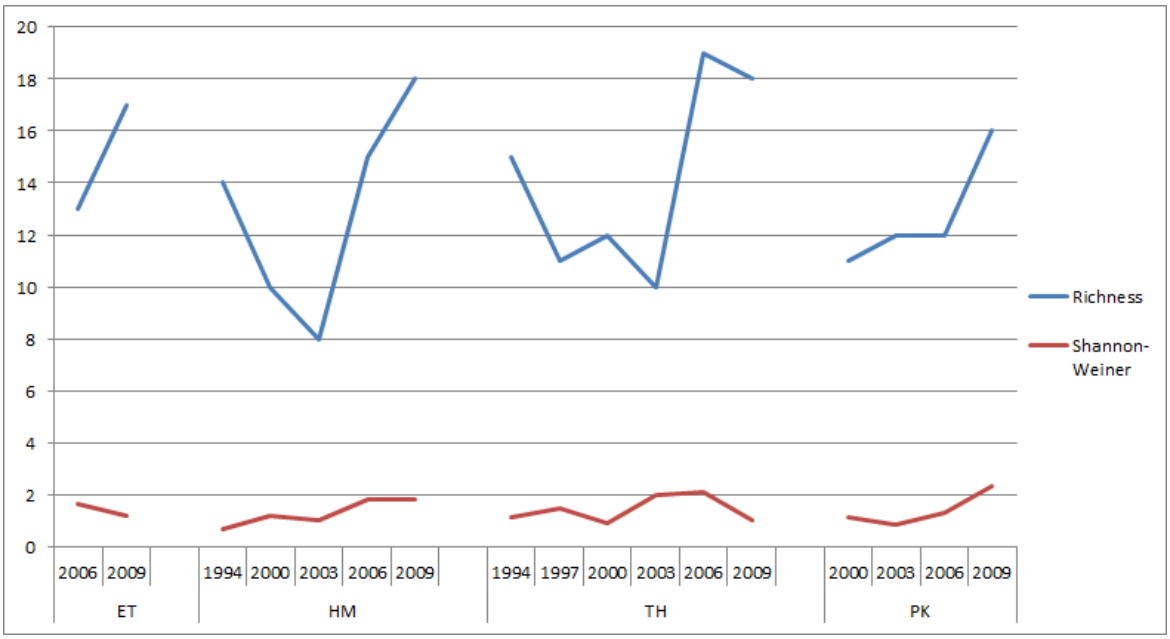

Figure 5: Species richness and Shannon-Weiner H' diversity by year of sampling at the Toronto region sites.

Phytoplankton

The Index phytoplankton samples were identified to species when possible, but generally were resolved to genus. Comments regarding sample composition and preservation can be found in Appendix 2. To simplify the display and analysis of the phytoplankton taxonomy data, major Divisions of phytoplankton were used in this analysis. The groupings include: Cyanophyta (cyanobacteria such as *Planktothrix*, *Anabaena*), Bacillariophyta (Diatoms, e.g. *Tabellaria*, *Asterionella*), Chlorophyta (greens, e.g. *Oocystis*), Chrysophyta (golden-brown algae, e.g *Dinobryon*, *Ochromonas*), Cryptophyta (Cryptomonad, e.g. *Cryptomonas*), Dinophyta (dinoflagellates, e.g. *Ceratium*, *Peridinium*) and Euglenophyta (e.g. *Euglena*) (see Fig. 6).

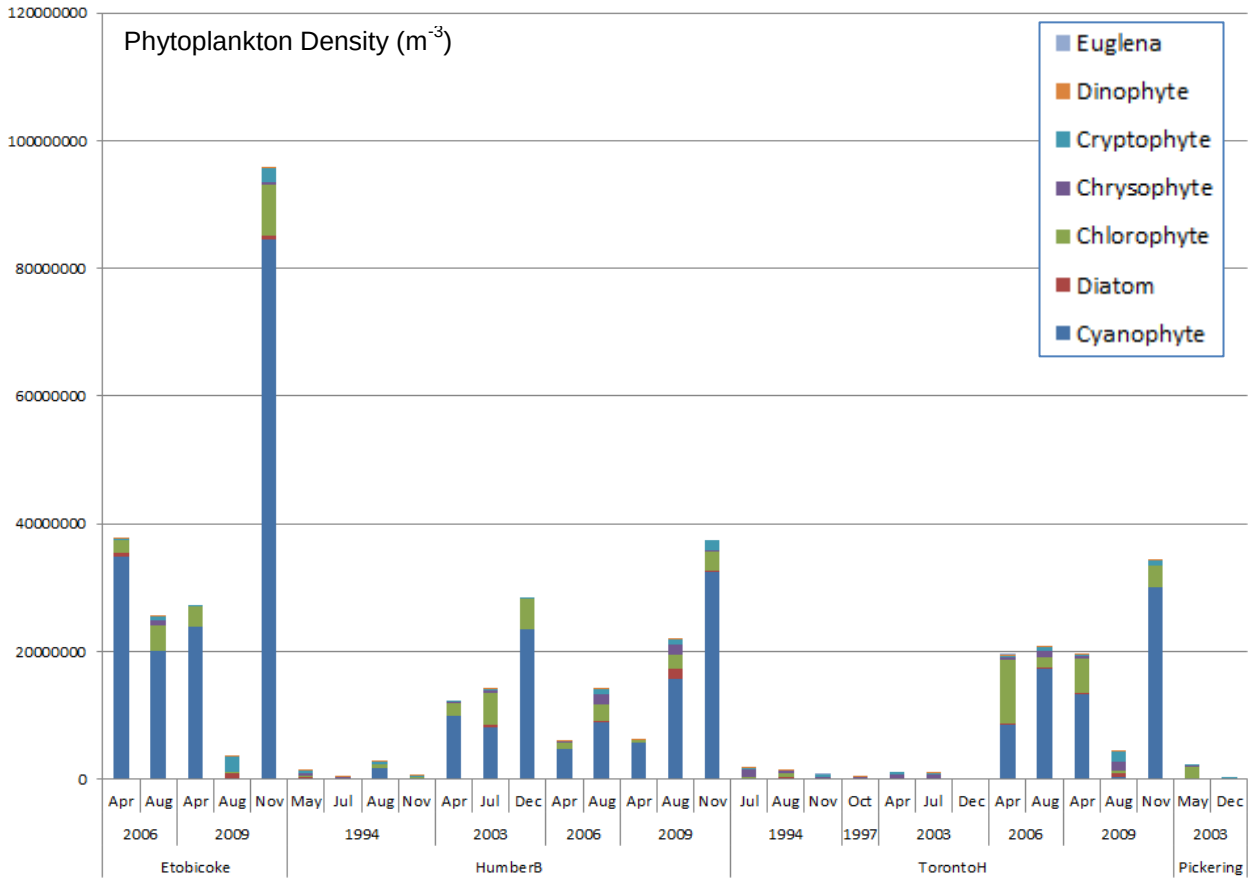

Figure 6: Phytoplankton densities (counts m^{-3}). All samples analyzed for phytoplankton composition from sites surroundingToronto Harbour AOC. ET=Etobicoke, HM=Humber Bay, TH=Toronto Harbour, PK=Pickering. Major groupings are explained in more detail in the text.

The overall counts and biomass indicate very high variability (Fig. 6-7), with some sites showing higher biomass in recent years. Biomass tends to be lowest in the early spring sample and highest in the mid-summer. Rapid changes in species composition or biomass are common in phytoplankton populations. Toronto Harbour had the highest biomass in 1994 due to high counts of a mixed bloom of large-sized dinoflagellates (primarily *Ceratium* but also *Peridinium*) which account for much greater biomass per individual, but is generally at or near biomass found at the other sites. Counts in the Toronto Harbour site have been much higher since 2006 compared to previous years.

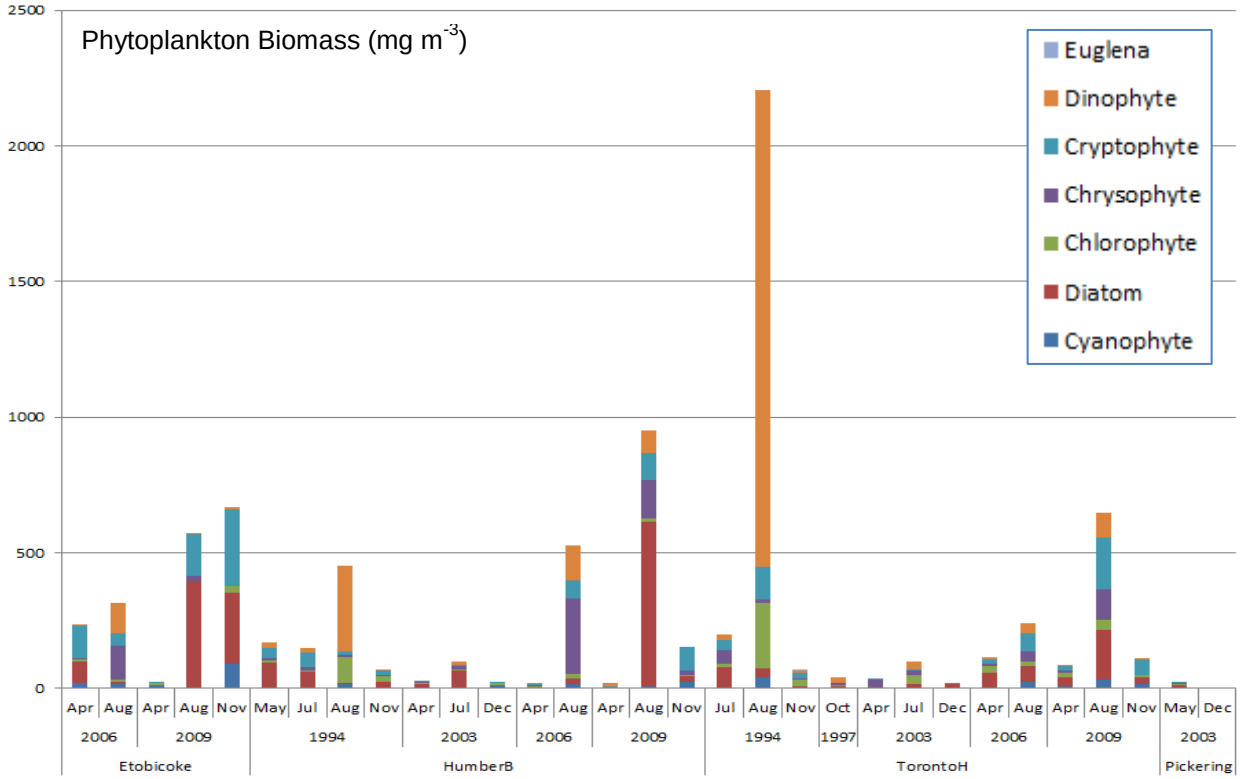

Figure 7: Phytoplankton biomass (mg m^{-3}). All samples analyzed for phytoplankton composition from sites surroundingToronto Harbour AOC. ET=Etobicoke, HM=Humber Bay, TH=Toronto Harbour, PK=Pickering. Major groupings are explained in more detail in the text.

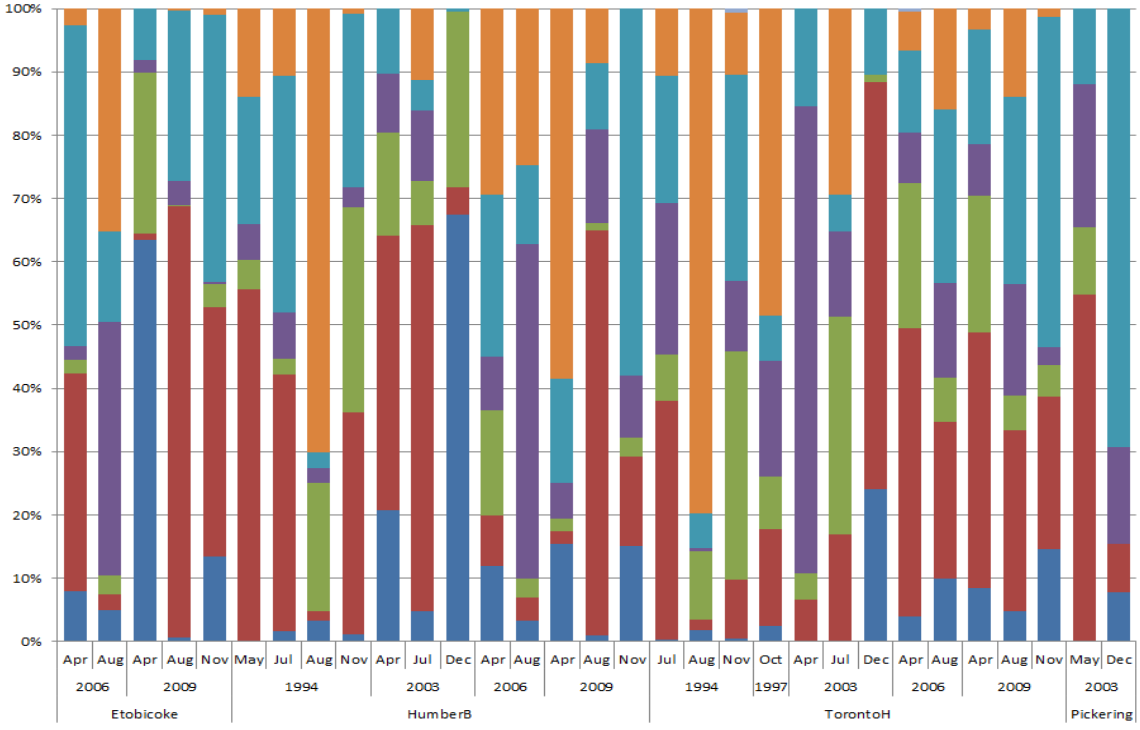

Figure 8: Percent composition of biomass by major algal group. All samples analyzed for phytoplankton composition from sites surrounding Toronto Harbour AOC. ET=Etobicoke, HM=Humber Bay, TH=Toronto Harbour, PK=Pickering. Groups are the same as from Fig. 7.

While the cyanophyta counts account for more than 50% of the total counts, these cells are generally very small so account for only a small proportion of the biomass (Fig. 7). A difference can be seen when comparing the Humber Bay and Toronto Harbour to the other sites when biomass is displayed as percentage by major group (Fig. 8), where higher percentages of dinoflagellates occur in these sites more regularly.

Species richness and diversity cannot be correctly calculated for phytoplankton as they were for zooplankton since taxonomic identification is mixed in that, while some species were identified, it is done mostly only to genus or to major group (e.g. “Tiny chrysophyte flagellates”).

Statistical Analysis

The number of sampling events is not even by year or by site which complicates analyses (Tables 1-2). The only years where all sites were sampled equally for zooplankton are 2006 and 2009. Humber Bay and Toronto Harbour were sampled in 1994, when 4 samples per year were taken, but a 6 year gap exists until 2000 where only Toronto was sampled once in fall 1997. This gap was a period of major changes to the Lake Ontario ecosystem with the introduction and expansion of Dreissenid (both Zebra and Quagga) mussels and the introduction of the large predaceous cladoceran *Cercopagis pengoi*. Phytoplankton samples available from the Index program are even more sparse than those of zooplankton (Table 2) and most of the early samples before 2003 are of questionable condition (Appendix 2).

Table 1: Dates and number of zooplankton samples from each Index station.

Site	Years Sampled	N = # samples
Etobicoke	2006,2009	6
Humber Bay	1994,2000,2003,2006,2009	16
Toronto Harbour	1994,1997 (once), 2000,2003,2006,2009	17
Pickering	2000,2003,2006,2009	12

Table 2: Dates and number of phytoplankton samples from each Index station.

Site	Years Sampled	N = # samples
Etobicoke	2006,2009	5
Humber Bay	1994, 2006	4
Toronto Harbour	1994,1997, 2003,2006,2009	11
Pickering	2003	2

To compare zooplankton densities, the data were log transformed to account for unequal sample sizes and profoundly unequal variance. Even with transformation, differences between sites for zooplankton densities could not resolved (Repeated Measures ANOVA, $p>0.40$) in part due to a strong yearly signal ($p<0.05$) and a highly significant difference between sampling season (spring, summer, fall $p<0.001$) (see Fig. 7). This indicates that the plankton density changes more due to successive samples at a given site than between sites (extremely high variability between samples). It cannot be determined if the reduction in zooplankton that occurred between 2000-2003 is a trend or a local minimum. Attempts to resolve any differences by site using seasonal grouping (e.g. spring only) reduced the-within error variability, but were still not significant ($p>0.05$). Attempts to use MANOVA to resolve any changes in ecological groups of zooplankton could not be accomplished due to uneven samples, low N and strong sample variability.

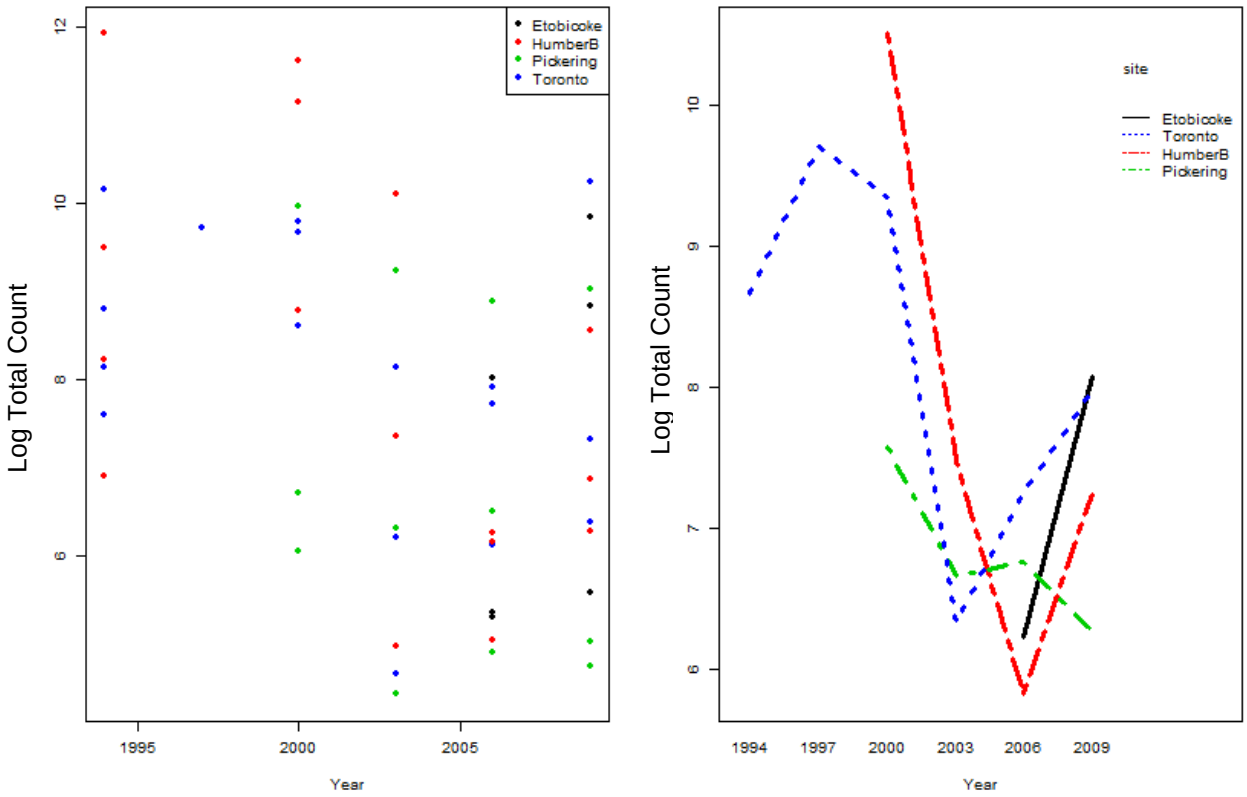

Figure 7: Output showing log-transformed mean zooplankton density values (left) for the Toronto area sites and the ANOVA interaction plot by year (right). Within a given year and between years, densities can vary by several orders of magnitude and trends cannot be determined with confidence.

To compare phytoplankton biomass and counts, the data were log transformed to account for unequal sample sizes and radically unequal variance. A Repeated Measures ANOVA was done by using each year as an independent realization, using season as the repeated sample, and comparing the sites. No differences were found when using density or biomass data ($p>0.4$). The only difference found was in biomass using a two-factor ANOVA for Site ($p=0.033$) with the Pickering-Toronto combination accounting for the majority of the difference (Tukey HSD, $p=0.038$). The finding is questionable however since Pickering had only 2 measurements (Fig. 9) from 2003 and the variances are significantly different ($p<0.01$). Attempts to resolve any differences by site using seasonal grouping (e.g. spring only), were still not significant ($p>0.05$). Attempts to use MANOVA to resolve any changes in ecological groups of phytoplankton could not be accomplished due to uneven samples, low N and strong yearly variability.

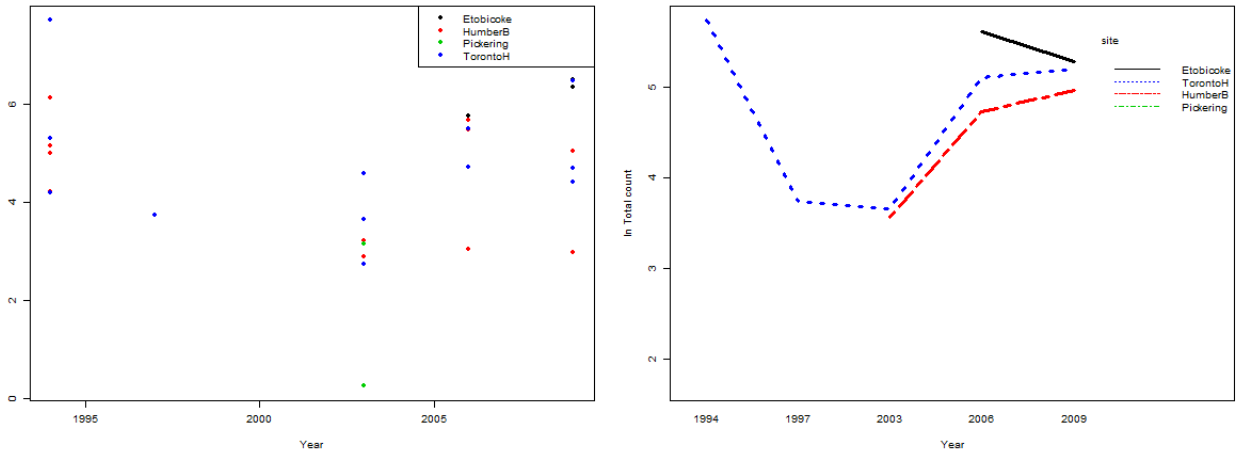

Figure 8: Output showing log-transformed mean phytoplankton biomass values (left) for the Toronto area sites and the ANOVA interaction plot (right). There is less variability year to year in phytoplankton density (~ 4 orders of magnitude) compared to zooplankton.

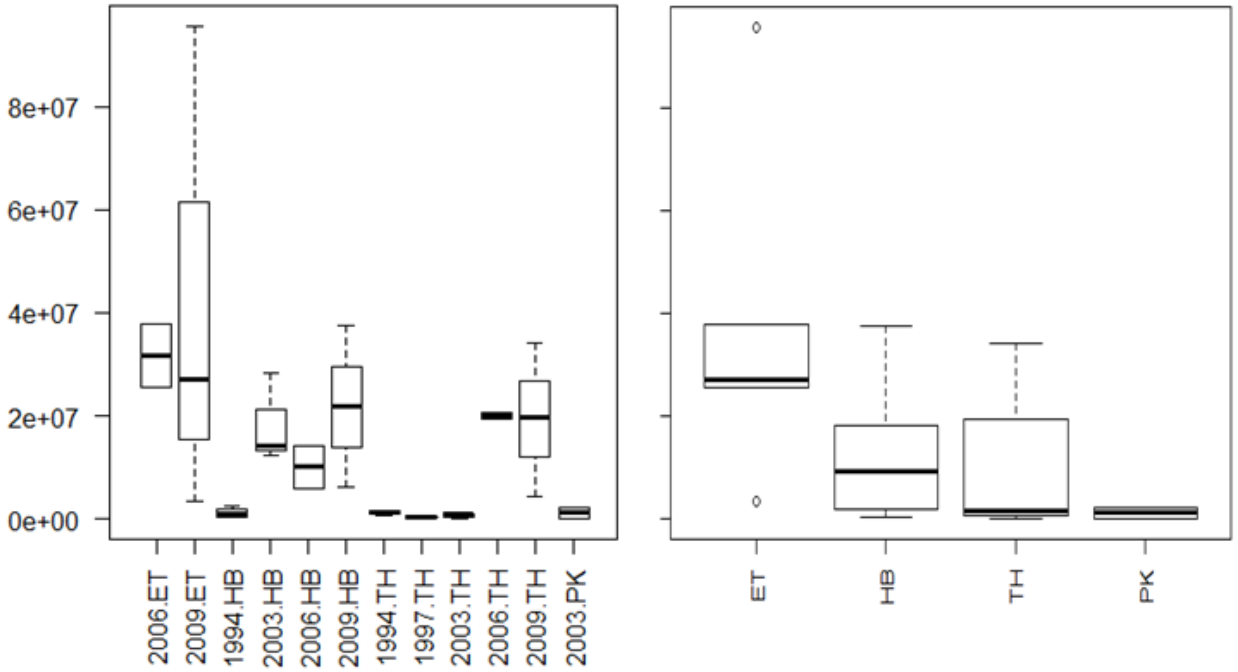

Figure 9: Box plots of phytoplankton density (counts m^{-3}). Upper and lower bars are maximum and minimum with outliers (>3/2 of upper quartile) marked with circles. Dark line is the median. The left plot gives boxplots for each year that a site has more than 2 measurements, while the right plot is for all years combined for each site. Some years have extremely low counts.

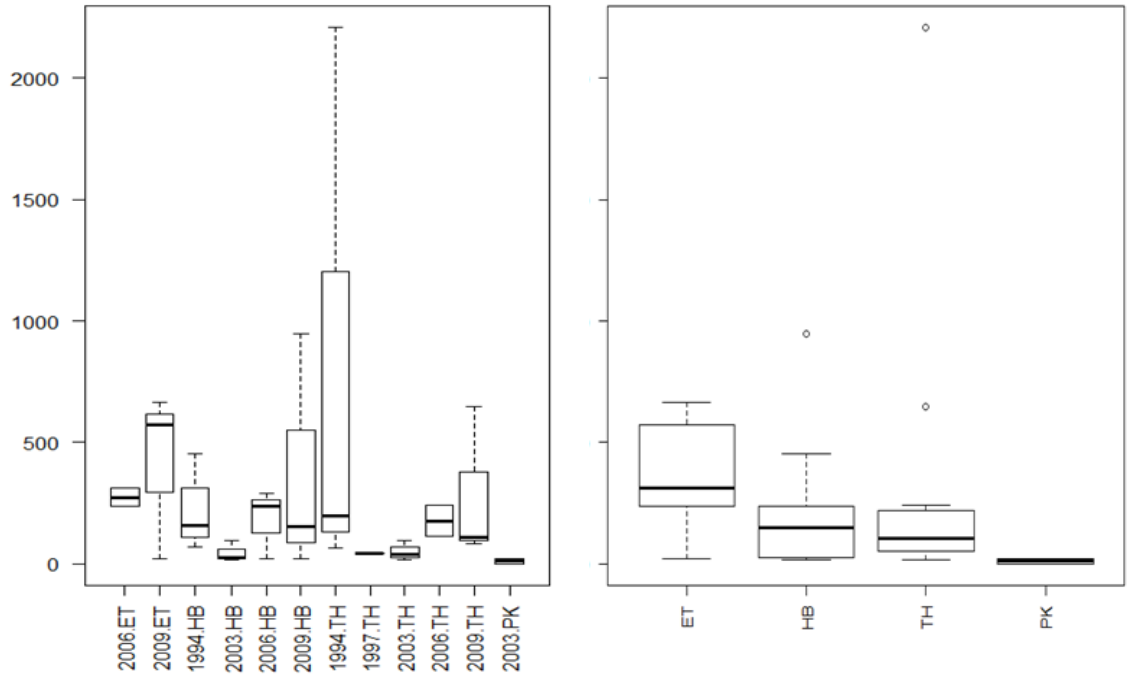

Figure 10: Box plots of phytoplankton biomass (mg m^{-3}). Upper and lower bars are maximum and minimum with outliers (>3/2 of upper quartile) marked with circles. Dark line is the median. The left plot gives boxplots for each year that a site has more than 2 measurements, while the right plot is for all years combined for each site.

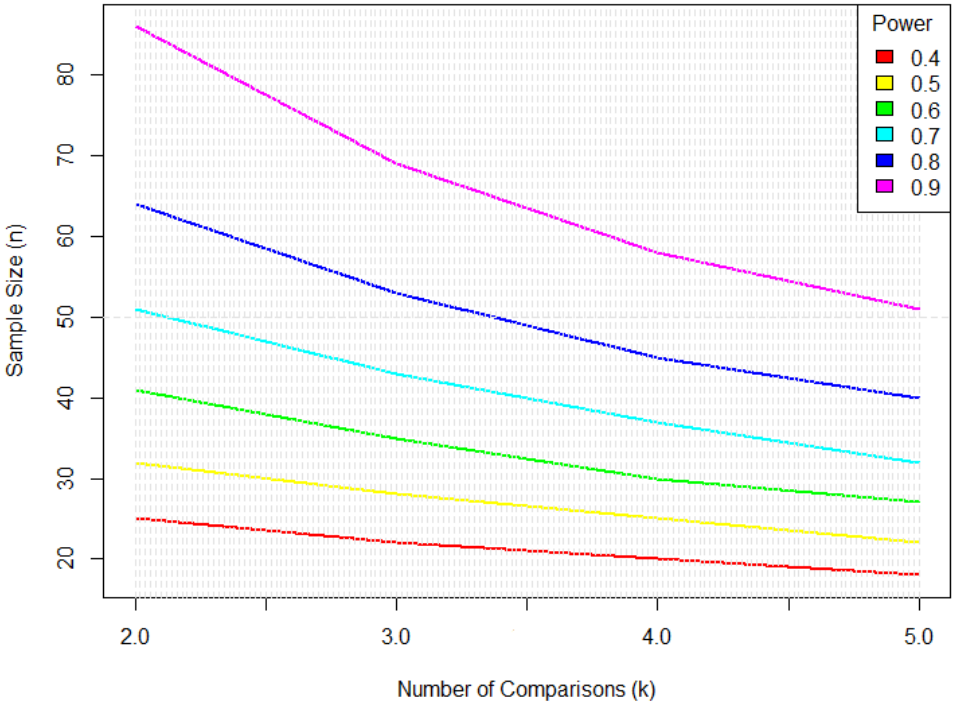

Figure 11: Power analysis graph of sample size required for a given number of comparisons using a two-tailed ANOVA test of means with α=0.05. Output is from the R function *anova.test* in the package *pwr*.

A power analysis was done to estimate the number of samples needed to give sufficient power in an ANOVA at α=0.05, given the number of site comparisons (Fig. 11).

Moderate power is generally given to be approximately 0.7 - 0.8, so for 4 sites, the number of samples collected at each site to detect a difference of one of the sites would be N = 38-44. To detect a difference between two sites, for instance inner Toronto Harbour to an outside reference site, the number of samples would be 51 – 64 per site under the same conditions. This could be done by increasing the temporal or spatial sampling (e.g. sampling at multiple stations within the AOC and/or more often).

Hamilton Harbour Case Study

To evaluate the number of samples needed to resolve the seasonality of plankton populations, a case study was done using Hamilton Harbour. This site has the advantage of being sampled by both MOE and DFO for 2 years (2006 and 2009) using similar methodology but DFO samples 13 samples per year while MOE samples 3 times per year. One methodological difference is the sampling depths at the station. HH258 is a 23m station but MOE collects 3x 30L Shindlers (2, 11, 21m) giving approximately 90L sampled. DFO collects 11x 40L Schindlers (1,3,5,7,9,11,13, 15,17,19,22 m) for about 440L. The consequence is that DFO sampling is more likely to collect depth strata that might have high biomass (such as near the thermocline) and have a greater chance of collecting rare species.

Zooplankton densities for DFO and MOE are shown in Fig. 12. The first obvious finding is that the large *Bosmina longirostris* spike in late spring (end of May-June) is missed by the MOE sampling. This is important because *Bosmina* is the most dominant zooplankton by count and biomass over the season in most embayment locations. The MOE samples are almost devoid of *Bosmina* entirely. The MOE overall yearly density and biomass estimate subsequently are half of that estimated from DFO sampling. When DFO's sampling is divided into spring, summer and fall samples to match those of the MOE, DFO mean density and biomass are still above that of MOE (Fig. 13) using Welch's non-parametric test of means (allowing unequal variance, $p<0.01$). The summer MOE sample is the closest for density or biomass estimates, but it underestimate veliger counts, likely due to vertical patchiness of their distribution. The early spring sample is so early that it catches mostly nauplii and copepodids of calanoid copepods (Fig. 14). The late fall sample is reasonably good for species composition, but it underestimates the density, possibly due to differences in methodology (number of Schindlers taken). This is conservative finding for BUI#13 since phytoplankton communities change even more rapidly over time (Dermott et al. 2006).

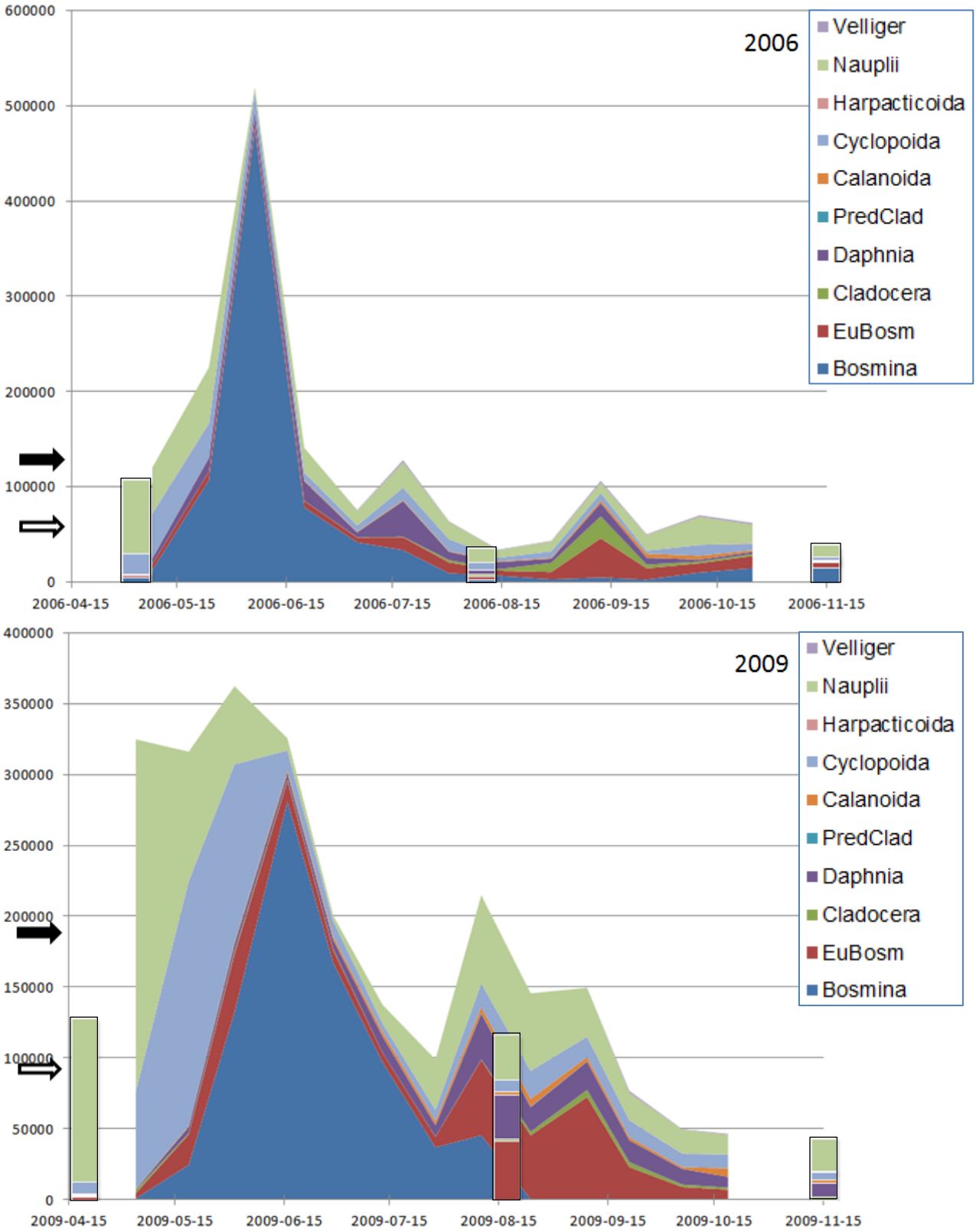

Figure 12: Zooplankton density (counts m^{-3}) for Hamilton Harbour. The 13 DFO samples are shown in the filled area graph while the MOE samples are shown by the stacked bars. Dark filled arrow indicate the yearly average for DFO, the outlined arrow average for MOE samples.

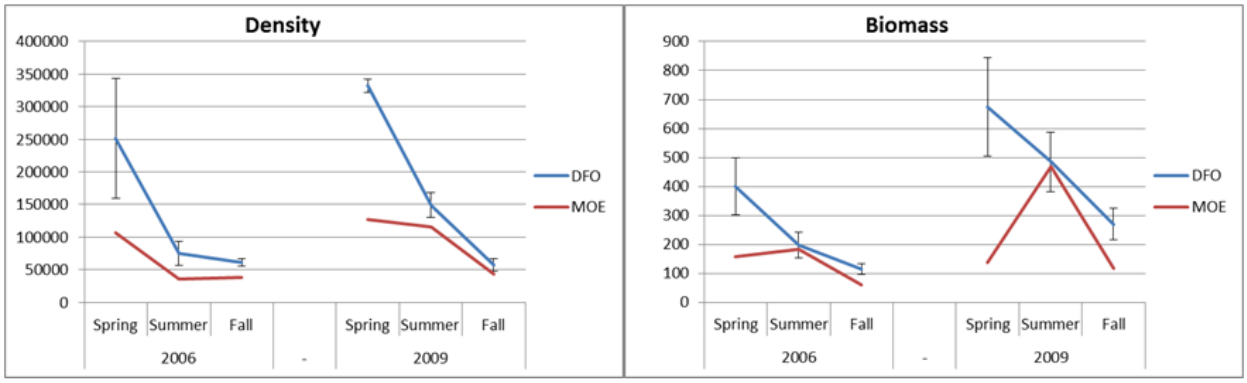

Figure 13: Zooplankton density (counts m^{-3}) and biomass (mg m^{-3}) comparison for spring, summer and fall samples. Error bars are ±SE. For DFO, those designated spring are the first 4 biweekly samples, summer are the next 5, and fall are the last 4.

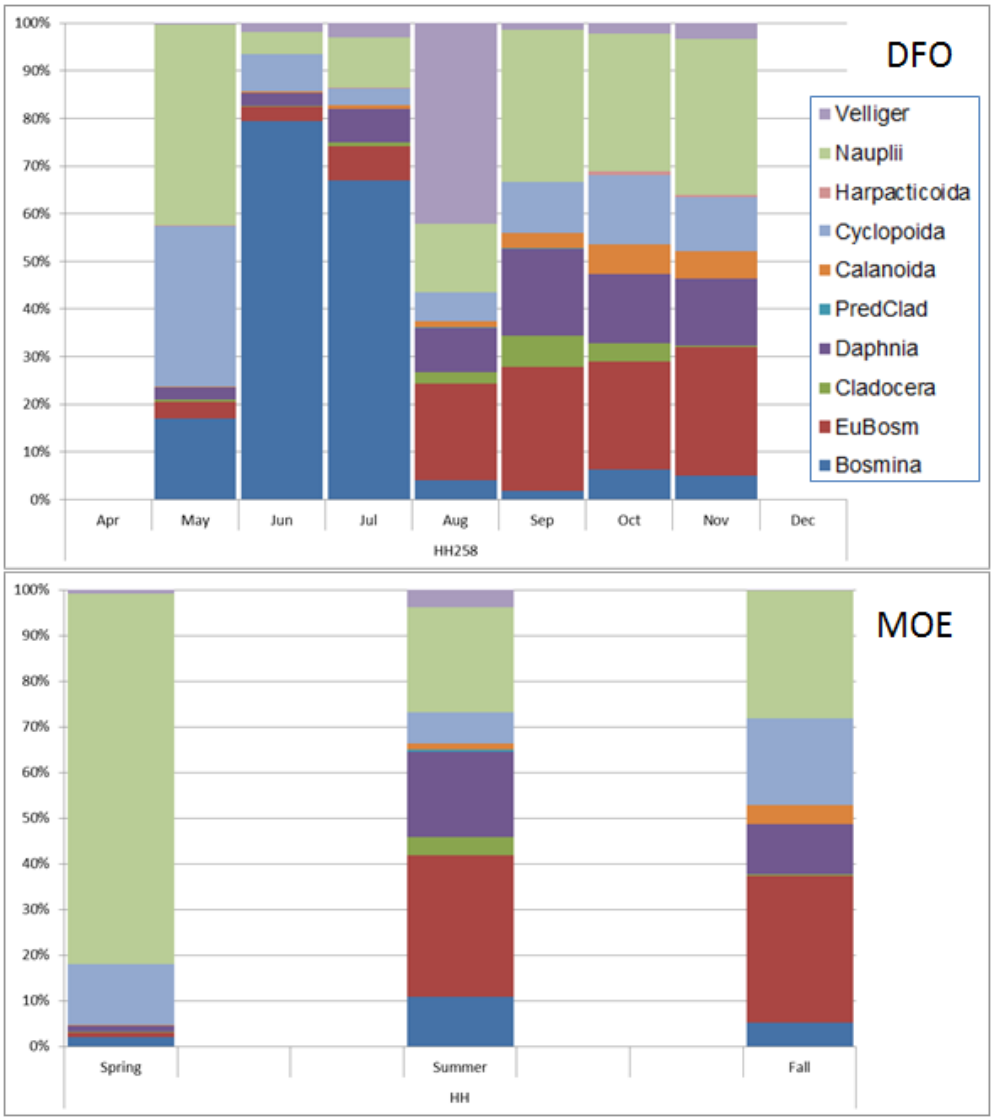

Figure 14: Zooplankton percent composition for DFO and MOE sampling of Hamilton Harbour central station for 2006 and 2009 combined.

By subsampling the DFO biweekly sampling series, it is possible to determine the necessary number of samples to capture both species composition and counts (Fig. 15). To match MOE sampling timing as closely as possible, the first and last sample taken in the season were always used, with the rest of the samples being as evenly spaced as possible, chosen by selecting the closest mid gap sample. In order to capture the *Bosmina* peak in June and July (Fig. 12), it is necessary to take at least 5 samples and preferably 6 over the course of the season. There is an overestimate of the *Bosmina* densities when using 5 samples because one of five samples falls exactly on the biomass peak. Both the 3 and 4 samples treatment evenly spaced over the year underestimate the density and biomass (~ 60%) and suggest the *Bosmina* composition is only 17% of the density when it is in fact 50% and 13% of biomass rather than 26%. Using 6 samples equates reasonably to monthly sampling.

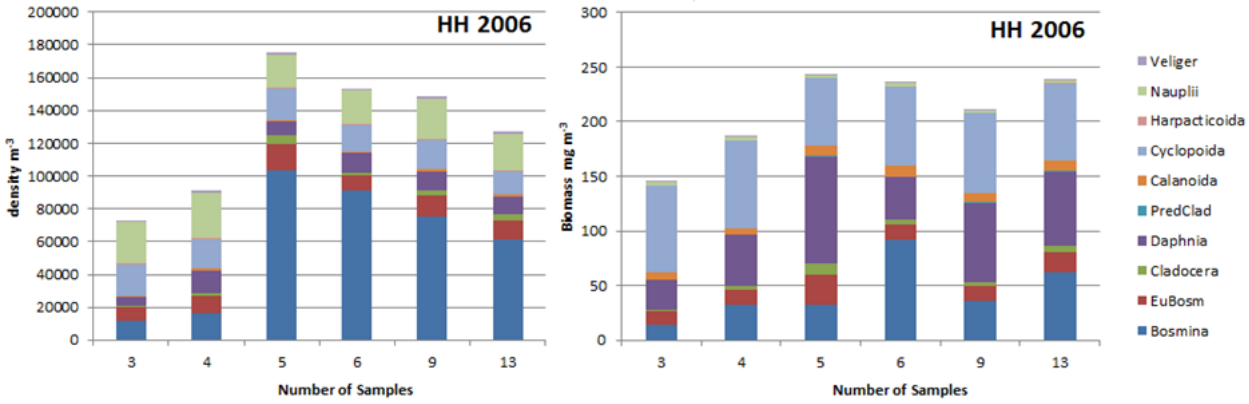

Figure 15: Estimates of density (left) and biomass (right) for zooplankton composition in Hamilton Harbour central station in 2006 as a function of number of subsamples of the total possible 13 samples. To most closely match MOE protocol, the first and last sampling dates were always used.

Summary

Major points:

- Zooplankton densities are very low at almost all of the sites as noted by the taxonomist (Appendix 1).
- A viewing of the taxonomist notes indicated that some sites may not be effective as a reference site for Toronto Harbour. The inner harbour is a protected site which differs considerably from Etobicoke which is exposed coastal. Etobicoke shares similar comments with Oakville (included in Appendix 1) in that it has very few rotifers, which are much more common in protected waters. This effectively suggests that the site has a different food-web than Toronto.
- The MOE Index samples are unevenly distributed by year and site resulting in difficulties for examining the data statistically. Furthermore, even if uneven variance and unbalanced design are ignored and a statistical analysis run, there are too few samples to make a determination on differences in zooplankton or phytoplankton populations by sampling site.
- A power analysis indicated that at least 50-60 samples would be needed from each site to resolve differences between 2 locations (within AOC to a reference site).
- The comparison of DFO to MOE sampling frequency in Hamilton Harbour indicated that the 3 samples taken per year by MOE is insufficient to account for changes in species composition and density over the sampling season. It is recommended that monthly sampling is necessary for zooplankton to give at least 6 samples per sampling year. Phytoplankton have higher variability so are likely to require more frequent samples.

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Appendix 1: Zooplankton taxonomist comments regarding sample viability/composition

Toronto Harbour
DATE: 940713, Rotifers very numerous both in number of taxa and as numerical abundance
DATE: 000516, Extremely poor sample in number of organisms.
DATE: 030430, A very poor sample in number or organisms.
DATE: 030730, A very poor sample in terms of number of organisms.
DATE: 061116, Poorly preserved and also very poor in terms of number of organisms sample.
DATE: 090424, A very poor sample in terms of number of organisms.
DATE: 090810, Algal bloom.
DATE: 091109, Very few rotifers.

Humber Bay
DATE: 001005, Rotifers very numerous.
DATE: 031201, An extremely poor sample in number of organisms
DATE: 030430, Rotifers extremely rare
DATE: 030730, Rotifers very numerous. *Asplanchna* sp. and *Synchaeta* sp. extremely numerous.
DATE: 060427, A poor sample in number of taxa and specimens.
DATE: 090424, A poor sample in terms of number of organisms.
DATE: 090810, Algae very numerous.

Etobicoke
DATE: 061120, No rotifers.
DATE: 090424, Rotifers very few
DATE: 090810, Algal bloom.
DATE: 091109, Rotifers not many

Pickering
DATE: 000529, A very poor sample in number of taxa and individuals.
DATE: 000831, *Keratella cochelaris* extremely numerous.
DATE: 001016, a very poor sample in number of taxa and specimens.
DATE: 030501, an extremely poor sample in terms of number of organisms. No rotifers.
DATE: 030811, a sample dominated by *Bosmina longirostris*. Otherwise the sample was poor in number of taxa and specimens.
DATE: 031204, a very poor sample in number of organisms. One single *Keratella cochlearis* occurred in the entire sample.
DATE: 060515, an extremely poor sample in number of organisms.
DATE: 061121, a very poor sample in number of organisms. Very rare rotifers
DATE: 090429, an extremely poor sample in number of organisms.
DATE: 091109, an extremely poor sample in number or organisms. Rotifers very few

Oakville
DATE: 940512, A sample very poor in number of taxa and specimens. Very few rotifers.
DATE: 000517, Extremely poor sample in terms of number of organisms. Rotifers very rare
DATE: 000810, A very poor sample in number of crustaceans. Rotifers very numerous
DATE: 060428, An extremely poor sample in terms of number of organisms.

Appendix 2: Phytoplankton taxonomist comments regarding sample viability.
Coloured flags were assigned based upon the taxonomist comments and composition of the sample. Red indicates serious degradation or dissolution resulting in a sample that is unsatisfactory and likely to be biased. A yellow flag indicates that caution should be used when using this sample in analysis.

SITE	FLAG	COMMENT
Toronto Harbour		
13-Jul-94		Not well preserved.. Dinobryon cells out of lorica.. Lorica counted and cell size estimated.. Plant remains starch and amorphous mass detritus masses.
25-Aug-94		Poorly preserved.. Detritus and broken fecal material .. Diatoms disolving but not as bad as some others.
10-Nov-94		High plant material flocculent detritus.. Decomposing zoo remains.. Dissolution .. Pseudfeces..
28-Oct-97		Fungal hypae present indicating that the sample became unpreserved prior to sending for analysis.. Very low density, diatom frustules gone.. High detritus- mucilagae clumps , theca of *Ceratium* present but no complete cells
30-Apr-03		Plant remains, empty benthic diatoms poor preservation .. With degradation.. Biomass seems like it might be under estimate.. Also lots of empty Dinobryon
30-Jul-03		-
03-Dec-03		Very sparse not healthy cells.. Near shore sample.. High detritus, fecal pellets, silty clay and Plant material cuticles, marsh pollen and starch grains
27-Apr-06		mucilaginous clumps and plant remains.. Lots of benthic algae.. Probably from near shore erosion.
15-Aug-06		Plant remains, Empty lorica of *Dinobryon sociale* v. *americanum*, empty benthic diatoms, mats of benthic chlorella(not include in biomass ~ 84*60 and 160^2 cells 3-6um in size)
24-Apr-09		-
10-Aug-09		High clay and detritus .. No picos counted
09-Nov-09		Mucilaginous clumping.. Plant remains.. Some empty benthics - possible near shore erosion .. Epiphytic taxa
Humber Bay		
12-May-94		Plant debris.. Diatom dissolution.. Often only chloroplasts remain or ghosts of the frustule. ..Poor preservation.. Or differentational preservation.
13-Jul-94		Diatoms dissolving.. *Pseudokephyrion* and *Dinobryon* lorica present but protoplast shrunk of disappeared. (*Dinobryon* included in count as some protoplasts still present.
26-Aug-94		Poor preservation .. Biomass likely an under estimate as difficult to ID remains of cells.
10-Nov-94		No count for pico blue or greens .. Due to high flocculent detritus. .. Si dissolution
30-Apr-03		Biomass probably significant under estimate… detritus and mucilaginous detritus.. Poor preservation.. Diatoms dissolving .. Not good count at 10x due to only protoplasts left for diatoms. .
30-Jul-03		Some diatoms with dissolution and dinobryon empty.. (recycled .. Also benthic epiphytic taxa present and empty .. Only recently live counted)
01-Dec-03		Plant material, littoral clumps of detritus , very little plankton and mostly empty frustules (only live counted)
27-Apr-06		Plant remains and diatoms very thin and dissolving
11-Aug-06		*Dinobryon Najakjaurensis* present but empty.
08-Nov-06		Still not great shape but better than the samples of 1994.
24-Apr-09		Plant remains present diatoms very thin
10-Aug-09		Pseudofeces and clumps of phytoplankton, empty benthic algae. Chrysophytes not in good shape.. Most dinobryon had left lorica.. Too much time between sampling and preservation!
09-Nov-09		Lots of benthic bacteria present

(Appendix 2 continued)

SITE	FLAG	COMMENT
Etobicoke		
28-Apr-06		Mucilangious benthic material, plant scales and fibers and empty benthic diatoms
14-Aug-06		
24-Apr-09		Some detritus and plant material, seems too low to be real, either concentrating error for original sample or a dilution due to excessive ppt or run off
10-Aug-09		Very high detritus.. Need to dilute extra to ID and enumerate algae.
09-Nov-09		-
Pickering		
01-May-03		Very low biomass.. Lots of plant material .. Diatom frustules dissolved..
04-Dec-03		Very little in samples.. A bit of plant scales and detritus.

SECTION 3: REPORT ON PLANKTON SURVEYS RELATED TO THE THUNDER BAY AOC

K.L. Bowen, H.A. Niblock, and W.J.S. Currie

Introduction

In 1987 the International Joint Commission identified Thunder Bay Harbour on Lake Superior as an Area of Concern (AOC). The main concerns in the AOC were degraded water and sediment quality associated with pulp and paper mill and wood preservation plant operations, grain mill operations and the Thunder Bay sewage treatment plant (Richman 2004; RAP 1991). These include discharges directly to Thunder Bay Harbour and into the lower Kaministiquia (Kam) River, which flows into Thunder Bay. The main contaminants of concern include dioxins/furans, polycyclic aromatic hydrocarbons (PAHs), creosote, polychlorinated biphenyls (PCBs) and mercury (InfoSuperior 2015). The Thunder Bay AOC includes approximately 28 kilometers of Lake Superior shoreline and extends up to nine kilometers offshore from the City of Thunder Bay, including the Welcome Islands (Fig. 1) (EC and OMOE 2011). The primary beneficial use impairments (BUI) that have been identified include sediment contamination and degradation of benthos, fish consumption advisories, impairments to fish populations and loss of species diversity, and loss of recreational value (e.g., beach closures) (RAP 1991). The BUI "degradation of zooplankton and phytoplankton populations" was assumed to be impaired in the 2005 Stage 2 RAP report, but it was not assessed prior to that determination (EC and OMOE 2011). Given the lack of available data on plankton in Thunder Bay Harbour, it has been given the status of "requires further assessment".

To advance knowledge of plankton in Thunder Bay, a 2005 study of total phosphorus (TP) and chlorophyll *a* was carried out by OMOE (Benoit et al. 2012). This study concluded that conductivity, TP and total Kjeldahl nitrogen (TKN) was elevated as a result of urban inputs in the nearshore study area, particularly in the deltas of the Kam and McKellar Rivers, but TP levels had improved in comparison to earlier studies (e.g., Anderson 1986, Richman 2004). Levels have likely further declined since 2005 following improvements to sewage treatment and operational reductions at the Bowater Abitibi pulp mill. Benoit et al. (2012) also showed rapid dilution of TP farther away from the river deltas, and that chlorophyll *a* levels were low and relatively unchanged over the years. They concluded that the area remains oligotrophic and there should be no issues with nuisance algae. While this study is useful in addressing the eutrophication BUI (#8), it does little to directly assess the plankton population BUI #13, especially zooplankton. They recognize that "knowledge of chlorophyll and phosphorus in the study area does not provide proof of healthy phytoplankton and zooplankton biomass in Thunder Bay. More information on plankton community composition would be needed to make that assessment overall". The Great Lakes Laboratory for Fisheries and Aquatic Science was approached in 2014 to process archived plankton samples from the OMOE Nearshore Index Program, but it has been determined that these samples are insufficient to assess BUI 13 in and off itself (see Section 2).

There is fairly limited published information on phytoplankton and zooplankton populations in Lake Superior (e.g. Barbiero et al. 2001; Watson and Wilson 1978; Munawar and Wilson 1978; Yurista et al. 2009; Munawar and Munawar 1978; Munawar et al. 1978; Munawar et al. 1987; Munawar and Munawar 2000; Munawar and Munawar 2009; Reavie et al. 2014; Munawar et al. 2015) and very few studies have included the Thunder Bay area. The intention of this report is to present and summarize the limited amount of zooplankton and phytoplankton data that is available to date from the Thunder Bay area. This has been assembled with the other, relatively more numerous, data from coastal, offshore and embayment areas in Lake Superior. We have reviewed available literature, searched Environment Canada's STAR database at the Canada

Centre for Inland Waters (CCIW) in Burlington ON for relevant information, and compiled data from several unpublished studies conducted by federal and provincial agencies in Canada and the United States. In some cases, we have taxonomically enumerated previously uncounted archived zooplankton samples.

Survey Procedures

1971 and 1973 Great Lakes Biological Laboratory Surveys

In 1970 and 1971, comprehensive lakewide surveys were undertaken in lakes Huron, Erie, Ontario and Superior by the Great Lakes Biological Laboratory at CCIW in Burlington, Ontario. Watson and Carpenter (1974) reported that in Lake Huron in 1971, zooplankton were collected using a 64 µm mesh, 40 cm diameter Wisconsin net, from a maximum depth of 50 m or 2 m off bottom at shallower locations. No corrections were made for net efficiency. One third of each sample was used for zooplankton counts, one third for determining organic material weight, and one third for determining the amount of chlorophyll *a* in the net sample. For zooplankton analysis, the sample was well mixed and two or more 1 mL subsamples were taken with a wide-bore pipette. A minimum of 200 animals (excluding nauplii, the first juvenile stage of copepods) were counted and identified. In all of the studies reported here, zooplankton were preserved in 4% sugar buffered formalin.

We have made the assumption that 1971 Lake Superior samples were collected the same way as the Lake Huron samples described in Watson and Carpenter (1974). Although some sampling information and physical / chemical data for the Superior samples were available in Environment Canada's Star database at CCIW, no zooplankton data were found. Watson (1974) also stated that no firm estimates were available for Lake Superior, indicating these samples were never originally counted. However, many of these zooplankton samples remain in the Fisheries and Oceans Canada (DFO) archival facility at CCIW. We counted archived samples from three stations (station 48 within the Thunder Bay AOC, and coastal stations 45 and 50) from early May and early July 1971 (Fig. 1, Table 1). Each sample was homogenized, and two or three 1 mL subsamples were drawn with a Henson-Stempler pipette. A minimum of 300 animals were enumerated from each sample in a Bogorov counting chamber, including nauplii. Cladocerans were identified to genus, and copepods were classified as cyclopoid, calanoid or nauplii. Lengths of up to 35 calanoids and cyclopoids were measured in each of these samples. Mean weights of cladoceran taxa (weighted for density) were taken from the 2011 Superior CSMI data described below. Length-weight regression equations used in biomass calculations are described in Bowen and Johannsson (2011).

In 1973, the Great Lakes Biological Laboratory at CCIW undertook one of the most comprehensive sampling programs to date in Lake Superior, completing six surveys through the May to November period (Watson et al. 1975, Watson and Wilson 1978, Munawar and Munawar 1978). Each survey, they measured temperature, chlorophyll *a* and chemistry at about 144 stations, and collected zooplankton at 80 sites. They collected zooplankton in the same manner as in 1971, except samples were taken from a maximum depth of 100 m. These stations included 139 within the offshore portion of current boundaries of the Thunder Bay AOC, 138 and 137 at the mouth of Thunder Bay, and 133, 142 and 144 in the coastal area between the mainland and Isle Royale (Fig. 1, Table 1). Sample information, physical, chemical data, and densities and biomass of main zooplankton groups (calanoids, cyclopoids and cladocerans) were obtained from the Star database. Nauplii were not counted in these samples.

Phytoplankton samples were taken from water collected from 0-20 m using an integrating sampler at 34 stations across the lake including stations 139 and 144. Samples were preserved in Lugol's iodine solution and F. Munawar identified species using a phase contrast inverted microscope (Utermohl 1958) using multiple magnifications such that all species present were counted. At least 200 entities were counted. Integrated water samples were also incubated to

measure uptake of ^{14}C in order to estimate total and size fractionated primary productivity as described in Munawar et al. (1978).

USGS June Surveys

As part of their June fish survey work, the Lake Superior Biological Station of the United States Geological Survey (USGS) from Ashland WI has sampled a number of coastal sites in Lake Superior, ranging in depth from 20 to 130 m (Table 2). Water depth, surface and bottom water temperatures were taken at the start and end of each trawling transect. A single total water column 50 cm diameter 64 µm zooplankton net was also taken at the offshore end of each transect. Samples taken in 1990, 1991 and 1992 at up to 33 stations were counted by an unknown contractor to species if possible. Juvenile copepods were only identified as "copepodids" in 1990 and 1991, but as "calanoid copepodids" or "cyclopoid copepodid" in 1992. Additional archived samples from five stations in the Thunder Bay area collected in 2001-2003, 2013 and 2014 were obtained by DFO and counted, as described for the 1971 samples above. Stations 401 to 403 are located in Thunder Bay and ranged from 43 to 80 m deep, 407 is in Black Bay to the east (29 m deep), and 400 is a coastal station to the west (64 m deep) (Fig. 1).

OMOE Index Survey

In 1999, 2005 and 2011, the Ontario Ministry of Environment and Climate Change (hereafter OMOE) surveyed two index sites in the Thunder Bay area in spring, summer and fall (Fig. 1, Table 1). These included Welcome Island (284) within Thunder Bay, and Flatland Island (283), a protected coastal station just south of Thunder Bay. Sturgeon Bay (285), a coastal site to the east, was also sampled in 2005 and 2011. Depths at these three sites averaged 17, 7 and 10 m deep, respectively. At each site, three 30 L Schindler-Patalas traps with a 64 µm sock were collected 2 m from the surface, mid-depth and 2 m above the bottom of the water column and pooled. Zooplankton in these samples were identified to the species level if possible, counted and measured by taxonomist C. Tudorancea as described in Bowen and Johannsson (2011).

More details of the OMOE Index program are provided in Section 2. Various water chemistry parameters were also measured as part of this program (N. Benoit, Ontario Ministry of the Environment, Toronto, ON, personal communication, 2012), although we obtained results from the OMOE only for the 2005 year.At these same sites, integrated water samples were collected and preserved with Lugol's iodine solution for phytoplankton enumeration. Samples were collected using a 'glug-glug' sampler over the euphotic zone (2 x Secchi or to the top of the metalimnion if stratified). Phytoplankton samples were counted by Hedy Kling following methods described in Findlay and Kling (1996).

OMNR 2005 Embayment Surveys

Lake Superior was the focus of intensive lake-wide monitoring programs in 2005 and 2011 as part of the multi-agency, binational Cooperative Science Monitoring Initiative (CSMI). As part of this program, the Ontario Ministry of Natural Resources and Forestry (hereafter OMNR) undertook spring, summer and fall surveys at four embayments in 2005, under the supervision of T. Johnson, Research Scientist OMNR. Three stations along a depth gradient of 10 m, 50 m and 100 m water depth were sampled at each of Thunder Bay (south of Pie Island), Nipigon Bay, the Apostle Islands and the Duluth MN area (Figs. 1 and 2, Table 1). All of the 10 m deep stations were within 0.5 km of shore. Given the steep bottom slope in coastal Lake Superior, the 100 m deep stations were at most only 4 km from shore. Secchi readings and a Hydrolab profile (temperature, conductivity and pH) were generally taken at each station. More details of this study are provided in Dietrich (2006).

Total water column zooplankton were collected from each station using either a 64 µm, 40 cm diameter net or a 153 µm, 50 cm diameter net, as outlined in Table 7. All of the available Thunder Bay samples and a subset of the 10 50 and 100 m deep samples from the other areas

were enumerated by taxonomist J. Foster, using the methods reported in the OMOE survey above. Nauplii counts are not provided due to inconsistencies in net mesh size, as they are not adequately captured by 153 µm mesh.

2001 Surveillance Survey

In 2001, in partnership with EC's surveillance program on board the CCGS Limnos DFO sampled 9 stations in May and 14 stations in August (Table 3a). Samples were collected with an integrating sampler from 0-20m and preserved in Lugol's iodine solution. Samples were enumerated by F. Munawar using the inverted microscope Utermohl technique (Utermohl 1958) and a minimum of 200 entities were counted. Integrated water samples were also incubated onboard with ^{14}C to estimate size fractionated primary productivity as described in Munawar et al. (2009).

2011 CSMI Survey

In 2011 as part of a lake wide CSMI survey, DFO sampled 16 stations in Lake Superior from late July to early August, and 10 stations from late September to early October (Fig. 2, Table 3b). This was in partnership with EC's surveillance program on board the CCGS Limnos. A single total water column zooplankton sample was taken at each site using a 50 cm diameter 153 µm net. These were taken to a maximum depth of 100 m, or 2 m off bottom at shallower stations. These were enumerated as described in the OMOE survey above. Temperature profiles and Secchi readings (during daylight hours only) were also taken on the surveillance cruises. Integrated water samples were collected from 0-50 m in spring and summer and 0-20m in fall. Samples were incubated with ^{14}C to estimate size fractionated primary productivity as described in Munawar et al. (2009).

Results and Discussion

Physical / Chemical Parameters: *Temperature*

Embayments in Lake Superior such as Thunder Bay begin warming more quickly in the spring than coastal and offshore areas, which gives zooplankton production in these protected areas a head start relative to the open lake. For example, during the early June surveillance cruise by EC in 2005, temperature at station 139 was 8.4 °C, compared to only about 3 °C offshore. During the USGS surveys in the early 1990s, June surface temperatures in Thunder Bay averaged about 12 °C at nearshore stations 401 and 402, and were slightly cooler (7.9 °C) at 403 near Pie Island due to its closer proximity to open water (Table 2). Temperatures in Black Bay ranged between 10.5 °C at the mouth to 15.7 °C in the protected inner bay. Western Nipigon Bay (stations 412 to 414) was also relatively warm (about 13 °C) compared to the stations 415-417 in the eastern area (7-10 °C). Eastern coastal stations were only around 3 °C in June. Southern and western coastal stations were intermediate in surface temperature, ranging from 5 to 8 °C. Monthly sampling in the early 1970s shows that in May, the Thunder Bay sites were similar in temperature to adjacent coastal areas, but by June they were beginning to warm relative to the lake (Tables 4 and 5). They tended to stay warmer through the summer months, but by October, the embayment stations were again similar to the coastal sites. This shows the lag effect in season in Superior; the coastal sites remain cool even in July, and temperatures in mid-September are still indicative of summer conditions.

The OMNR embayment sampling in 2005 showed that in early June, both the Nipigon Bay (NB) and Thunder Bay (TB) sites had just started warming at the 10 m deep stations (Table 6), but temperatures were still ≤5 °C. Surface warming was evident at the Dululth sites by mid-June (7-8 °C). By mid-July, the TB stations had reached 16-18 °C at the surface, but the upper water column was still unstable as temperature declined rapidly with depth. Epilimnetic temperatures ranged from 14 to 17 °C at the TB sites through the summer, and the epilimnion had deepened to >20 m by late September. Even in mid-October, the surface was still 14 °C, and the epilimnion had reached a depth of about 37 m at TB50. The highest temperatures during the

OMNR survey were observed at the NB sites in early August (19 °C) and the Apostle Island (AI) sites in early September (18 °C). The coastal Duluth sites remained cooler, reaching only 6-10 °C in mid-August and about 13 °C in early September.

During the 2011 CSMI lakewide survey, epilimnetic temperature at 139 in Thunder Bay was 16 °C in early August and 13 °C in late September (Table 3b). Epilimnetic temperatures at the coastal stations were similar, ranging from 16 to 21 °C in the summer and 10 to 17 °C in the fall. Although epilimnetic temperatures in the offshore were generally cooler than the coastal stations in the summer (9 to 18 °C), they were more similar in the fall (10 to 15 °C).

Secchi Depth

Secchi depth, an indicator of water clarity, is generally quite low in the Kam River delta area due to tributary inputs of sediment and DOC, and increases farther offshore. Benoit et al. (2012) reported secchi depths of only 0.3 to 2 m in the river and delta, and values between 1.3 and 7 m beyond the delta. Secchi values ranging from 4 to 6 m were observed in Thunder Bay during the early 1970s (Tables 4 and 5). The lowest value (1.5 m) was observed on 2-Jun-1971 at station 48, indicating relatively high turbidity at that location. Coastal Secchi depths usually ranged between 9 and 14 m in May and June 1971, and between 5 and 9 m from July to October. In 2005, the OMOE Thunder Bay stations 283 and 284 were also turbid in mid-May (Secchi = 1.3 m) and again at 283 in early October (1.2 m) (Table 7). Station 283 is shallow and may be experience shoreline turbulence, whereas both 284 and 48 are closer to the City of Thunder Bay and may be influenced by discharge from the Kaministiquia (Kam) River. The Thunder Bay OMOE stations were less turbid during August, with Secchi depths of 4-6 m. Water clarity at Sturgeon Bay (Station 285) was moderate, ranging from 3-4.8 m. Unfortunately, physical and chemical data were not readily available from the OMOE stations in 1999 and 2011.

In contrast, water clarity was greater at Thunder Bay area sites farther from the Kam River during other 2005 surveys. Secchi readings at station 139 were about 8 m in both early June and mid-August 2005 (CSMI, EC Surveillance). The OMNR Thunder Bay area stations were located to the south of Pie Island and also appeared to be more indicative of Lake Superior coastal conditions. On 30 May, Secchi was 9.8 m at TB10, 11.3 m at TB50 and 16.8 m at TB100. This was the highest Secchi value observed during the 2005 OMNR surveys. On the remaining dates, Secchi at the TB sites ranged from 7.2 to 12.6 m. Water tended to be clear at Duluth and the Apostle Islands in summer and fall, with Secchi depths ranging between 9.0 and 13.8 m. Water clarity in Nipigon Bay was generally lower, with Secchi depths between 5.6 and 9.2 m. During the summer 2011 CSMI survey, water clarity was generally high, with Secchi depths ranging from 8 to 13 m in the coastal areas, and 11-16 m in the offshore (Table 3). In the fall, offshore values were 8 to 12.5 m. Fall Secchi depth at the Duluth station (221) was only 2.5 m, and 6 m at 139 in Thunder Bay.

Water Chemistry

In the early 1970s, TP values were often slightly elevated in Thunder Bay (2.8 to 7.7 µg L^{-1}) relative to adjacent coastal areas (1.9 to 6.1 µg L^{-1}) (Tables 4 and 5), but were still within the oligotrophic range (Vollenweider et al, 1974, after Wetzel, 2001). The highest value was observed during a turbid spring day in 1971 at station 48 near the Kam River mouth, and was likely due to sediment loading. Soluble reactive phosphorus (SRP) was also very low in in the early 1970s, usually under 1.5 µg L^{-1}. Turbidity was also generally below 1 FTU. In 2005, TP was elevated at the OMOE sites in May (12.3 to 23.3 µg L^{-1}), and at 283 in October (11.7 µg L^{-1}) (Table 7). However, this coincided with higher turbidity and much of this likely represented phosphorus bound with suspended sediment. Phosphate phosphorus, the dissolved fraction available for algal uptake, was generally ≤1 µg L^{-1}. During the EC 2005 surveillance cruises, TP values at Station 139 in June (4.4 µg L^{-1}) and August (3.0 µg L^{-1}) were in the same range as seen offshore (EC Star Database, CCIW). In May 2001, TP at stn 139 was higher than the

offshore, while in August it was in the same range as offshore stations. Benoit et al. (2012) reported elevated phosphorus in the immediate area of the Kam River delta and along the inner harbour adjacent to the city (e.g., 6-54 µg L^{-1}). Levels quickly diminished farther offshore, ranging from 6 to 16 µg L^{-1} in the spring and 3 to 8 µg L^{-1} in the summer and fall. Jackson et al. (1990) also showed that TP and other nutrients in the Thunder Bay area were similar to other Canadian shoreline sites in Lake Superior.

Total chlorophyll *a* values were also very low (≤2.2 µg L^{-1}) in the Thunder Bay area throughout the 1973 season (Table 5), again indicating oligotrophic conditions. In 2005, values for this parameter were similar, ranging between 1.4 and 3.8 µg L^{-1} at OMOE stations 283 and 284, and 1.8 µg L^{-1} or less at 285 (Table 7). EC Star Database data from 2001 show 139 with the highest chl *a* value in the August cruise although it was still very low. Benoit et al., (2012) also showed that chlorophyll levels were low in the Thunder Bay area in 2005, with median values ranging from 1.1 to 2.7 µg L^{-1}. The highest concentrations were generally observed in the nearshore adjacent to the City of Thunder Bay.

Phytoplankton

Biomass and Community Composition

The seasonal aspect of the phytoplankton community in offshore Thunder Bay (station 139) was captured during the 6 surveys undertaken in 1973 where biomass increased through spring to a peak in late July and remained relatively stable through to December (Table 8, Fig. 3). Total biomass was ultra-oligotrophic at all dates, with a peak of 277 mg m^{-3} in July and a low of 51 mg m^{-3} in October. All cruises (except July) were dominated by Cryptophyceae (26-78% of the total biomass), closely followed by Chrysophyta (9-40%) and Diatomeae (3-47%, Fig. 3). *Rhodomonas minuta* was common throughout the year and composition did not change much through the season (Table 8, Munawar and Munawar, 1978)**.** The total biomass observed at 139 and 144, the two stations in the Thunder Bay area, are in the range of open lake stations but did not come close to the peaks in biomass observed in the western arm stations (Fig. 4).In 1983, total phytoplankton biomass at stn 139 remained in the ultra-oligotrophic range, at less than 300 mg m^{-3}, but was more constant throughout the year than it was in 1973 showing no defined peak (Fig. 3). As in 1973, the annual average of 250 mg m^{-3} at this offshore Thunder Bay station was in line with the biomass at other offshore stations across the lake which averaged 253±44 mg m^{-3} in June and 224 ±13 mg m^{-3} in September (Fig. 4) and was lower than the biomass observed near Duluth. There was a more even mix of taxa in the biomass in 1983 with less contribution by Cryptophyceae and increased Diatomeae and Chrysophyceae (Munawar and Munawar, 2000). Chlorophyta were still low and constant throughout the year (Fig. 3).

Phytoplankton biomass at 139 was in the oligotrophic range in May 2001 (1943 mg m^{-3}) and slightly eutrophic in August (3332 mg m^{-3}, Fig. 3), which is a large increase in overall biomass from the earlier surveys (Munawar and Munawar, 2009). Composition in May and August was dominated by Diatom taxa (57% and 76% biomass) and the importance of Cryptophycea had completely diminished (4% biomass). Chrysophyceae still contributed 13 and 20% to the total phytoplankton biomass measured. Another interesting change is that while the Thunder Bay station was in line with other offshore stations in 1973 and 1983, in 2001 it contained the highest biomass (Fig. 4), surpassing even the nearshore station at Duluth (221) which had much higher biomass than Thunder Bay in 1973 and 1983.

2001 spring biomass at 139 was dominated by *Asterionella formosa* Hassall while summer biomass was dominated by *Tabellaria fenestrata* (Lyngb.) Küetzing and *Tabellaria flocculosa* (Roth) Küetzing. There were 80 taxa identified in the May cruise (Table 9). Of these, 5 were oligotrophic indicators and 8 were eutrophic indicators (Munawar and Munawar 2009). In August there were 122 taxa of which 10 were oligotrophic indicators and 11 eutrophic indicators. The biomass of the oligotrophic indicators was higher than the eutrophic indicator in both months.

Phytoplankton taxonomic data from Thunder Bay offshore station 139 showed an increasing trend in biomass from ultra-oligotrophic in 1973 to mesotrophic in 2001. A shift in percent composition was also apparent with decreased unicellular flagellated Cryptophycea and increases in Diatoms (Fig. 6). This station also shifted from having biomass similar to other offshore stations and much lower than the west end /Duluth area stations in 1973 and 1983 to having the highest observed biomass in 2001.

Phytoplankton biomass from samples collected during the seasonal OMOE index surveys in the Thunder Bay area in 1999, 2005 and 2011 are presented in Fig. 7. At all 3 locations and seasons total biomass appears to be increasing or holding steady over this time period. Overall the biomass is in the ultra-oligotrophic range and so much lower than the values measured in 2001 by Munawar and Munawar (2009). Composition is dominated by Diatoms and Chrysophyceae at all stations and dates and this is similar to the 2001 sampling by Munawar and Munawar (2009).

Species composition is given in table 10. The Chrysophyte genera *Ochromonas* and *Pseudopedinella* are common at all stations, *Tabellaria* and *Fragillaria* Diatoms are very common. Cryptophytes *Cryptomonas* and *Rhodomonas* are found at all stations but at higher biomass in the Welcome and Flatland Islands sites compared to Sturgeons Bay.

Phytoplankton productivity

Phytoplankton productivity averaged between 1.08 and 2.06 mg C m^{-3} hr^{-1} across Lake Superior during cruises from June through December, 1973 (Fig. 5) with a low of 0.27 to a high of 12 mg C m^{-3} hr^{-1} (Munawar et al. 1978). The primary productivity at station 139 was consistently higher than the monthly average and was the highest value recorded in the lake for the June-September (Fig. 5). Activity coefficient or productivity to biomass ratios (P:B) averaged across Lake Superior from June through December, 1973 ranged between 2.16 and 2.68 (g C m^{-3} d^{-1} / g Biomass m^{-3}) $x10^{-1}$ with a low of 0.25 to a high of 6.62 (g C m^{-3} d^{-1} / g Biomass m^{-3}) $X10^{-1}$ (Munawar et al. 1978). Productivity to biomass was variable at 139 being highest in the lake in June, higher than average in September and October and lower than average in July and December. In 1983 productivity was not estimated in the Thunder Bay area. Lakewide primary productivity was higher than in 1973 and averaged 2.6 ± 0.48 mg C m^{-3} hr^{-1} in July and 4.7± 1.12 mg C m^{-3} hr^{-1} in August.

In 2001, lakewide average primary productivity averaged 0.46± 0.05 mg C m^{-3} hr^{-1} in May and 1.11 ± 0.12 mg C m^{-3} hr^{-1} in August (Munawar and Munawar 2009). Station 139 had the highest rate recorded in May and second highest in August (Fig. 5). Average productivity in May was dominated by the mid-sized nano-plankton (2-20 µm, 55%) followed by small pico (>2 µm, 37%) and then net (>20µm, 7%) plankton while productivity at station 139 was more of a mix of size classes with more of the large plankton than average (26%). In August, lakewide average productivity had relatively more mid (65%) and large (14%) sized plankton compared to May. Station 139 showed different conditions with 47% of the productivity coming from the largest size category. Taxa that would be included in this large category are colonial or chain forming species such as *Tabellaria fenestrata*, a large chain forming Diatom that was a 47% of the phytoplankon biomass in August (Table 9).

In 2001, lake wide average P:B was higher in August (1.2 ± 0.16 mg C m^{-3} d^{-1} / mg Biomass m^{-3}) than in May (0.5 ± 0.05 mg C m^{-3} d^{-1} / mg Biomass m^{-3}). The Thunder Bay station was fairly consistent in spring and summer at 0.47 and 0.54 mg C m^{-3} d^{-1} / mg Biomass m^{-3} in May and August respectively. In 2011, primary productivity was measured during summer and fall cruises and the lakewide average was 1.12 ± 0.12 mg C m^{-3} hr^{-1} in summer and 0.62 ± 0.09 mg C m^{-3} hr^{-1} in October (Fig. 5) (Munawar et al. 2015). The 2011 summer lake wide averages were

almost exactly that found in 2001. The productivity at station 139 was very close to the lakewide average, with values of 1.23 and 0.58 mg C m^{-3} hr^{-1} in summer and fall respectively.

Rates of primary productivity declined at station 139 over the 1973 to 2011 time period (Fig. 6) and were consistently dominated by the <20 µm sized algae. While there appeared to be an increase in netplankton in 2001 compared to summer 1973, the nanoplankton became more important in the 2011 sampling. More frequent sampling is needed to determine trends.

Zooplankton

Zooplankton Density, Biomass and Community Composition

Zooplankton community composition in Thunder Bay and elsewhere in Lake Superior is seasonal in nature, and the timing of seasonal succession is influenced by temperature. Generally, densities and biomass are low in the spring, peak in the summer, and begin declining in the fall. Overall, Lake Superior zooplankton densities are low compared to most other Great Lakes sites (Watson and Wilson 1978, Barbiero et al. 2001). Zooplankton species richness was relatively low at all of the Lake Superior sites, especially in the offshore. When juvenile forms that were not identified to genus or species were excluded, only 11 taxa were identified at the offshore sites in both summer and fall (Table 12). At the coastal sites, the number of taxa increased to a maximum of 19 in the fall. Most of the same taxa were found in Thunder Bay as the coastal sites, although richness was slightly less in Thunder Bay, with a maximum of 16 taxa in the summer. Taxa richness at the other embayment sites ranged from only 6 taxa at Duluth in the spring, to 19 taxa at Nipigon in the spring. The number of taxa is partly dependant on the number of samples counted (Table 11), as rare taxa are more likely to be encountered as the number of samples increases.

Copepod nauplii (larvae which were not consistently identified as cyclopoid or calanoid) were often numerically a dominant part of the zooplankton community in Lake Superior, especially in the spring (Table 11, Figs. 5, 12 and 13). The highest nauplii densities observed within Thunder Bay occurred in June and July 1971 (Fig. 8) and May and July 1999 (Fig. 13), when densities ranged from 12 213 to 20 673 ind m^{-3}. Nauplii densities also intermittently fell between 5 000 and 12 000 ind m^{-3} during the spring USGS surveys at the Thunder Bay area sites (Fig. 12). However, values were usually <5000 ind m^{-3} during most surveys. Nauplii comprised about 84% of total zooplankton density at spring coastal sites but only 4% at offshore fall sites. In Thunder Bay, napulii made up 71% of total density in the spring, 23% in the summer, and 22% in the fall. However, they were generally unimportant in terms of biomass due to their small size, comprising ≤ 6% of the total, or <1 mg m^{-3} (Table 12). However, this group was not always captured effectively, through the use of coarse mesh (153 µm) in plankton nets, or counted in all surveys, especially those in the offshore and the other embayments.

When nauplii were excluded, zooplankton densities in Thunder Bay averaged 1183 ind m^{-3} in the spring, 15 992 ind m^{-3} in the summer, and 3966 ind m^{-3} in the fall, based on 1990 to 2011 surveys (Table 11). Thunder Bay values were about twice as high as those seen at the coastal stations, and summer values were about 10 times higher than in the offshore. In fact, the Thunder Bay summer mean was the highest density observed in any area in Table 11. The highest spring zooplankton densities (excluding nauplii) were found in Black Bay (4243 ind m^{-3}) and Nipigon Bay (2 903 ind m^{-3}), comprised mostly of cyclopoid and calanoid copepods (Fig. 10).

Zooplankton biomass of Lake Superior tends to be higher and more variable in nearshore areas than in the offshore. For example, Yurista et al. (2009) reported late summer 2006 means of 41, 17 and 22 mg m^{-3} for station depths of <30 m, 30-150 m and >150 m, respectively. For the studies summarized in this report (Table 12), zooplankton biomass in coastal areas of Lake Superior was low in the spring (mean = 6 mg m^{-3}), increased in the summer to about 20 mg m^{-3},

and declined in the fall to about 10 mg m^{-3}. Mean spring and fall values in Thunder Bay were similar to the coastal areas, but summer biomass in Thunder Bay reached an average of 64 mg m^{-3} between 1999 and 2011. Thunder Bay area sampling by OMOE in 1999, 2005 and 2011 showed zooplankton biomass <4 mg m^{-3} in the spring, and higher biomass in the summer (19-59 mg m^{-3}) and fall (7-33 mg m^{-3}) (Fig. 13). In recent years, the highest biomass values were seen in the OMNR 2005 samples; particularly the 50 m deep Thunder Bay coastal site in early August (123 mg m^{-3} at TB50) and the shallow Apostle Island site in late October (95 mg m^{-3} at AI10) (Fig. 14). Over the whole study period, the highest biomass was found at Station 48 in Thunder Bay in early July 1971, at 154 mg m^{-3} (Fig. 8). In contrast, biomass in Thunder Bay never exceeded 30 mg m^{-3} throughout the 1973 sampling season (Fig. 9), and averaged 10-20 mg m^{-3} (Watson and Wilson, 1978). During the 2011 CSMI summer and fall cruises, zooplankton biomass in Thunder Bay, the Apostle Islands and Duluth were about two or more times higher than elsewhere in Lake Superior (Fig. 15). This was driven largely by increases in cyclopoid copepods and *Daphnia* in these protected areas. The highest CSMI values were seen at Thunder Bay in fall 2011 (47 mg m^{-3}). Offshore CSMI values averaged 10 and 12 mg. m^{-3} in summer and fall, respectively.

Calanoid copepods are generally the most dominant group by biomass found in Lake Superior due to their relatively large size, comprising on average between 51 and 94% in coastal and offshore areas of Lake Superior (Table 12), and most species are indicative of oligotrophic, cool-water conditions (Balcer et al., 1984). The lowest proportion of calanoids was seen in Black Bay in the spring (28%), but generally calanoids comprised between 40 and 89% of zooplankton biomass in the embayments. In spite of this, mean calanoid densities rarely exceeded 5000 ind m^{-3} (excluding nauplii). Numbers tended to be lowest in the spring (<1200 ind m^{-3}) and peaked in the summer. The highest mean summer value observed was in Thunder Bay (5476 ind m^{-3}), and means ranged between 2200 and 4200 ind m^{-3} at the other coastal and embayment sites. At the coastal sites, calanoids comprised 65% of total density in the spring, 32% in the summer and 41% in the fall. The proportion of calanoids in Thunder Bay tended to be less than the coastal sites in the spring and fall, but similar in the summer. Calanoids were also the most commonly encountered group at offshore sites, but their densities averaged only 1025 ind m^{-3} in the summer (85%) and 1886 ind m^{-3} in the fall (73%) (Fig. 15).

Leptodiaptomus sicilis was the most common calanoid species in the spring at the coastal, offshore, Thunder Bay and Nipigon sites. *Limnocalanus macrurus* was another dominant species, especially in the offshore and coastal areas. Both species prefer the hypolimnion of large, cold, deep lakes (Balcer et al., 1984). *Leptodiaptomus minutus*, a small cool-water calanoid, was common at the Apostle Islands and Duluth sites throughout the season, and at the Thunder Bay and Nipigon sites in the fall. Calanoid copepodids (juvenile forms not identified to species), were also important, comprising between 9% (Black Bay) and 65% (offshore) of the total density (excluding nauplii). *Leptodiaptomus siciloides*, a calanoid indicative of warm eutropic embayments, was only found occasionally at the Duluth and Apostle Island sites, and was absent at the remaining sites.

Cyclopoid copepods were usually less dominant than calanoids in Lake Superior, especially at the offshore and coastal sites. In terms of density (excluding nauplii), they comprised between 13% to 20% and 25% to 48% in the two areas, respectively (Table 11). They were less important in terms of biomass due to their smaller size (5% to 27%). In the embayments, they tended to be most dominant in the spring, especially in Black Bay (82% by density) and Thunder Bay (51%). The highest mean cyclopoid abundances were seen in Thunder Bay in the summer and Duluth in the fall (around 4500 ind m^{-3}), and means ranging between 2000 and 3500 ind m^{-3} were recorded in the other nearshore areas. Almost all of the cyclopoids identified to species were *Diacyclops thomasi*. This is a common, cool water species that prefers the thermocline

(metalimnion) during stratified conditions (Stewart 1974). It is predatory, consuming other small zooplankton (Balcer et. al, 1984). Occasionally *Mesocyclops edax* and *Acanthocyclops vernalis* were found at the embayment and coastal sites. Cyclopoid copepodids (juveniles) were common, but these were probably almost all *D. thomasi*.

Cladocerans were the third dominant zooplankton group at the Superior sites, with the highest densities seen in the embayments in summer and early fall (Fig.s 9, 13-15). These values ranged from 1000 to 5000 ind m^{-3}, with the highest density seen in Thunder Bay in summer. They were more abundant in warmer, more protected locations (such as upper Black Bay and upper Nipigon Bay) earlier in the spring (Figs. 10 and 11). In Thunder Bay, they were uncommon in the spring, but reached about 30% of total density in the summer and fall (Table 11). In the coastal areas, they comprised only about 1% of zooplankton density (excluding nauplii) in the spring, but 20% to 34% later in the season. Cladoceran density and biomass remained low in the offshore throughout the year (Fig. 15), reaching a mean of only 177 ind m^{-3} (7% of total density) by the fall. The proportions of cladocerans by biomass (Table 12) were usually fairly similar to those of density. In the embayments and coastal areas, the most common cladocerans during the warmer months were *Daphnia retrocurva* and *Bosmina longirostris*. *Daphnia galeata mendoate* and *Eubosmina coregoni* tended to dominate in the fall, along with *Holopedium gibberum* in the coastal areas. These three latter taxa were also the most dominant cladocerans in the offshore. All are herbivores, filtering phytoplankton and other microscopic organisms. The invasive predatory cladoceran *Bythotrephes* was ocassionally found.

Veligers, the larval form of Zebra and Quagga mussels (*Dreissena* sp.) were rare in the Superior zooplankton, especially at the coastal sites, though veligers are under-sampled when using 153 µm mesh nets. They were not found offshore. They reached their highest proportion of total density (excluding nauplii) in Thunder Bay during the summer (7%), although they comprised only 2% of biomass due to their small size.

Summary of Existing Zooplankton Data

Embayments in Lake Superior such as Thunder Bay and Nipigon Bay tend to warm more quickly in the spring and reach higher temperatures in the summer than adjacent coastal areas. This, combined with slightly higher nutrient levels, results in earlier seasonal succession and higher overall zooplankton densities and biomass in the embayments. Temperature appears to be an important driver of zooplankton biomass in nearshore Lake Superior (Yurista et al. 2009; Watson and Wilson 1978). This is particularly evident with cladocerans such as *Bosmina* and *Daphnia* and cyclopoid copepods. Populations of these taxa tend to develop first in the nearshore and spread offshore as the summer progresses (Watson and Wilson, 1978). In the studies summarized here, Thunder Bay generally supported the highest zooplankton populations in Lake Superior. However, total phosphorous and chlorophyll results suggest that Thunder Bay is still usually in the oligotrophic range. Zooplankton densities and biomass values in Thunder Bay are also very low relative to more productive areas in the lower Great Lakes. For example , seasonal mean biomass values in eutrophic embayments in Lake Ontario such as the Bay of Quinte and Hamilton Harbour are approximately an order of magnitude higher (Bowen and Johannsson 2011; Dermott et al. 2007). The zooplankton communities in these enriched southern areas are usually dominated by cladocerans, particularly *Bosmina*, *Eubosmina* and *Daphnia*. In contrast, calanoid copepods tend to dominate in Lake Superior, even in the embayments. Zooplankton species richness in Thunder Bay and elsewhere in Lake Superior is generally quite low, with the community dominated by a few species. Most of the calanoid copepods found tend to be indicative of cold, nutrient-poor environments.

Unlike the other Laurentian Great Lakes where dramatic changes in zooplankton populations have been observed over the last 40 years (e.g. Lake Ontario, Lake Michigan (Barbiero et al.

2014; Vanderploeg et al. 2012), the zooplankton community in the Thunder Bay area of Lake Superior appears to have been relatively stable since the early 1970s (Fig. 16). However, determining long term temporal trends is challenged by year to year variability, lack of consistency in sampling station locations, and a general paucity in long-term data.

Conclusions

This report presents all available plankton data from the Thunder Bay area, and compares to other embayment, coastal and offshore areas in Lake Superior. However, most of the Thunder Bay area stations summarized here are either located outside of the AOC boundaries (e.g., OMOE's 283, OMNR's TB10, TB50 and TB100 and USGS' 401 and 402), or are at the southern, coastally influenced portion of the AOC (EC-DFO's 139 and USGS 403), as shown in Fig. 1. Very few plankton samples have been collected from the AOC in close proximity to the City of Thunder Bay and the Kam River, where human impacts are most likely to occur. Fig. 16 highlights the infrequency of zooplankton sampling within the AOC, starting in 1971. The closest station to the river mouth is OMOE's Welcome Island (284), and it has only been sampled nine times over a twelve year period. Furthermore, even this station is still too far outside the zone of eutrophication, based on the TP and chlorophyll results in Benoit et al. (2012). Turbidity (as indicated by Secchi disk depth) and TP were intermittently elevated at stations 48 (sampled in 1971 only) and 284; stations in the southern part of the AOC and those south of Pie Island appear to be more coastal in nature and less indicative of AOC conditions. Although the USGS has sampled a number of sites in Thunder Bay and the surrounding coastal areas since 1990, June is not an ideal time to sample zooplankton in Lake Superior as the lake is still very cold and the zooplankton not very diverse. Zooplankton populations tend to be fairly homogeneous early in the season, consisting of calanoids and *Diacyclops thomasi* which persist year-round (Watson and Wilson 1978). Most differences among areas develop through the summer as cladocerans and other taxa preferring warmer temperatures appear.

In order to properly assess whether phytoplankton and zooplankton populations within the Thunder Bay AOC are impacted, it is necessary to sample the areas where impacts are most likely to occur, such as locations close to the river mouth and areas with historically contaminated sediment such as the North Harbour area (Cole Engineering, 2014; Benoit et al. 2012). The Thunder Bay RAP identified the Kam River, the inner Thunder Bay Harbour and Chippewa Beach as the areas of highest degradation, with impacts radiating out from the river's delta (Ontario Ministry of Environment et al. 1991; Richman 2004). Sampling should be carried out at several stations along a gradient away from the most impacted areas, as shown in Benoit et al. (2012). Sampling would also need to be done repeatedly over the course of one or more seasons, with emphasis on the July to September period when the zooplankton community is most developed. This would provide data on spatial variability within Thunder Bay harbour, and determine if a trophic gradient exists. Data contained in this report could be used as a baseline or reference for any new studies.

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Table 1: Locations and station depths of zooplankton survey stations in the Thunder Bay area from 1971 to 2014, including the Ontario Ministry of Natural Resources 2005 Superior embayment survey sites.

Station	Area	Description	Latitude	Longitude	Depth
Great Lakes Biological Laboratory (1971)					
47	Thunder Bay	central Thunder Bay	48.3667	-88.9967	56
48	Thunder Bay	north	48.4300	-89.1467	30
45	Coastal	Black Bay mouth - nearshore	48.3767	-88.5283	70
46	Coastal	Thunder Bay mouth offshore	48.1600	-88.9250	246
49	Coastal	south Pie Island - nearshore	48.1683	89.1800	99
50	Coastal	NW Isle Royale- offshore	47.9667	-89.3750	236
Great Lakes Biological Laboratory (1973)					
137	Thunder Bay	Sibley Peninsula tip	48.3017	-88.9500	40
138	Thunder Bay	outer harbour mouth	48.3000	-89.0667	27
139	Thunder Bay	NW Pie Island	48.2983	-89.1800	25
135	Coastal	Black Bay mouth - nearshore	48.3300	-88.6333	98
133	Coastal	Black Bay mouth - offshore	48.2833	-88.5972	187
140	Coastal	south Pie Island - nearshore	48.1500	-89.1483	220
142	Coastal	south Pie Island - offshore	48.0833	-89.0950	240
OMOE Index suveys (1999, 2005, 2011)					
283	Coastal	Flatland I. SW Thunder Bay	48.2133	-89.2631	6
284	Thunder Bay	Welcome Island	48.3669	-89.1561	15
285	Coastal	Sturgeon Bay	48.5277	-88.4455	8
OMNR Embayment Survey (2005)					
TB10	Thunder Bay	S. Pie Island	48.2124	89.1560	10
TB50	Thunder Bay	S. Pie Island	48.2042	89.1410	5
TB100	Thunder Bay	S. Pie Island	48.1964	89.1124	100
NB10	Nipigon Bay		48.8059	87.5994	10
NB100	Nipigon Bay		48.8083	87.6132	100
DS10	Duluth	Knife R.	46.9177	91.8451	10
DS100	Duluth	Knife R.	46.9056	91.8226	100
AI10	Apostle Islands		46.8719	90.5951	10
AI100	Apostle Islands		46.8868	90.5776	100

Table 2: Locations and station depths (m) of USGS zooplankton survey stations along the Canadian coast of Lake Superior, sampled between 1990 and 2014. Temperatures are the 1990 to 1992 means in C. * indicates the location is approximate.

station	Area	Description	latitude	longitude	depth	temper.
401	Thunder Bay	MacKenzie Bay	48.5048	-88.9316	46	12.0
402	Thunder Bay	Sawyer Bay	48.3897	-88.9100	80	12.1
403	Thunder Bay	Pie Island	48.2538	-89.1787	43	7.9
406	Black Bay	George's Point	48.4907	-88.6239	43	12.8
407	Black Bay	Central	48.5587	-88.5788	29	12.7
408	Black Bay	Northeast	48.6028	-88.5007	20	15.7
400	W. coastal	Cloud Bay	48.0729	-89.3992	64	4.8
404	W. coastal	Thunder Cape	48.3070	-88.9110	65	6.3
405	W. coastal	Black Bay mouth	48.4073	-88.6888	74	10.5
410	W. coastal	Borden Island	48.5119	-88.3390	41	5.6
411	W. coastal	Shesheeb Bay	48.5993	-88.3059	55	8.0
412	Nipigon Bay	SW Nipigon Bay	48.8319	-88.1155	51	13.2
413	Nipigon Bay	Red Rock	48.9350	-88.2244	29	13.8
414	Nipigon Bay	Dublin Creek	48.9378	-87.9790	30	12.5
415	Nipigon Bay	Rainboth Point	48.8802	-87.7642	45	9.9
416	Nipigon Bay	Sampson Island	48.8283	-87.6668	117	9.8
417	Nipigon Bay	Schreiber Channel	48.8312	-87.4759	70	6.5
450	East coastal	Michipicoten Island	47.7993	-85.6933	88	2.8
451	East coastal	Dog River	47.9241	-85.1784	68	2.9
453*	East coastal	Old Woman Bay	47.7831	-84.9619	70	-
454	East coastal	Red Rock River Bay	47.6756	-85.0007	80	2.9
455	East coastal	Gargantua Bay	47.5470	-84.9805	110	2.7
456	East coastal	Agawa Bay	47.3102	-84.6670	85	3.7
457	East coastal	Alona Bay	47.1664	-84.7218	130	3.2
462	East coastal	Dore' Bay	47.9403	-84.9456	110	3.2
463	East coastal	The Flats	47.9015	-85.4375	80	3.2
464	East coastal	Crane Island	47.9397	-85.8202	120	3.0
465	East coastal	Otter Island	48.1197	-86.0710	100	3.1
466	East coastal	Richardson Harbor	48.0269	-85.9960	110	3.0
458*	S coastal	Batchawana Bay	46.9030	-84.5748	46	-
459	S coastal	Maple Island	46.7637	-84.6250	72	7.8
460	S coastal	Goulais Point	46.6566	-84.5787	62	6.7
461	S coastal	Pancake Point	46.9288	-84.7284	72	6.5

Table 3a. 2001 Survey locations in Lake Superior 2001. Data courtesy of Environment Canada. – indicates station was not sampled in the fall. N/A indicates Secchi readings could not be taken because the station was visited after dark. Temp indicates epilimnetic water temperatures.

				May 10-15, 2001		Aug 17-23, 2001	
Station	Latitude	Longitude	Depth (m)	Secchi (m)	Temperature (°C)	Secchi (m)	Temperature (°C)
2	46 32 39	-84 44 56	101.4	N/A	2.6	9	19.3
12	47 02 12	-85 06 10	171.8	8	2.06	N/A	16.7
22	46 58 05	-85 43 43	159.7	-	-	N/A	17.2
23	47 12 51	-85 38 07	135.6	N/A	2.5	N/A	16.6
25	47 27 19	-85 16 28	245.9	9	2.1	N/A	17.5
31	47 55 11	-84 54 50	100.5	9	2.4	10.5	17.6
39	47 41 22	-85 58 02	133.5	14	2	15	16.9
42	47 19 25	-86 22 22	175	N/A	2.6	N/A	17.7
43	47 04 49	-86 28 44	199.7	N/A	2.5	N/A	18.1
45	46 54 30	-86 35 49	364.5	N/A	2.7	N/A	19.6
51	46 31 02	-87 20 15	18.9	N/A	4.9	8	21.1
57	46 56 02	-87 18 21	142.3	11	2.1	12	20.4
59	47 09 36	-87 16 55	155.6	13	2.4	N/A	19.2
68	47 00 56	-88 11 00	145.9	N/A	3.1	11.5	19.0
76	47 24 06	-87 24 43	160.4	13	2.1	N/A	19.2
80	47 34 57	-86 57 05	313.4	N/A	2.5	12	16.8
82	47 51 33	-86 38 12	247.1	N/A	2.6	N/A	16.3
95	48 13 02	-87 00 55	198.7	N/A	2.2	N/A	16.0
97	48 26 16	-87 15 09	151.9	11.5	2.2	7	15.6
100	48 45 21	-86 58 27	114.3	9	2	N/A	16.9
113	48 08 42	-87 42 12	274.3	12	2.3	11.5	15.8
115	47 50 49	-87 27 24	174.3	N/A	2.1	14	16.5
118	47 36 26	-87 42 34	166.3	N/A	2.6	N/A	18.5
125	47 36 19	-88 13 02	262.1	N/A	2.4	N/A	19.5
127	47 50 53	-88 20 12	262.2	N/A	2.3	8	16.3
139	48 15 12	-89 10 47	45	N/A	3.8	N/A	16.8
153	47 41 18	-89 27 59	161.9	14	2.4	11.5	17.0
155	47 48 13	-89 08 49	67	15	2.2	N/A	17.2
157	47 36 50	-89 00 03	204.4	14.5	2.4	N/A	16.4
160	47 22 00	-88 49 07	146.4	N/A	2.8	9	20.9
164	47 01 37	-89 02 20	24	N/A	4.3	8.5	20.8
169	47 12 24	-89 40 03	200.4	18	2.6	9.5	18.6
177	47 44 24	-90 14 30	128.5	10	2.3	11	17.2
196	46 44 54	-90 42 10	29.1	3	7.6	8	19.9
201	47 07 54	-91 06 46	197	-	-	N/A	19.2
218	46 49 05	-91 53 04	130	-	-	N/A	19.7
221	46 46 54	-92 03 13	22.3	N/A	7.9	N/A	19.6

Table 3b: 2011 CSMI survey locations in Lake Superior sampled by DFO in from 26 July 26 to 04 August (Summer) and 27 September to 03 October (Fall). – indicates station was not sampled in the fall. N/A indicates Secchi readings could not be taken because the station was visited after dark. Temp indicates epilimnetic water temperatures.

						Summer		Fall	
Station	**Area**	**Description**	**Latitude**	**Longitude**	**Depth**	**Secchi (m)**	**Temp (C)**	**Secchi (m)**	**Temp (C)**
2	Coastal	Whitefish Bay	46.5433	-84.7483	95	N/A	19.8	9	16.8
23	Offshore	central east	47.2133	-85.6333	126.4	11	12	10	13.1
31	Coastal	Michipicoten ON	47.9183	-84.9128	91.7	N/A	19.8	-	-
43	Offshore	southeast	47.0800	-86.4778	192.9	13	9	12.5	12.5
51	Coastal	Marquette MI	46.5167	-87.3367	17.6	N/A	19	-	-
68	Coastal	Keweenaw Bay	47.0167	-88.1833	145.4	13	16	-	-
80	Offshore	central deep hole	47.5833	-86.9517	312	N/A	9.3	N/A	13.6
100	Offshore	Jackfish Bay	48.7567	-86.9758	112	N/A	16.6	12	15.1
113	Offshore	central	48.1450	-87.7033	275.8	16	9.1	N/A	11.5
127	Offshore	central	47.8483	-88.3367	266.6	N/A	11.8	-	-
139	**Thunder Bay**	**Thunder Bay ON**	**48.2533**	**-89.1800**	**44**	**N/A**	**15.5**	**6**	**12.5**
164	Coastal	west Keweenaw Pen.	47.0267	-89.3383	23	N/A	18	-	-
169	Offshore	west central	47.2067	-89.6667	201	N/A	14.1	8	11.7
177	Coastal	NW coast	47.7467	-90.2350	128.8	8	15.5	-	-
196	Apostle Islands	Apostle Islands South	46.7483	-90.7033	28.8	12	20.5	-	-
201	Offshore	Apostle Islands NW	47.1316	-91.1116	193	N/A	17.6	10	9.6
221	Duluth	Duluth	46.7817	-92.0542	21.5	N/A	17.8	2.5	10

Table 4. Physical and chemical information collected at the Thunder Bay (TB) area stations during the 1971 surveys. Sur. Temp is the surface temperature, and TWC is the whole water column temperature averaged at 1, 5, 10, 25, 50, 100, 150 and 2 m off bottom. TB-UF is unfiltered total phosphorus. Chemistry results are averaged for the TWC. Coast NS = coastal nearshore stations, and Coast Off = coastal offshore stations. Station 48 inside the AOC is shown in bold.

Date	Station	Area	Secchi (m)	Sur. Temp. (degC)	TWC Temp (degC)	NO3/NO2 mg/L	NH3 (mg/L)	TOC (mg/L)	DO (mg/L)	SRP (ug/L)	TP-UF (ug/L)	Conduct. (useimens)	turbidity (FTU)
2-Jun-71	47	TB	5	4	3.9	0.267	0.008	2.00	13.0	0.30	6.00	100	3.50
2-Jun-71	**48**	**TB**	**1.5**	**8.6**	**8.6**	**0.209**	**0.014**	**4.17**	**12.4**	**0.30**	**7.68**	**96**	**11.88**
2-Jun-71	49	Coast NS	4.5	3.4	3.5	0.262	0.007	2.17	13.2	0.30	3.32	100	8.13
30-May-71	45	Coast NS	7	2.7	3.1	0.272	0.010	1.87	13.6	0.30	2.55	99	0.42
31-May-71	46	Coast Off	10	2.4	2.5	0.271	0.007	1.93	13.4	0.53	3.25	98	0.36
2-Jun-71	50	Coast Off	-	2.2	2.5	0.280	0.013	1.07	13.5	0.85	2.76	97	0.55
7-Jul-71	47	TB	4	14	7.5	0.202	0.007	2.37	11.7	0.58	6.60	97	0.45
7-Jul-71	**48**	**TB**	**4**	**15.1**	**15.1**	**0.194**	**0.005**	**3.13**	**11.4**	**0.30**	**7.58**	**101**	**0.45**
7-Jul-71	49	Coast NS	5	6.9	5.1	0.244	0.008	1.63	12.9	0.55	3.46	98	0.27
5-Jul-71	45	Coast NS	-	7.1	5.7	0.211	0.007	2.17	13.3	0.66	3.64	100	0.20
5-Jul-71	46	Coast Off	7	3.6	3.5	0.251	0.004	2.30	13.3	0.30	4.78	95	0.24
7-Jul-71	50	Coast Off	-	3.5	3.6	0.253	0.002	1.87	13.2	0.30	4.54	97	0.40
11-Oct-71	47	TB	-	10.8	8.4	0.238	0.002	1.90	10.9	0.30	2.78	98	0.50
11-Oct-71	**48**	**TB**	**5**	**10.9**	**9.0**	**0.259**	**0.003**	**1.75**	**10.7**	**0.46**	**3.28**	**100**	**0.90**
11-Oct-71	49	Coast NS	-	10.8	7.8	0.255	0.005	1.83	11.4	0.36	2.94	98	0.49
11-Oct-71	45	Coast NS	-	11	7.8	0.257	0.004	1.60	11.5	0.36	2.21	98	0.24
11-Oct-71	46	Coast Off	-	10.2	5.3	0.264	0.004	1.30	12.0	0.48	1.91	97	0.34
11-Oct-71	50	Coast Off	6	10.4	5.6	0.252	0.003	1.87	11.8	0.42	4.43	96	0.36

Table 5. Physical and chemical information collected at the Thunder Bay (TB) area stations during the 1973 surveys. Sur. Temp is the surface temperature, and TWC is the whole water column temperature averaged at 1, 5, 10, 25, 50, 100, 150 and 2 m off bottom. TP-UF is unfiltered total phosphorus. Chemistry results are averaged for the TWC. Coast NS = coastal nearshore stations, and Coast Off = coastal offshore stations. Station 139 inside the AOC is shown in bold.

Date	Station	Area	Secchi (m)	Sur. Temp. (degC)	TWC Temp (degC)	Chlor. a (ug/L)	NO3/NO2 mg/L	NH3 (mg/L)	DO (mg/L)	SRP (ug/L)	TP-UF (ug/L)	Conduct. (useimens)	turbidity (FTU)
19-May-73	137	TB	-	2.5	2.7	1.3	0.32	0.003	13.6	-	-	-	0.36
19-May-73	138	TB	-	-	-	1.7	0.31	0.003	13.4	-	-	-	0.35
19-May-73	**139**	**TB**	**-**	**-**	**-**	**1.7**	**0.29**	**0.004**	**13.2**	**-**	**-**	**-**	**0.53**
19-May-73	135	Coast NS	-	2.2	2.0	0.8	0.33	0.004	13.7	-	-	-	0.24
19-May-73	133	Coast Off	-	2.1	2.1	0.9	0.33	0.004	13.6	-	-	98	0.23
19-May-73	140	Coast NS	8.0	2.2	2.0	0.9	0.33	0.004	13.7	-	-	-	0.20
19-May-73	142	Coast Off	14.0	2.0	1.8	0.9	0.33	0.003	13.7	-	-	-	0.20
24-Jun-73	137	TB	-	8.7	6.9	1.2	0.26	0.005	12.9	-	-	-	0.42
19-May-73	138	TB	5.0	9.4	8.1	1.7	0.26	0.008	12.3	-	-	-	0.43
19-May-73	**139**	**TB**	**-**	**-**	**-**	**2.1**	**0.25**	**0.005**	**11.9**	**-**	**-**	**-**	**0.48**
22-Jun-73	135	Coast NS	9.0	3.5	3.6	-	0.28	0.004	13.7	-	-	-	0.24
22-Jun-73	133	Coast Off	12.0	3.2	3.2	1.0	0.28	0.004	13.8	-	-	95	0.24
22-Jun-73	140	Coast NS	14.0	3.2	3.2	0.9	0.29	0.007	13.5	-	-	-	0.20
22-Jun-73	142	Coast Off	13.0	3.0	3.1	0.9	0.29	0.007	13.5	-	-	-	0.24
2-Aug-73	137	TB	5.0	16.7	10.9	1.6	0.25	0.006	11.7	1.14	4.63	-	0.64
3-Aug-73	138	TB	5.0	11.5	7.9	2.2	0.26	0.010	12.1	1.22	5.30	-	0.48
3-Aug-73	**139**	**TB**	**5.0**	**16.8**	**11.3**	**1.4**	**0.25**	**0.009**	**11.6**	**1.64**	**5.77**	**-**	**0.56**
2-Aug-73	133	Coast NS	8.0	11.5	5.9	1.3	0.28	0.005	13.0	1.26	3.10	92	0.23
2-Aug-73	135	Coast Off	7.0	11.8	8.9	1.5	0.27	0.007	12.4	1.28	4.53	-	0.24
3-Aug-73	140	Coast NS	4.5	14.7	9.8	1.6	0.26	0.004	12.1	0.94	4.87	-	0.48
3-Aug-73	142	Coast Off	6.5	15.8	10.1	1.8	0.26	0.006	12.2	1.20	6.10	-	0.36
12-Sep-73	137	TB	6.0	13.5	8.2	1.0	0.27	0.008	12.2	-	-	-	0.40
13-Sep-73	138	TB	4.0	15.8	11.3	1.3	0.26	0.008	11.1	-	-	-	0.34
13-Sep-73	**139**	**TB**	**5.0**	**12.6**	**9.9**	**1.3**	**0.27**	**0.006**	**11.7**	**-**	**-**	**-**	**0.58**
12-Sep-73	133	Coast NS	6.0	14.3	7.2	1.7	0.28	0.005	12.3	-	-	91	0.30
12-Sep-73	135	Coast Off	4.5	11.0	8.3	1.1	0.28	0.007	12.4	-	-	-	0.56
13-Sep-73	140	Coast NS	-	11.8	9.3	1.3	0.27	0.012	11.7	-	-	-	0.28
13-Sep-73	142	Coast Off	-	14.0	9.8	1.6	0.26	0.011	11.7	-	-	-	0.30
22-Oct-73	137	TB	-	8.0	7.2	1.2	0.28	0.008	11.8	1.80	7.37	-	0.55
22-Oct-73	138	TB	6.0	8.5	7.8	1.4	0.28	0.007	11.6	1.38	7.23	-	0.68
22-Oct-73	**139**	**TB**	**5.0**	**7.4**	**7.4**	**1.3**	**0.28**	**0.005**	**12.0**	**0.98**	**6.20**	**-**	**0.53**
22-Oct-73	133	Coast NS	-	8.5	6.4	1.5	0.29	0.005	12.4	0.87	3.99	91	0.44
22-Oct-73	135	Coast Off	-	7.9	7.3	1.5	0.28	0.006	12.1	1.08	5.75	-	0.45
22-Oct-73	140	Coast NS	9.0	7.9	7.3	1.7	0.28	0.003	12.2	0.90	5.17	-	0.35
22-Oct-73	142	Coast Off	9.0	8.1	7.5	1.7	0.28	0.003	12.0	0.60	5.13	-	0.33
24-Nov-73	137	TB	5.0	4.5	4.3	1.6	0.29	0.006	12.3	0.57	5.75	-	0.73
24-Nov-73	138	TB	7.5	5.0	4.9	1.2	0.28	0.006	12.2	1.50	7.33	-	1.00
24-Nov-73	**139**	**TB**	**4.0**	**4.5**	**4.3**	**1.5**	**0.28**	**0.006**	**12.3**	**1.33**	**6.53**	**-**	**0.57**
24-Nov-73	133	Coast NS	-	5.2	4.9	1.2	0.29	0.003	12.4	1.08	4.38	89	0.28
24-Nov-73	135	Coast Off	6.0	5.3	5.2	1.2	0.29	0.004	12.3	0.43	5.37	-	0.33
25-Nov-73	140	Coast NS	10.0	4.5	4.9	0.9	0.29	0.005	12.4	1.00	4.80	-	0.20
25-Nov-73	142	Coast Off	10.0	4.9	4.8	0.9	0.29	0.003	12.4	0.73	6.60	-	0.30

Table 6. Physical and chemical information collected at embayment stations by the OMNR during the 2005 surveys. TWC is the total water column, and unstr. indicates unstratified conditions. * indicates that no clear epilimnion was present. The mesh column indicates whether a zooplankton sample was counted, and the net mesh size used.

Station	Date	mesh (um)	Secchi Depth (m)	temperature (C) surface	temperature (C) TWC	pH	Conductivity (usiem.cm^{-1})	Bottom epi (m)	Bottom meta (m)
AI10	19-Jul-05	64	10.2	15.9	13.5	8.2	94.2	unstr.	unstr.
AI50	19-Jul-05	153	10.9	16.5	8.7	8.2	94.5	3	22
AI100	19-Jul-05	-	11.9	16.7	9.2	8.1	94.1	15	20
AI10	07-Sep-05	-	-	17.9	17.8	8.4	96.4	unstr.	unstr.
AI50	07-Sep-05	153	10.0	17.9	10.7	8.3	96.4	11	33
AI100	07-Sep-05	153	11.8	17.2	10.6	8.2	96.1	16	31
AI10	26-Oct-05	153	-	10.1	10.1	8.4	92.4	unstr.	unstr.
AI50	26-Oct-05	-	-	10.0	9.6	8.4	92.4	40.0	>49
AI100	26-Oct-05	153	9.0	10.1	9.6	8.5	92.4	40.0	>49
DS10	21-Jun-05	153	5.2	7.3	6.2	8.0	90.7	unstr.	unstr.
DS50	21-Jun-05	153	8.5	6.8	4.7	7.9	90.5	6	8
DS100	21-Jun-05	-	7.7	7.9	4.6	7.9	92.3	6	10
DS10	15-Aug-05	-	12.7	5.8	5.4	7.6	90.6	unstr.	unstr.
DS50	15-Aug-05	-	13.5	7.8	5.2	7.8	91.6	2	9
DS100	15-Aug-05	-	11.1	10.1	5.6	7.9	92.4	2	7
DS10	06-Sep-05	64	12.0	12.9	12.4	8.2	93.3	unstr.	unstr.
DS50	06-Sep-05	-	12.5	13.2	8.4	8.2	93.4	8	22
DS100	06-Sep-05	153	12.1	13.1	8.3	8.2	93.3	10	27
DS10	27-Sep-05	64	12.5	-	-	-	-	-	-
DS50	27-Sep-05	153	13.0	-	-	-	-	-	-
DS100	27-Sep-05	-	13.8	-	-	-	-	-	-
NB10	06-Jun-05	153	8.8	5.0	5.0	7.8	91.4	unstr.	unstr.
NB50	06-Jun-05	153	8.4	4.7	4.7	7.8	90.9	unstr.	unstr.
NB100	06-Jun-05	-	9.2	4.4	4.2	7.8	92.7	unstr.	unstr.
NB10	08-Aug-05	64	5.6	19.0	17.2	8.2	105.9	unstr.	unstr.
NB50	08-Aug-05	153	6.1	18.8	11.1	8.3	106.1	4	21
NB100	08-Aug-05	-	6.3	18.5	10.1	8.3	105.2	9	15
NB10	18-Oct-05	64	-	13.2	13.2	8.5	97.8	unstr.	unstr.
NB50	18-Oct-05	-	6.5	13.2	10.0	8.4	98.2	22	26
NB100	18-Oct-05	64	6.0	13.1	10.1	8.4	98.3	22	31
TB10	30-May-05	153	9.8	5.0	4.6	7.7	90.6	unstr.	unstr.
TB50	30-May-05	153	11.3	3.6	3.8	7.7	90.1	unstr.	unstr.
TB100	30-May-05	153	16.8	3.1	3.0	7.7	89.7	unstr.	unstr.
TB10	13-Jul-05	-	7.4	17.9	11.8	8.2	99.7	2	4
TB50	13-Jul-05	-	7.2	15.7	8.2	8.2	99.6	*	11
TB100	13-Jul-05	-	8.0	16.4	8.3	8.3	98.8	*	22
TB10	25-Jul-05	-	8.9	14.4	13.0	8.2	96.3	unstr.	unstr.
TB50	25-Jul-05	-	9.6	15.3	8.8	8.1	96.7	3	9
TB100	25-Jul-05	-	9.1	16.5	8.3	8.1	97.4	6	21
TB10	05-Aug-05	64	8.6	17.2	16.2	8.2	99.0	2	5
TB50	05-Aug-05	64	8.7	17.5	9.5	8.3	98.7	2	25
TB100	05-Aug-05	-	8.9	16.8	8.7	8.2	98.1	9	18
TB10	12-Sep-05	-	8.7	14.7	11.1	8.2	96.4	unstr.	unstr.
TB50	12-Sep-05	-	8.5	12.4	7.2	8.1	95.9	*	14
TB100	12-Sep-05	-	12.6	11.1	5.4	8.1	94.6	*	9
TB10	22-Sep-05	-	-	16.3	16.3	8.3	94.4	unstr.	unstr.
TB50	22-Sep-05	-	-	16.2	15.3	8.3	94.4	28	43
TB100	22-Sep-05	-	-	16.3	15.2	8.2	94.5	22	24
TB10	03-Oct-05	-	10.9	14.8	14.2	8.4	94.4	3	4
TB50	03-Oct-05	-	10.9	14.7	8.3	8.4	94.4	4	22
TB100	03-Oct-05	-	11.5	14.7	8.8	8.4	94.4	17	20
TB10	11-Oct-05	153	10.8	13.8	13.8	8.3	93.8	unstr.	unstr.
TB50	11-Oct-05	153	10.8	13.9	13.5	8.3	94.0	37	43
TB100	11-Oct-05	153	10.3	13.9	13.2	8.3	94.1	23	27

Table 7. Physical and chemical information collected at the Thunder Bay (TB) area stations by the OMOE during the 2005 surveys. Chlor A is total chlorophyll a, TP is total phosphorus and DOC is dissolved organic carbon.

date	station	Secchi (m)	DOC ($mg.L^{-1}$)	Chlor. A $ug.L^{-1}$	Conductivity $usiem.cm^{-1}$	NH^3+NH^4 $mg.L^{-1}$	NO3/NO2 $mg.L^{-1}$	pH	TP $ug.L^{-1}$	Turbidity FTU
14-May-05	283	1.3	4.37	3.80	110	0.0063	0.2897	7.89	23.3	5.42
16-May-05	284	1.3	2.57	2.17	102	0.0093	0.3290	7.87	15.0	3.95
14-May-05	285	3.0	1.80	1.60	94	0.0043	0.3080	7.95	12.3	0.77
18-Aug-05	283	4.0	1.77	2.07	104	0.0020	0.2947	7.76	5.7	0.84
18-Aug-05	284	6.0	1.67	1.43	102	0.0020	0.2920	7.77	3.0	0.52
17-Aug-05	285	4.8	1.53	0.80	101	0.0143	0.2743	7.97	7.3	1.08
6-Oct-05	283	1.2	1.90	1.93	103	0.0090	0.2907	8.02	11.7	6.09
6-Oct-05	284	4.5	1.53	1.63	98	0.0073	0.3053	8.05	2.7	0.86
8-Oct-05	285	4.0	1.40	1.47	98	0.0020	0.2883	8.05	2.3	0.90

Table 8. Seasonal changes in phytoplankton biomass (mg m^{-3}) at station 139 Thunder Bay, Lake Superior, 1973 (Munawar and Munawar 1978).

	May	Jun	Jul/Aug	Sep	Oct	Nov/Dec
Cyanophyta						
Chroococcus dispersus var. minor G.M. Smith	0.47	1.08	0.25	0.25	0.82	0.90
spores						0.28
Oscillatoria limnetica Lemmermann		0.97				
Oscillatoria sp.	4.15					
Chlorophyta						
Ankistrodesmus falcatus (Corda) Ralfs		0.12				
Carteria sp. (Carter) Diesing		1.15				
cysts						0.67
Chlamydomonas metapyrenigera Skuja	1.95				2.28	
Chlorella sp.			0.64			
Scenedesmus bijuga (Turpin) Lagerh.	4.43	1.98	0.90	0.96	1.12	0.36
Chrysophyceae						
Chromulina sp. Cienkowski	0.09			0.19		
Chrysochromulina parva Lackey	6.16	3.28	5.56	2.45	2.13	6.27
Dinobryon bavaricum Imhof	2.82					
Dinobryon sp.			2.66	7.45		
Dinobryon divergens Imhof			22.07			
Ochromonas sphagnalis Conrad		1.21	0.36		0.35	
Ochromonas sp. Wyssotzki	6.70	69.46	39.20	18.07	2.63	18.52
Stelexomonas sp.						0.94
Diatomeae						
Asterionella formosa Hassall	3.95	2.61	64.36			19.14
Asterionella gracillima (Hantzsch) Heiberg			10.15			
Cyclotella comta (Ehr.) Kütz.		5.17	8.78			
Cyclotella glomerata Bachmann			4.60			
Cyclotella stelligera (Cleve & Grunow) Van Heurck				6.72	1.70	
Fragilaria crotonensis Kitton			39.64			
Rhizosolenia eriensis H.L. Smith		0.24	1.23			
Synedra acus var. radians (Kütz.) Hustedt		1.46	2.02			
Synedra maria			0.82			
Synedra sp.		0.90				
Tabellaria fenestrata (Lyngb.) Kütz.	23.06	14.97				
Cryptophyceae						
Cryptomonas erosa Ehrenberg		13.69	11.41	10.11	9.82	17.33
Cryptomonas marssonii Skuja		10.01	12.08			
Katablepharis ovalis Skuja	1.51	7.91	4.52		0.93	1.90
Rhodomonas minuta Skuja	23.83	45.00	42.69	39.87	27.96	32.80
Rhodomonas minuta var. nannoplanctica Skuja			3.46	3.80	1.54	3.83

Table 9. Seasonal changes in phytoplankton biomass (mg m^{-3}) at station 139 Thunder Bay, Lake Superior, 2001.

	May	August
Cyanophyta		
Anabaena flos-aquae		2.64
Aphanocapsa delicatissima West & West	7.27	0.36
Chroococcus dispersus var. minor G.M. Smith	21.36	6.30
Gomphosphaeria lacustris Chodat	2.63	
Merismopedia sp.	1.51	
Oscillatoria limnetica Lemmermann	9.47	2.34
Oscillatoria sp.		2.22
Chlorophyta		
Ankistrodemus falcatus var. acicularis (A. Braun) G.S. West	0.17	
Ankistrodesmus falcatus (Corda) Ralfs	0.18	
Ankistrodesmus falcatus var. mirabilis (West & West) G.S. West	1.87	0.03
Ankistrodesmus falcatus var. spirilliformis G.S. West	0.40	0.02
Chlamydomonas globosa Snow		3.20
Chlamydomonas sp.	7.28	0.99
Chlorella homosphaera Skuja	13.61	5.64
Chlorella vulgaris Beyerinck	17.44	3.39
Cosmarium phaseolus Brebisson		1.92
Dictyosphaerium cells	11.67	
Dictyosphaerium pulchellum Wood	0.43	
Elakatothrix gelatinosa Wille	0.31	
Gemellicystis neglecta		17.12
Gloeocystis cyst	4.68	
Gloeocystis gigas (Kuetz.) Lagerheim	4.88	
Gloeocystis planctonica (West & West) Lemmermann		1.35
Gloeocystis sp.	7.17	
Green cells	71.99	0.53
Kirchneriella lunaris (Kirch.) Moebius		0.25
Oocystis gloeocystiformis Borge		3.50
Oocystis lacustris Chodat		1.43
Oocystis parva West & West		0.38
Oocystis submarina Lagerheim		6.97
Pedinomonas minutissima Skuja		0.75
Quadrigula lacustris (Chod.) G.M. Smith		1.15
Scenedesmus bijuga (Turp.) Lagerheim		0.96
Tetraedron minumun cyst	2.76	
Tetraedron minumun var. tetralobulatum Reinsch		21.75
Tetrastrum sp.		16.66
Chrysophyceae		
Chromulina mikroplankton Pascher		0.34
Chromulina minima Dolf.	3.22	1.61
Chromulina obconica		0.33
Chromulina sp.		5.88
Chromulina sphaerica Doflein		1.43

	May	August
Chrysophyceae (cont.)		
Chromulina sphaeridia		1.56
Chrysamoeba sp.		0.85
Chrysidalis peritaphrena Schiller		12.26
Chrysochromulina parva Lackey	71.35	28.40
Chrysococcus sp.	8.76	
Chrysolykos planctonicus Mach		0.15
Chrysomonad cells cyst	63.85	
Chrysomonad flagellate D		1.09
Chrysomonad sp.	8.46	58.27
Chrysosphaera sp.		4.38
Diceras chodatii Reverdin		0.80
Dinobryon bavaricum Imhof		1.55
Dinobryon cylindricum alpinum		1.85
Dinobryon cylindricum Imhof	7.18	
Dinobryon divergens cyst		6.97
Dinobryon divergens Imhof		185.03
Dinobryon sociale Ehrenberg	0.59	
Dinobryon sociale var stipitatum (Stein) Lemmermann		1.48
Dinobryon sp.	18.88	19.46
Dinobryon sp.	0.59	
Erkenia subaequiciliata Skuja	9.03	8.65
Kephyrion boreale		0.59
Mallomonas bispinosa		0.15
Mallomonas denticulatus	33.56	
Mallomonas genevensis		1.77
Mallomonas globosa Schiller		10.55
Mallomonas Heimii	4.92	
Mallomonas Hirsuta	1.17	
Mallomonas horrida		1.87
Mallomonas lata Conrad	3.18	
Mallomonas radiata		3.10
Mallomonas sp.	39.36	42.39
Monas sp.	1.04	
Monochrysis parva		0.10
Ochromonas elegans Doflein	24.94	4.99
Ochromonas nana Doflein	4.59	0.90
Ochromonas scintillans Conrad	1.70	
Ochromonas silvarum Doflein	31.83	5.43
Ochromonas sp.		4.50
Ochromonas sphagnalis Conrad	25.70	1.88
Pseudokephryion depressum Schmid	2.00	
Pseudokephryion sp.	0.40	0.50
Pseudokephyrion poculum Conrad	1.26	

Table 9. continued.

	May	August
Chrysophyceae (cont.)		
Rhizochrysis sp.	2.11	
Salpingoeca frequentissima (Zacharias) Lemmermann		0.54
Sphaleromantis tetragona		0.29
Stelexmonas dichotoma Lackey	6.93	
Stelexmonas sp.	19.80	
Stichogloea sp.		6.59
Synura sp.		1.67
Diatomeae		
Asterionella formosa Hassall	820.68	27.35
Asterionella gracillima (Hantzsch) Heiberg	92.13	9.27
Cyclotella atomus Hustedt	19.98	9.64
Cyclotella bodanica Eulenstein		35.71
Cyclotella comta (Ehr.) Kütz.	13.04	30.94
Cyclotella glomerata Bachmann	45.36	9.87
Cyclotella michiganiana		4.85
Cyclotella ocellata Pantocsek	27.22	1.42
Cyclotella pseudostelligera		6.48
Cyclotella sp.		24.24
Cyclotella stelligera (Cleve.) Grunow		5.43
Cymbella ventricosa Kuetzing	1.57	
Diatoma elongatum (Lyngb.) Agardh		10.88
Fragilaria capucina Desmazieres	5.59	2.98
Fragilaria crotonensis Kitton	40.88	154.98
Fragilaria sp.		2.22
Gomphonema sp.	0.71	
Melosira islandica O. Muller	40.25	
Navicula exigua (Greg.) O. Muller	1.33	
Navicula sp.		2.15
Nitzschia acicularis (Küetz.) W. Smith		1.21
Nitzschia gracilis Hantzsch		0.75
Nitzschia sp.		0.50
Nitzschia vermicularis (Kuetz.) Grunow		2.10
Rhizosolenia eriensis H.L. Smith		0.46
Rhizosolenia gracilis H. L. Sm.		0.39
Stephanodiscus astraea var. minutula (Küetz.) Grunow		43.47
Synedra acus Küetzing		1.19
Synedra acus var. radians (Küetz.) Hustedt		1.88
Synedra sp.		2.16
Tabellaria fenestrata (Lyngb.) Küetzing		1561.14
Tabellaria flocculosa (Roth) Küetzing		597.63

	May	August
Cryptophyceae		
Chroomonas acuta Utermöhl		0.64
Chroomonas breviciliata Nygaard		11.32
Chroomonas minor		0.48
Chroomonas Nordstedtii Hansgirg		4.50
Cryptaulax rhomboidia Skuja	0.48	0.25
Cryptomonas caudata Schiller	12.85	3.68
Cryptomonas cyst	10.92	
Cryptomonas erosa cyst	5.95	
Cryptomonas erosa Ehrenberg	8.99	15.48
Cryptomonas gracillis		1.38
Cryptomonas Marssonii Skuja	8.19	3.51
Cryptomonas ovata Ehrenberg	4.92	10.88
Cryptomonas pusilla		1.13
Cryptomonas reflexa cyst		23.57
Cryptomonas sp.	3.79	
Cryptomonas sp. cyst		7.96
Cryptomonas tetrapyrenoidosa Skuja	10.14	
Katablepharis ovalis Skuja.	3.61	0.63
Rhodomonas lens Pascher & Ruttner		2.15
Rhodomonas minuta Skuja	17.98	44.95
Rhodomonas minuta var. nannoplanctica Skuja	6.12	8.44
Rhodomonas sp.	0.25	
Dinophyceae		
Amphidinium luteum		0.69
Ceratium hirundinella (O.F. Muell.) Schrank		24.61
Dinoflagellate cyst		11.59
Glenodinium bogoriense		5.23
Glenodinium cyst	29.68	
Glenodinium pulvisculus (Ehr.) Stein	21.04	5.95
Gymnodinium albulum		1.26
Gymnodinium cyst	21.90	4.64
Gymnodinium helveticum Penard	5.40	
Gymnodinium lacustre Schiller		1.31
Gymnodinium ordinatum Skuja		2.73
Gymnodinium profundum Schiller		6.80
Gymnodinium sp.	28.07	6.50
Gymnodinium uberrimum (Allman) Kofoid & Swezy	11.88	
Gymnodinium uberrimum cyst		27.86
Gymnodinium varians Maskell	17.32	9.05
Peridinium sp.	22.01	

Table 10. Time series of Phytoplankton biomass (mg m^{-3}) at OMOE index stations near Thunder Bay 1999, 2005, 2011.

	Flatland Island									Sturgeon Bay						Welcome Island								
	1999			2005			2011			1999	2005		2011			1999			2005			2011		
	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall
Total Biomass mg m-3	165.7	58.2	31.7	307.7	193.9	187.2	283.7	417.7	192.1	71.7	88.3	74.6	150.4	115.4	126.4	85	101.1	35	134.2	232.6	122.9	123.9	90.5	279.6
Cyanophyta																								
Achnanthidium sp.						1.4																		
Anabaena flos aquae Br.ex Born. Flah.																		0.6						
Anabaena lemmermannii Rich									1.3					16.3	0.6									20.3
Anabaena sp.									0.7											2.6		1.8		
Aphanocapsa elachista					0.1							0.1												
Aphanocapsa holsatica (Lemm) Cronb & Kom.								0.1	0.2			0								0.2				
Aphanocapsa incerta (Lemm) Cronb. & Kom.															0.8	0.4					0.6			
Aphanocapsa sp.															6									0
Aphanotheca sp.									47.2															
Aphanothece sp.																						0.2		
Chroococcus minutus (Kutz) Naeg.									0.2												1.3			3.3
Coelosphaerium kuetzingianum Naegeli						4.4																		
Cyanodictyon planctonicum B.Meyer												0.3									1			0.3
Cyanodictyon reticulatum (Lemmermann) Geitler																					2			
Gloeocapsa sp.																0.1								
Limnothrix sp.							3.7						0.4									1		
Merismopedia punctata Meyen						0.1																		
Planktolyngbya limnetica Komárková-Legnerová & Cronberg						0.1						2.4			0.1						0.1	0	0.1	
Planktolyngbya sp.													0.5											
Pseudanabaena contorta Kling & Watson	0.3			0.5	0.4		0.3			0.6						0.2			1			0.4		
Pseudanabaena limentica (Lemmermann) Komárek	0.1				0.1		0.1						0.1		0.2									
Pseudanabaena sp.							1.2		0.1	0.3	0		0.5		0.2		0.1				0.1	0.4		
Radiococcus Geminata									0.1															
Snowella sp.																							0.9	
Synechococcus sp.	0.1	0.1						0.3		0.1			0.1	0.1	2	0.1		0.1	0		0.2		0.3	0.3
Woronichinia compacta (Lemmermann) Komárek & Hindák									0.3			0.1			0.3						0.4			0.2
Unknown Cyanophyceae	2.2		2.6	12.7	6.7	5.8	12.7		25	3.6	3.6		37.6	11	9	2.1		5.4	26	21	5.6	10.6	2.6	9.2
Chlorophyta																								
Actinastrum hantzschii Lagerh.				0.9																				
Ankistrodesmus falcatus	0	0	0.2	0.2			0.1	0		0.2		0.1	0.2		0	0	0.1	0.1	0.1		0	0.3	0	
Botryococcus braunii																4.5								
Botryococcus pila						0.3					0.3													
Chlamydomonas sp.	1.4			0.8			0.8		0.1															0.4
Closterium aciculare T. West		2.6																						
Closterium acutum Breb							0.1																	
Closterium limneticum Lemmermann	0.5				1.8																			
Collodictyon triciliatum H. Carter							12.8																	
Cosmarium abbreviatum Reciborski						0.1														0.1				0.3
Cosmarium sp.		0.6																						
Crucigeniella pulchra																					3.5			0.2
Crucigeniella quadrata (Morren) Gaillon	0	0.3									0.3				0.3									
Crucigeniella tetrapedia								0.1	0.3															
Dictyosphaerium sp.															2.2									
Didymocystis sp.															0.1									
Elakatothrix genevensis (Reverd.) Hindak	0		0.1					1.8	0.4												0.6			0
Elakatothrix sp.																								0

Table 10: continued

	Flatland Island									Sturgeon Bay						Welcome Island								
	1999			2005			2011			1999	2005		2011			1999			2005			2011		
	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall
Chlorophyta cont.																								
Elakatothrix sp.																								0
Franceia sp.															1.2									
Gloeotila pelagica (Nyegaard) Skuja															1.9			0.8						
Koliella sp.				0.1																				
Lagerheimia subsalsa Lemmermann																					0.4			
Monoraphidium arcuatum (Korshikov) Hindák				0.2																				
Monoraphidium contortum (Thurs.) Kom	0				0.1																			
Monoraphidium griffithii (M. J. Berkeley) Komarkova-legn.						0.2	0.3		0.1															
Monoraphidium komarkova															0.6									
Monoraphidium minutum (Nägeli) Komárková-legnerová					0			0.1			0.1			0.1	0.2		0.1				0			
Monoraphidium sp.																			0.4	0.2				
Mougeotia sp.					0.1																			
Nephrochlamy subsolitaria (G.S.West) Korsh.	0.1				0.2			0.3						0.1										
Nephrocytium agardhianum Naegeli															0.5									
Nephroselmis sp.								1																
Oocystis apiculata (Skuja) Kom.																								0.3
Oocystis lacustris Chodat		2.2	0.1			0.5	0.8		0.6								0.1							
Oocystis solitaria Wittrock														0.4										
Oocystis sp.	1.5				2.4			1.8		0.5		0.2						0.3		2.8	5.5	0.2		
Oocystis submarina Lagerheim	0.7																							
Paulschulzia pseudovolvox					2.6																			
Pseudosphaerocystis lacustris									0.2															
Quadrigula closterioides (Bohlin) Printz									0															
Quadrigula sp.						0.6																		
Scenedesmus sp.				0.2		0.1									0.3		0.6			1			1	
Spermatozopsis exsultans Korshikov						0	0	0						0	0									0.1
Stichococcus sp.																0.1					0.4			0.1
Tetraëdron minimum (A. Br.) Hansg.			0.7				0.3	0.7	0.2			2.2		0.4	0.4	0.7	2.8					0.1		
Tetraëdron minimum var. tetralobulatum Reinsch.																					0.4			
Unknown Chlorophyceae	4	0.7	0.2	31.7	2.5	9.2	16.4		3.2	5.2	11.5	0.3	19.5	2.4	5	1.9	12.6	8.1	4.8	10.6	2.5	8.6	0.8	5
Chrysophyceae																								
Bitrichia chodatii		0.1															0.1							
Bitrichia longispina								0.2																
Chrysochromulina parva	0.4	0.2	0.5	2.3	1.4	0.1	4.1	0.9	0.1	1.6	0.3	0.5	3.6	0.7	1.7	0.6	0.8		2.8	0.3	0.1	2	1.1	
Chrysococcus sp.												0.5												
Chrysoikos skuja																						0.3		
Chrysolykos planktonicus Mack								0.2		0.4						0.3							0.1	
Dinobryon attenuatum Hilliard							2.8			0.1			6.3			3.5								
Dinobryon bavaricum Imhof		0.1	0.1	0.9	0.5			0.5	0.4			0.4			1.7		0.1	0.1					0.1	2
Dinobryon bavaricum var. vanhoeffenii (Bachmann) Krieger			0.1			0.2			0.1			0			0.3						0.2			
Dinobryon crenulatum West and West					0.5										1.2		0.5			1.1				
Dinobryon cylindricum Imhof			0	12.8			25.1	1.6		0.1			1.2		0.2	40.3	0.6		10.8			0.9	0.3	
Dinobryon dilalatum						1.6																		
Dinobryon divergens Imhof		0	0.5		3.3	5.4		0.8	0.4		8.5	0.2		0.7	0.7		0.2	0.5		3.8	4.9		0.2	10.2
Dinobryon pediforme (Lemm.) Steinecke		0	0.1		5.4		3.1		0.4					0.1	0.1		0.2	0.1			0.1		0.2	
Dinobryon sertularia Ehrenberg						9		9.9	11.5	0		0.1			1.5						5.5		0.3	38.1
Dinobryon sociale Ehrenberg		0					1.2	7.9				0	6.1		0.2		0.7							

Table 10: continued

	Flatland Island									Sturgeon Bay						Welcome Island								
	1999			2005			2011			1999	2005		2011			1999			2005			2011		
	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall
Chrysophyceae cont.																								
Dinobryon sociale var. americanum (Brunthaler) Bachmann															0.2								0	
Dinobryon sociale var. stipitatum (Stein) Lemmermann									0.2			0.2		0	0.8									
Dinobryon sp.				5.5		14.9			6.6				1.2	0.4	5.5	0.8	9	3.3	3.6	1.4	1.9	1.4	2.8	33.3
Dinobryon suecicum Lemmermann				0.8	0.1							0.1												
Kephyrion boreale Skuja																					0.1			
Mallomonas caudata Iwanoff																								1.1
Mallomonas elongatum Reverdin																								1.1
Mallomonas sp.	11.9				1.4		0.5	5.4							2.8								0.1	0.7
Ochromonas sp.	7.4	1.5	3.4	70.1	2.3	10.4		175	4.4	9.4		3.6	25.1	15.7	19.4	2.5	8.7	2.9	14.8	5	4.2	9.1	2.5	39.2
Pseudokephryion sp.		0.3								0.7		0.1	1.1		1.7	0.4	1			0.2				
Pseudokephyrion alaskanum Hilliard																						0.5		
Pseudopedinella sp.	0.5	2.2	1.1	35.1	14.8		5.4	4.9	2.2	5.4	3.2	5.4	10	5.4	14.7	1.1	4.3		1.1	3.2	3.2	3.2	12.8	4.3
Rhizochrysis limnetica G.M. Smith						4.4	2.8	2.8							5.5		0.3			1.9		0.1		
Salpingoeca frequentissima (Zacharias) Lemmermann								0.1					0.1						0.3	1.1	0.6	0.3		
Spiniferomonas sp.							0.8	1.1							0.3									
Stelexomonas dichotoma Lackey							1.2																	
Stichogloea doederleinii (Schmidle) Wille								1				1.3		1.3									1.6	
Synura sp.				4.2																				
Unknown Chrysophyceae	4.5	0.9	9	4.9	2.1	0.9	74	12.2	13.6	8.6	20.2	6.7	0.6	2.3	18.4	2.3	16.1	0.8	8.6	12.5	8.2	1.4	13.4	5.6
Diatomeae																								
Achnanthidium minutissimum	0.3					1	0.8	0.4																
Amphipleura pelucida						0.4																		
Asterionella formosa		0.3		0.8	0.7	1.8	5.2	11.4	6	0.9	0.1	1.4	1.2	1.7	1.1	0.1	0.1		1.7	0.4	6.4	10.8	1.2	14.6
Aulacoseira ambigua				0.8		0.1		0.3	2.5															
Aulacoseira granulata	3.1			1.2																				
Aulacoseira islandica	26.2	9.3		10.5			1		4.6				1.9			6.1			5.2			12.9		
Aulacoseira sp.					0.3													0.4		0.2				
Aulacoseira subarctica							1.4		0.6						0.5							0.9		
Cocconeis sp.						2.6																		
Cyclotella bodanica Eulenstein		4.3	0.7		9.2	3.4	0.5	8	2.5	0.7	4	20.8	0.6	4.8	0.3	1.3		0.5		17.6	9.1		7.9	4
Cyclotella sp.											9.9													
Cymatopleura solea (Bréb. & Godey) W. Smith																			4.2					
Diatoma tenue C. Agardh				1.8																				
Diatoma tenue var. elongatum Lyngb.	2			1.5			7			0			0.2		0.1									
Diatoma vulgare Bory							1.7																	
Encyonema sp.						1.5																		
Fragilaria capucina Desmazières	0.3			0.4			0.9												0.7					
Fragilaria crotonensis Kitton		0.5		1.7	34.7	10.3	19.3	3.3	20.9		1.9	4.7	1.3		1.4				0.3	48.8	8.2	3.2	3.6	34.5
Fragilaria pinnata Ehrenberg						1.6																		
Fragilaria sp.	1.2						0.4	0.5		0.2							0.5	0.3						
Gyrosigma sp.													3.8											
Melosira varians C.A. Agardh.						9.3																		2.3
Navicula radiosa Kütz.												0.3								0.4				
Navicula sp.						0.3	0.5		0.8	0.2														
Nitzschia acicularis (Kütz) W. Smith							2.1					0.1							0.1					
Nitzschia palea (Kütz.) W. Smith				1.2																		0		
Nitzschia sigmoidea (Nitzsch) W. Sm.							0.6																	

Table 10: continued

	Flatland Island									Sturgeon Bay						Welcome Island								
	1999			2005			2011			1999	2005		2011			1999			2005			2011		
	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall	spring	summer	fall
Diatomeae cont.																								
Nitzschia sp.	0.2			1.5	0	0.1	2.3	0.3	0.2	0.1			0.5					0	0.5			1		
Rhicosphenia abbreviata												0.4												
Rhopalodia gibba									3.6															
Stephanodiscus niagarae Ehrenberg	17			4.3				9.8																
Stephanodiscus sp.		1.2																						
Stephanodiscus subtransylvanicus Gasse.				0.7			8.7			0.4									5			7.5		
Surirella sp.																			0.8			4.2		
Synedra acus var. radians (Kütz.) Hustedt				4				0.3				0.4	3.3		0.5					0.1		0.2		
Synedra nana Meister						0				0.8			0.2		0.2	1.4						1.5		
Synedra sp.			0.8	3.3	0.5		7.2	0.8	0.4	2.2	0.1					0.3	1.5	0.4	5.7			4.3		0.2
Synedra ulna (Nitzsch) Ehrenberg				2.6	1.6	0.6						1.3	0.2											
Synedra ulna v. danica	0.4																							
Tabellaria fenestrata (Lyngb.) Kütz.	61.8	8.2	0.4	12.3	30.9	30.9		59.4	10.6		3.2	0.6		9.2	3.1	3.8	0.9	1.7	5.4	28.8	9.3	4.6	6.7	10.1
Tabellaria flocculosa (Roth) Kütz.					8.4			18.4	1.7	3.7	5.3		1.8	3.7					1.2	8.4		1.8	5.5	3.7
Urosolenia eriensis Crawford & Mann							1.8	0.2	0.1				0.9		1.4				0.3	0.2			0.1	
Urosolenia longiseta (Zach.) M. B. Edlund & Stoermer																						0.5		
Unknown Diatom	4.5		1.7	2.9	12.5	7.3	4.9	38.2	1.8	2.5	10.1	8.3	4.6	5.1	4.8	2.5	1.8	0.2	0.5	23.2	9.7		10.4	1.7
Cryptophyceae																								
Cryptomonas erosa Ehrenberg																			2.1					
Cryptomonas marssonii Skuja	0.7		0.1		1.4	2.9	3.7	1.4	0.2					2.4					1.1				0.7	7.1
Cryptomonas ovata Ehrenberg				10.7												0.7								
Cryptomonas pusilla Bachmann	0.8			8.2						0.5														
Cryptomonas reflexa Skuja	4	2.7	2.7	0.2	12.7	37.6	3.4	2.7	3.2	2.3	2.3	3.4	1.1	2.1	1.6		2	0.4	2.3	2.7	2.8	4.2	5	3.2
Cryptomonas rostratiformis Skuja																								1.4
Cryptomonas sp.		4.7		12.7			0.5	11.5		1.9							8.8							
Katablepharis ovalis Skuja		0.5	0.1	1.9	0.1		0.3	0.1		0.4	0.2	0.4	1.2		0.3				0.3	0.1		0.5	0.1	0.2
Rhodomonas lacustris Pascher & Ruttner	2.2			9.5			23.8		1.6	2.5									11.8		3.2	5.2		10.3
Rhodomonas lens Pascher & Ruttner					6.6																0.6			
Rhodomonas minuta Skuja	3.2			4.9	19.4	4		0.5	1.4	1.8	1.2	3.4	2.3	1.1	1.4	0.7	1.5	0.7	5.2	6	0.2		3.2	1.9
Rhodomonas minuta var. nannoplanctica Skuja	0.1	0.7	0.4		5.6	1.8							1.2							0.3			0.7	
Dinophyceae																								
Amphidinium sp.				1.9																				
Ceratium furcoides														19						26.4				
Ceratium hirundenella								15.7									10.1							
Glenodinium sp.	2.1	6.9	3.2								2		0.3			3.7		4.4				4.9	0.9	
Gymnodinium helveticum Penard			2.9	4.8						4.5			2.5			2.5		2.9	2.2			2.5		5.7
Gymnodinium mirabile Penard																					13.5			
Gymnodinium sp.		2.6		13			8.6	0.9	6.5	9.3		4.3	4.4	1.1	0.6		0.4		2.4		4.4	9.9	3.1	2.9
Peridinium inconspicuum Lemmermann		4.5			0.5			3.2						0.9			14.5							
Peridinium polonicum Woloszynska														6.8										
Peridinium pusillum (Pénard) Lemmermann																							0.2	
Other																								
Aulomonas perdyi				2.6											0.3							0.2		
Aulomonas sp.							5.7						1.2						0.9					
Chlamydomonas granularis							0.4						0.1	0.1								0.3		0.2
Colorless flagellate				1.9			0.4		2.8				1.4											
Gyromitus cordiformis Skuja																					1.9			

Table 11. Number of replicates, mean total zooplankton density (excluding copepod nauplii) and percent composition by density (excluding nauplii) of all zooplankton taxa found seasonally (Sp=spring, Su=summer and F=fall) in Lake Superior. Copepod nauplii as a percent of total density (nauplii included) are also shown. Data from: USGS (spring 1990 to 1992), OMNR (2005), OMOE Index (1999 to 2011) and CSMI (2011). The dominant taxa are shown in bold. – indicates the taxon was not found. Stations within each area are given in Tables 1-3.

% Composition by Density	Apostle Islands		Black Bay	Duluth Area			Nipigon Bay			Thunder Bay			Coastal Superior			Offshore	
	Su	F	Sp	Sp	Su	F	Sp	Su	F	Sp	Su	F	Sp	Su	F	Su	F
Number of replicates	5	2	7	2	3	3	20	2	2	13	5	5	48	7	3	8	7
Density (No.m^{-3}) - w/o nauplii	5565	9447	4243	1596	10051	9661	2903	7685	6980	1183	15992	3966	721	8543	3157	1359	2671
Total Cladocerans	***29.4***	***26.5***	***4.8***	***-***	***24.8***	***25.3***	***5.6***	***27.9***	***38.3***	***3.2***	***30.7***	***25.4***	***1.1***	***20.2***	***34.0***	***1.4***	***6.8***
Alona sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0	0.3	-	-
Bosmina longirostris	9.9	1.4	3.5	-	4.0	1.6	1.9	8.8	7.5	0.9	11.8	4.7	0.4	14.0	11.3	0.5	0.3
Bythotrephes longimanus	0.0	-	-	-	-	0.0	0.0	0.0	-	0.0	-	0.0	0.0	0.0	0.1	0.0	0.0
Chydorus sphaericus	-	-	-	-	-	-	-	-	-	-	-	-	0.0	-	0.1	-	-
Daphnia galeata mendotae	1.4	-	0.9	-	3.3	8.0	1.0	1.7	0.3	0.9	2.8	5.2	0.1	1.8	0.9	0.5	3.5
Daphnia pulex	-	-	-	-	0.1	-	0.0	-	-	-	-	-	-	-	-	-	-
Daphnia longiremis	-	-	0.1	-	-	-	0.2	-	-	0.1	-	-	0.0	-	-	-	-
Daphnia retrocurva	10.4	24.8	0.1	-	17.3	14.6	2.0	16.1	21.4	0.1	12.5	5.5	-	0.9	0.2	0.1	-
Daphnia sp.	-	-	-	-	-	-	-	-	-	0.2	-	-	0.0	-	-	-	-
Diaphanosoma birgeii	0.2	-	-	-	-	-	-	-	-	-	-	-	-	0.0	-	-	-
Eubosmina coregoni	4.6	0.2	-	-	-	0.0	0.2	-	8.4	0.2	1.5	5.5	-	2.2	12.2	0.3	1.3
Holopedium gibberum	2.9	0.1	0.1	-	0.1	1.0	0.2	1.3	0.6	0.9	2.1	4.4	0.4	1.2	8.9	0.0	1.7
Leptodora kindti	-	-	0.0	-	0.0	-	-	-	-	-	0.0	0.1	0.0	-	-	-	-
Polyphemus pediculus	-	-	0.0	-	-	-	0.0	-	-	-	-	-	0.1	0.0	-	-	-
Total Cyclopoids	***15.0***	***17.4***	***81.9***	***33.2***	***28.5***	***38.0***	***43.1***	***30.2***	***22.6***	***51.2***	***28.6***	***23.0***	***34.5***	***48.3***	***25.0***	***13.4***	***20.2***
Acanthocyclops vernalis	-	-	-	-	-	-	3.6	0.1	-	-	0.3	-	0.1	-	-	-	-
Diacyclops thomasi	1.4	-	53.2	5.3	4.8	0.8	18.9	2.8	0.4	22.8	5.0	0.9	29.8	6.4	1.5	2.9	1.5
Eucyclops agilis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.1	-	-
Mesocyclops edax	-	-	-	-	0.0	-	0.1	-	0.8	-	-	-	-	0.0	0.1	-	0.0
Tropocyclops extensus	-	-	-	-	-	-	-	-	-	-	0.0	-	-	-	0.1	-	-
Cyclopoid copepodid	13.5	17.4	28.7	28.0	23.7	37.1	20.6	27.3	21.3	28.4	23.4	22.1	4.6	41.9	23.0	10.5	18.7
Total Calanoids	***72.3***	***56.1***	***13.3***	***66.8***	***46.8***	***36.6***	***51.3***	***41.2***	***39.0***	***45.6***	***34.0***	***31.7***	***64.5***	***31.5***	***41.0***	***85.2***	***73.0***
Epischura lacustris	7.5	2.8	0.3	2.5	0.4	1.5	1.0	2.0	4.5	0.3	1.7	4.1	0.0	0.1	1.8	0.1	0.2
Leptodiaptomus ashlandi	0.1	-	-	-	0.1	-	0.0	-	-	-	0.0	-	-	0.0	-	-	-
Leptodiaptomus minutus	17.1	9.5	0.5	13.5	3.8	7.8	1.3	4.1	10.4	4.0	3.6	5.7	0.4	0.0	0.3	-	-
Leptodiaptomus sicilis	4.8	1.4	1.5	6.8	1.6	1.0	12.9	1.5	1.4	15.1	3.1	1.4	41.0	2.5	0.4	37.0	2.1
Leptodiaptomus siciloides	0.7	0.2	-	-	-	1.4	-	-	-	-	-	-	-	-	-	-	-
Limnocalanus macrurus	5.2	18.2	1.7	5.7	5.9	0.3	8.1	7.6	3.8	7.3	2.5	0.8	10.4	1.3	0.8	16.6	5.6
Senecella calanoides	-	-	-	-	-	0.0	0.1	-	-	-	-	-	0.7	0.0	0.1	0.5	0.3
Skistodiaptomus oregonensis	5.7	3.5	-	0.1	0.0	1.5	0.1	-	4.9	0.1	0.9	2.6	0.0	0.3	1.2	-	-
Calanoid copepodid	31.1	20.4	9.3	38.1	35.0	23.1	27.7	26.0	14.1	18.9	22.2	17.0	12.0	27.3	36.4	30.9	64.8
Veligers	***-***	***-***	***-***	***-***	***-***	***0.2***	***-***	***0.7***	***-***	***-***	***6.6***	***0.4***	***-***	***-***	***0.2***	***-***	***-***
Copepod Nauplii (% of total)	***13.3***	***11.4***	***45.2***	***51.4***	***15.5***	***19.3***	***64.4***	***35.4***	***33.8***	***71.3***	***23.0***	***21.6***	***83.6***	***23.6***	***22.2***	***57.6***	***4.1***

Table 12. Total number of taxa, mean zooplankton biomass (excluding copepod nauplii) and percent composition by biomass (excluding nauplii) of all zooplankton taxa found seasonally (Sp=spring, Su=summer and F=fall) in Lake Superior. Copepod nauplii as a percent of total biomass (nauplii included) are also shown. Data from: USGS (1990 to 1992), OMNR (2005), OMOE Index (1999 to 2011) and CSMI (2011). The dominant taxa are shown in bold. – indicates the taxon was not found. Mean weights of the taxa used in these biomass calculations are also given.

% Composition by Biomass	mean	Apostle Islands		Black Bay	Duluth Area			Nipigon Bay			Thunder Bay			Coastal Superior			Offshore	
	wt (ug)	Su	F	Sp	Sp	Su	F	Sp	Su	F	Sp	Su	F	Sp	Su	F	Su	F
Number of Taxa		15	10	12	6	14	15	19	12	12	13	16	14	16	18	19	11	11
Biomass (mg.m^{-3}) w/o nauplii		19.6	69.2	15.2	8.2	36.5	34.4	13.5	28.4	26.0	5.7	64.1	15.8	6.1	20.4	9.8	9.5	11.8
Total Cladocerans		***28.8***	***16.2***	***5.0***	**-**	***30.8***	***47.4***	***6.4***	***30.6***	***36.9***	***3.9***	***35.5***	***40.3***	***1.1***	***22.9***	***36.4***	***1.3***	***12.8***
Alona sp.	1.15	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0	0.1	-	-
Bosmina longirostris	1.39	4.2	0.2	1.4	-	1.2	0.5	0.7	4.0	2.1	0.2	5.0	2.5	0.1	8.0	5.2	0.1	0.1
Bythotrephes longimanus	102.68	0.1	-	-	-	-	0.0	0.1	0.0	-	0.0	-	1.4	0.0	1.1	3.8	0.1	0.8
Chydorus sphaericus	4.83	-	-	-	-	-	-	-	-	-	-	-	-	0.0	-	0.2	-	-
Daphnia galeata mendotae	11.07	3.9	-	3.0	-	7.7	26.1	2.7	2.4	0.5	2.1	10.2	16.2	0.3	7.9	3.6	0.8	9.0
Daphnia pulex	4.48	-	-	-	-	0.0	-	0.0	-	-	-	-	-	-	-	-	-	-
Daphnia longiremis	5.41	-	-	0.2	-	-	-	0.2	-	-	0.1	-	-	0.0	-	-	-	-
Daphnia retrocurva	5.41	10.4	15.8	0.2	-	21.6	18.8	2.5	23.2	28.6	0.1	16.5	7.8	-	1.9	0.4	0.1	-
Daphnia sp.	5.41	-	-	-	-	-	-	-	-	-	0.2	-	-	0.0	-	-	-	-
Diaphanosoma birgeii	2.40	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0	-	-	-
Eubosmina coregoni	1.94	2.1	0.0	-	-	-	0.0	0.1	-	4.7	0.1	0.7	3.1	-	1.3	7.0	0.2	0.6
Holopedium gibberum	5.69	8.0	0.1	0.1	-	0.2	1.9	0.2	0.9	1.1	1.1	3.1	9.2	0.5	2.6	16.0	0.1	2.2
Leptodora kindti	10.50	-	-	0.1	-	0.1	-	-	-	-	-	0.1	0.1	0.0	-	-	-	-
Polyphemus pediculus	2.15	-	-	0.0	-	-	-	0.0	-	-	-	-	-	0.0	0.0	-	-	-
Total Cyclopoids		***5.5***	***2.5***	***66.9***	***11.2***	***13.4***	***12.9***	***22.0***	***10.4***	***7.5***	***26.4***	***13.7***	***7.3***	***14.9***	***26.5***	***10.9***	***4.8***	***6.5***
Acanthocyclops vernalis	4.55	-	-	-	-	-	-	3.7	0.2	-	-	0.3	-	0.0	-	-	-	-
Diacyclops thomasi	3.56	1.9	-	56.8	3.6	6.2	0.9	12.8	2.2	0.2	18.7	5.0	0.8	13.9	8.3	1.7	1.6	1.2
Eucyclops agilis	1.43	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0	-	-
Mesocyclops edax	6.99	-	-	-	-	0.1	-	0.1	-	0.9	-	-	-	-	0.1	0.2	-	0.0
Tropocyclops extensus	0.93	-	-	-	-	-	-	-	-	-	-	0.0	-	-	-	0.0	-	-
Cyclopoid copepodid	1.11	3.5	2.5	10.1	7.6	7.1	11.9	5.5	8.0	6.5	7.8	8.4	6.5	1.0	18.1	8.8	3.2	5.3
Total Calanoids		***65.8***	***81.3***	***28.1***	***88.8***	***55.8***	***39.7***	***71.6***	***58.7***	***55.5***	***69.7***	***48.5***	***52.3***	***84.0***	***50.6***	***52.7***	***93.9***	***80.7***
Epischura lacustris	17.75	11.2	5.4	1.5	8.1	1.3	6.2	3.8	5.0	14.3	1.0	6.7	20.6	0.0	0.4	10.4	0.2	0.9
Leptodiaptomus ashlandi	6.15	0.2	-	-	-	0.1	-	0.0	-	-	-	0.1	-	-	0.0	-	-	-
Leptodiaptomus minutus	4.12	7.1	4.8	0.6	*10.1*	*2.7*	*7.5*	*1.1*	*2.5*	*7.5*	*3.5*	*3.1*	*6.2*	*0.2*	*0.0*	*0.4*	-	-
Leptodiaptomus sicilis	9.66	5.2	1.9	4.2	12.5	2.7	2.6	15.5	1.9	2.6	22.5	7.4	3.1	44.5	7.9	1.3	33.4	3.9
Leptodiaptomus siciloides	4.19	0.2	0.1	-	-	-	1.3	-	-	-	-	-	-	-	-	-	-	-
Limnocalanus macrurus	28.87	17.9	60.1	13.9	35.5	24.8	2.4	33.8	28.0	16.1	31.1	11.0	5.5	31.8	11.5	7.0	44.0	33.6
Senecella calanoides	49.89	-	-	-	-	-	0.2	1.1	-	-	-	-	-	2.7	0.3	1.5	2.3	3.0
Skistodiaptomus oregonensis	7.45	4.5	2.7	-	0.1	0.0	2.9	0.2	-	6.7	0.2	1.4	5.3	0.0	1.0	2.9	-	-
Calanoid copepodid	2.68	19.6	6.4	7.9	22.5	24.2	16.6	16.1	21.4	8.4	11.4	18.8	11.6	4.7	29.3	29.3	14.1	39.2
Veligers	1.30	-	-	-	-	-	*0.1*	-	*0.3*	-	-	*2.3*	*0.1*	-	-	*0.1*	-	-
Copepod Nauplii (% of total)	0.11	***0.6***	***0.3***	***2.5***	***2.7***	***0.7***	***0.9***	***4.2***	***2.0***	***1.9***	***5.7***	***1.0***	***0.6***	***6.3***	***1.8***	***1.1***	***3.3***	***0.1***

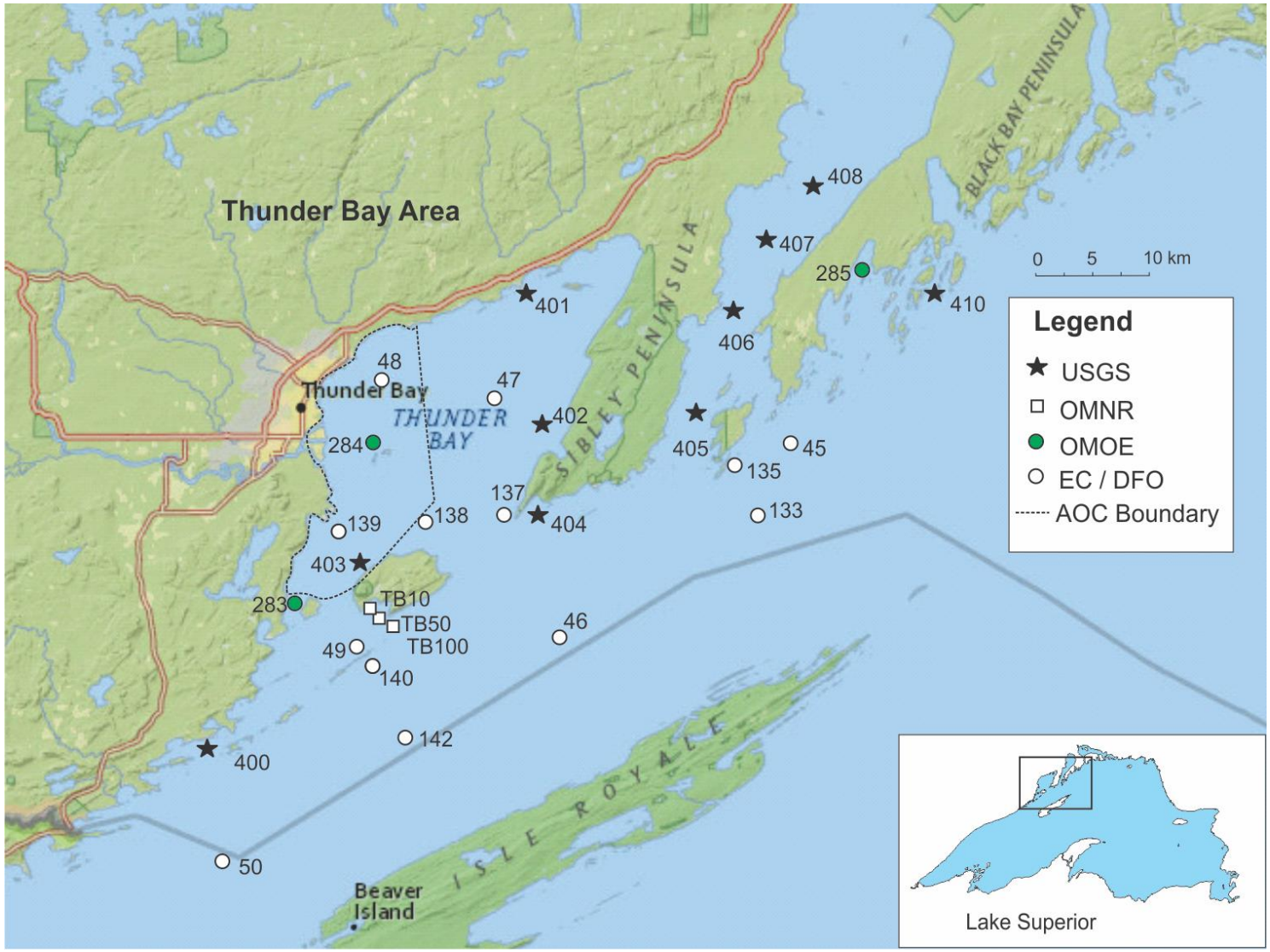

Figure 1: Map of the Thunder Bay area of Lake Superior showing stations sampled by various agencies between 1971 and 2014. The approximate AOC boundary is indicated by the dashed line.

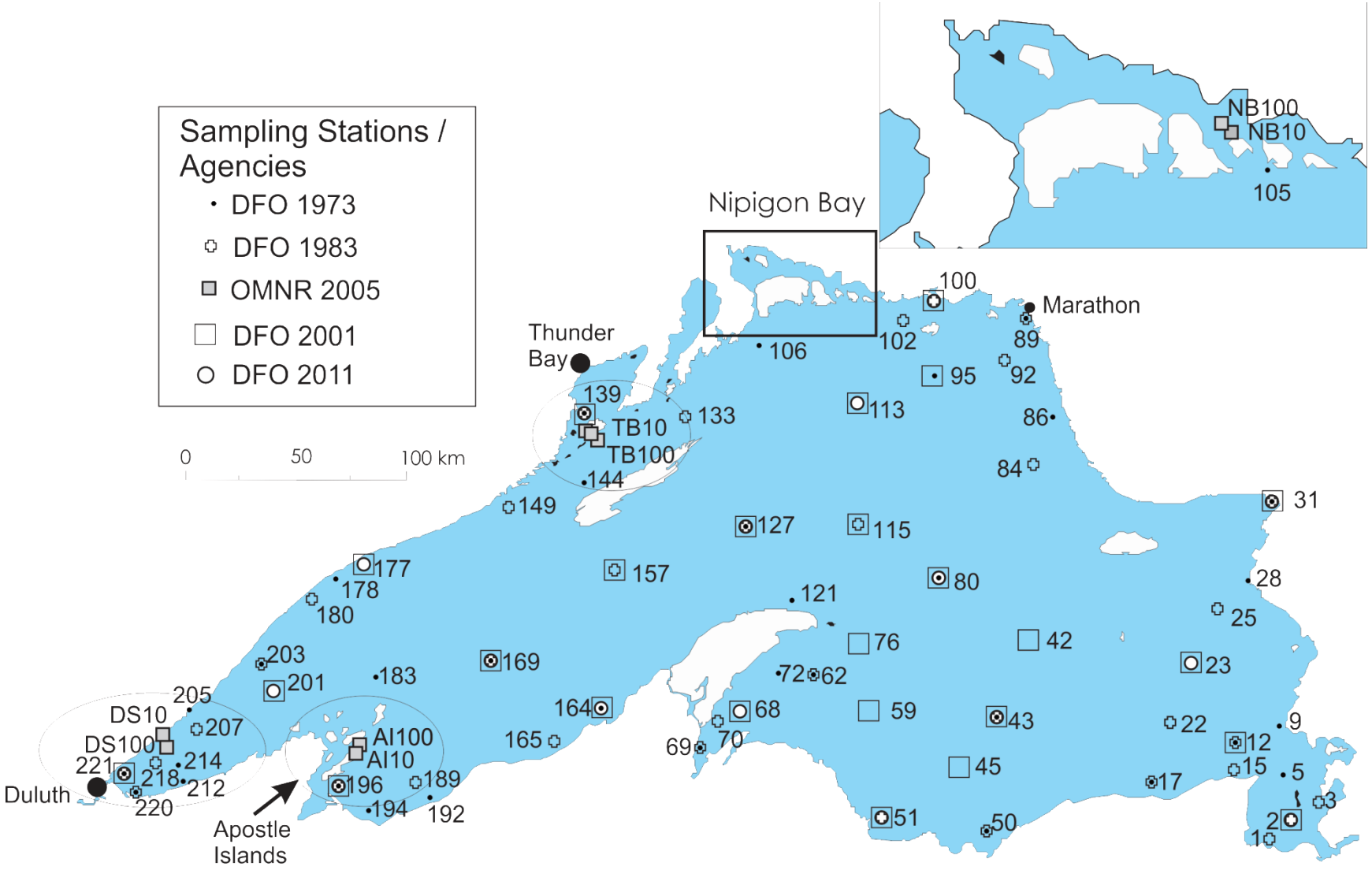

Figure 2: CSMI Lake Superior Study stations sampled by DFO, and embayments sampled seasonally in 2005 by OMNR.

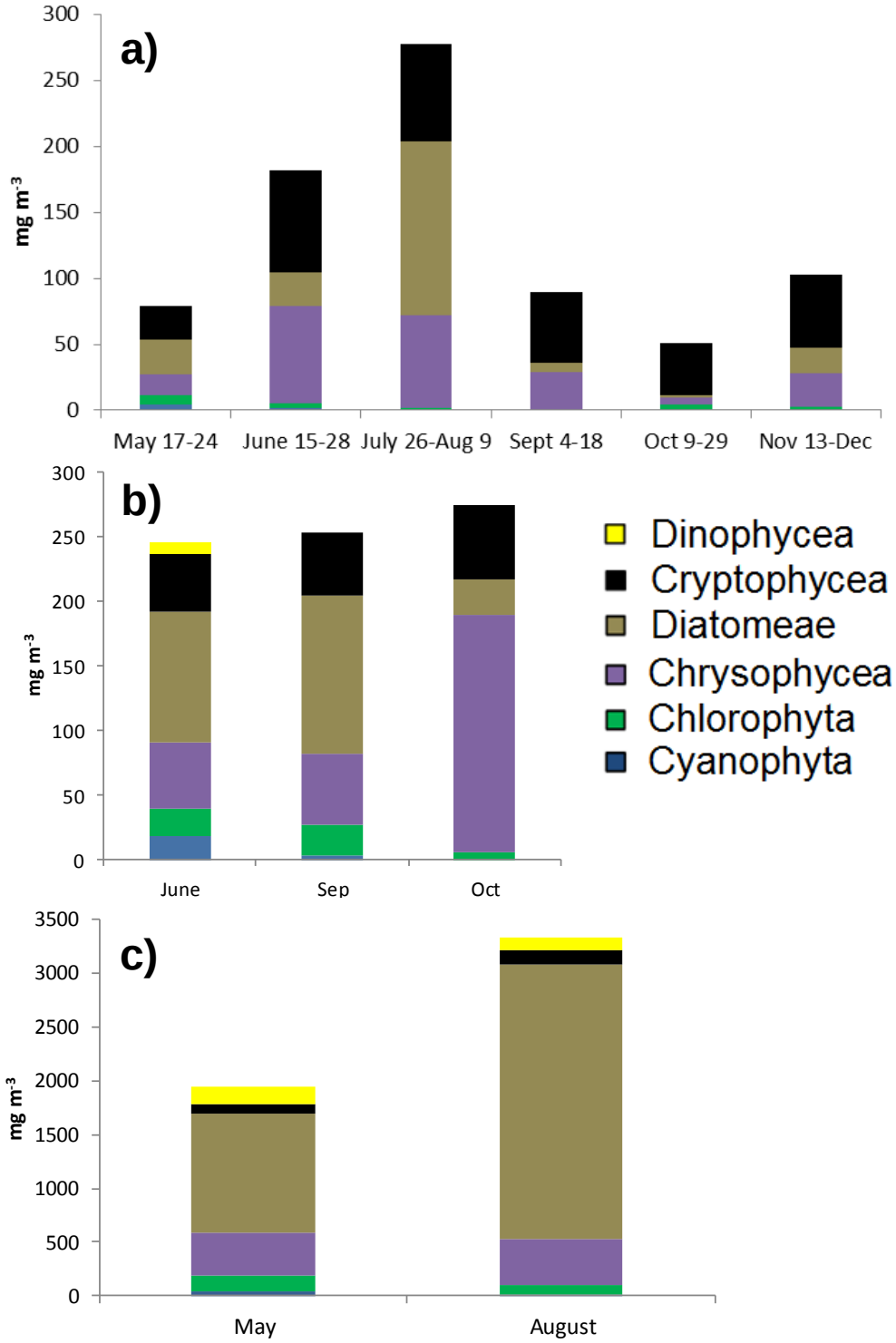

Figure 3. Phytoplankton biomass (mg m^{-3}) at offshore Thunder Bay station 139 during a) 1973 b) 1983 c) 2001.

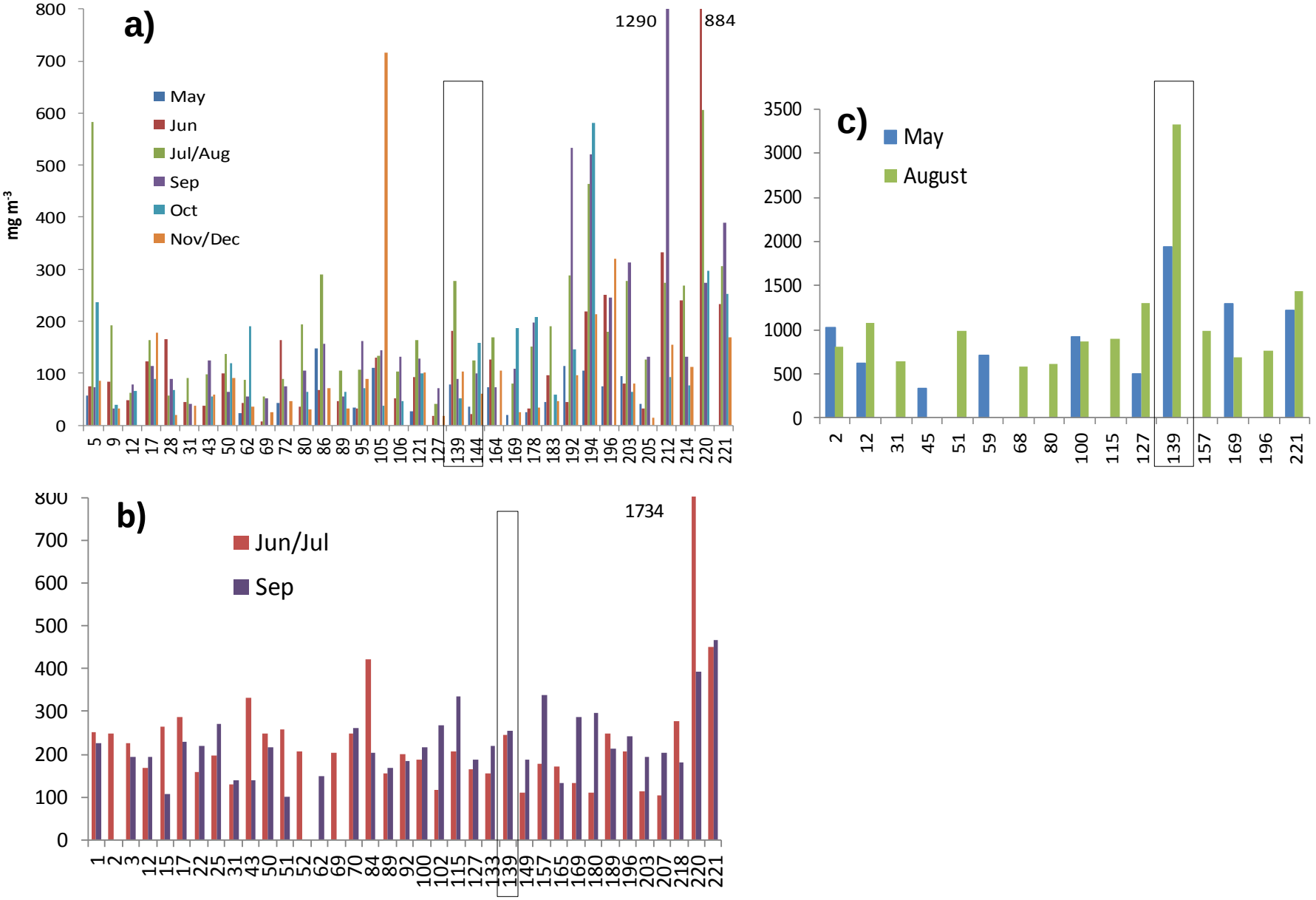

Figure 4. Phytoplankton biomass (mg m^{-3}) at all stations sampled during a) 1973, b) 1983 and c) 2001. Thunder Bay area stations outlined.

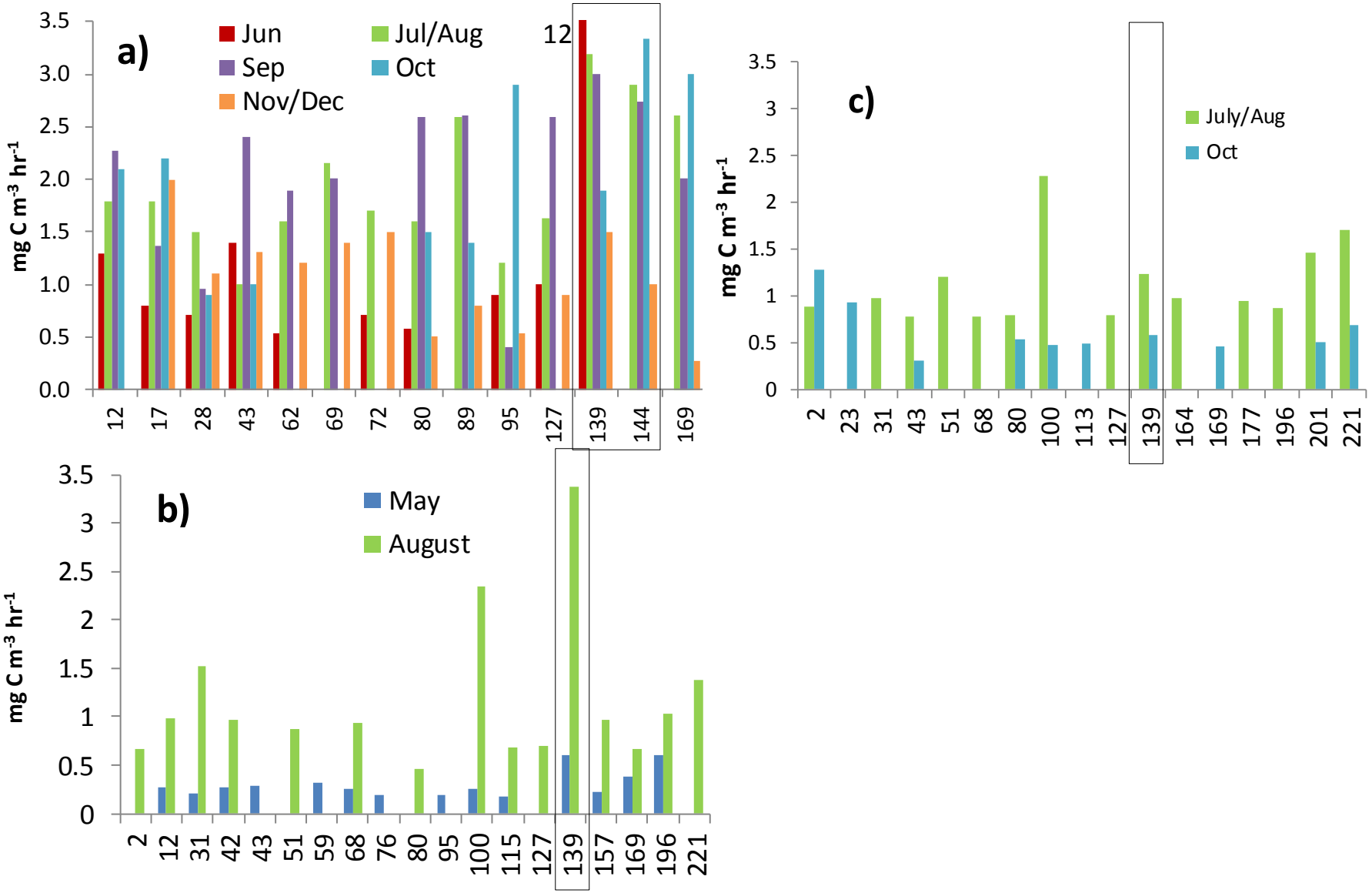

Figure 5. Lake wide Primary Productivity (mg C m^{-3} hr^{-1}) a) 1973 b) 2001 and c) 2011. Thunder Bay area stations outlined.

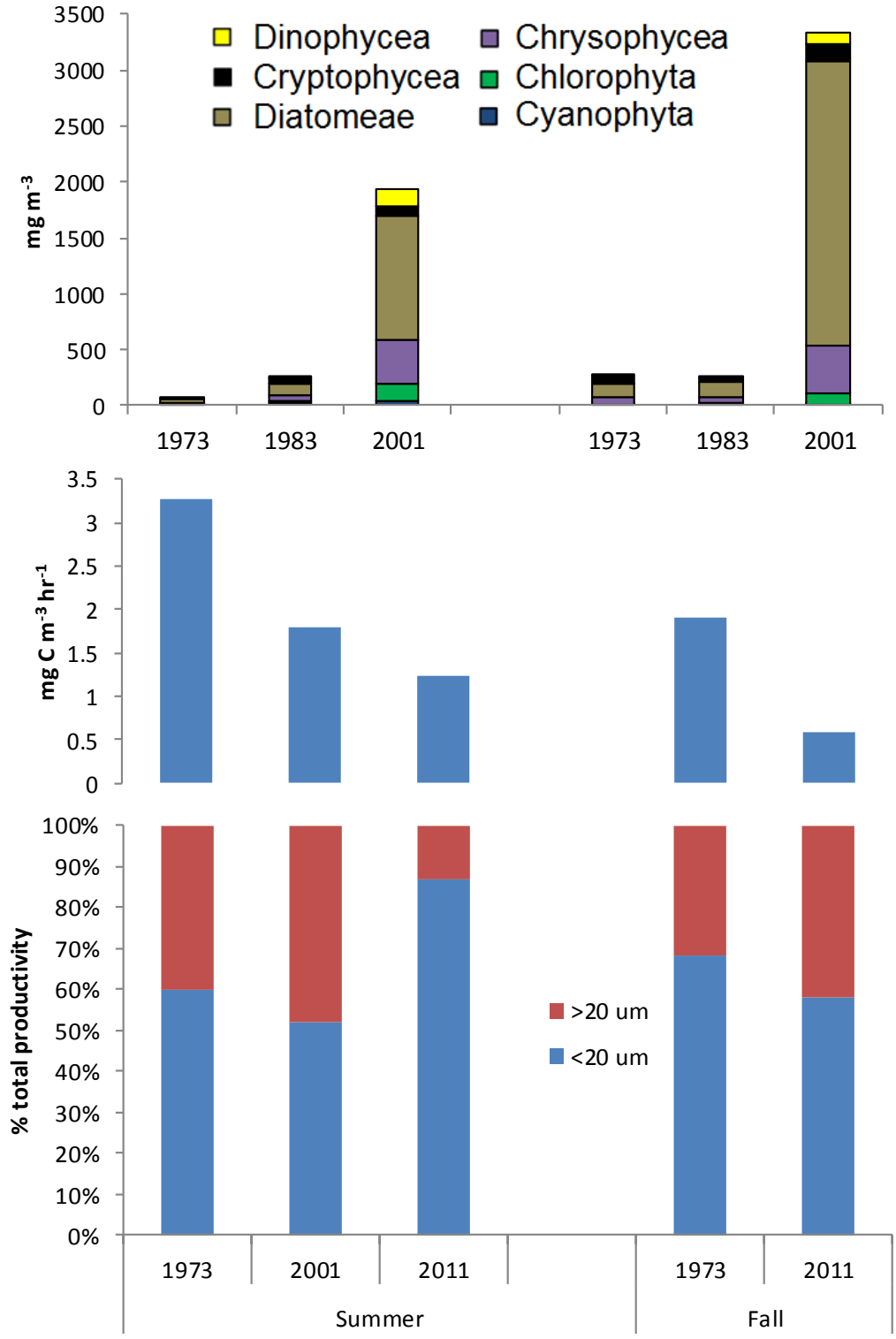

Figure 6 Thunder Bay station 139 long term comparison of a) phytoplankton biomass (mg m^{-3}) and composition b) primary productivity (mg C m^{-3} hr^{-1}) and c) proportion of productivity from large (>20 um) and small sized phytoplankton (<20 um).

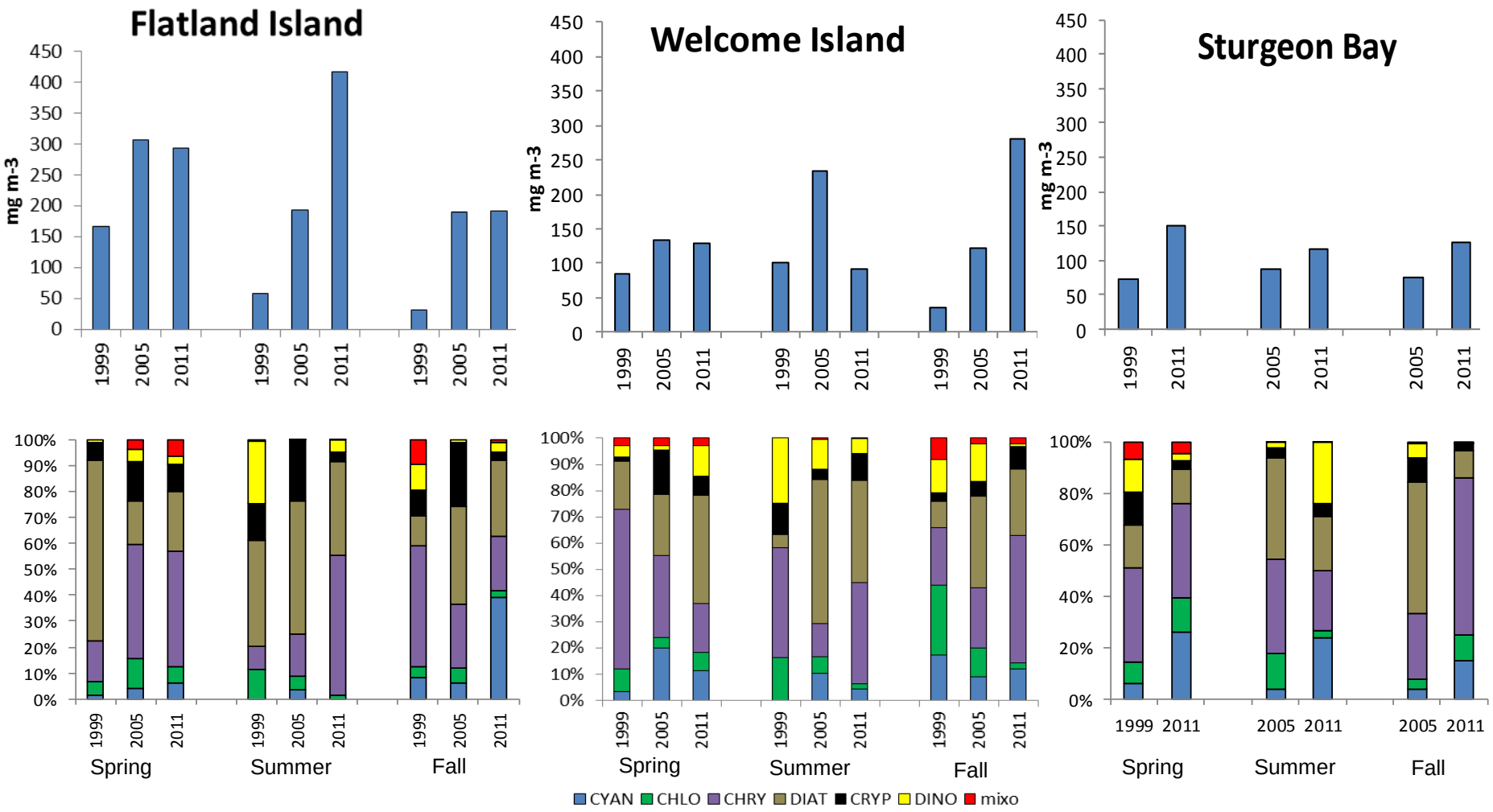

Figure 7. Phytoplankton biomass (mg m^{-3}, top panels) and composition (lower panels) during the seasonal OMOE Index surveys in the Thunder Bay area in 1999, 2005 and 2011. The Welcome Island station (284) is located in the outer AOC, and Flatland Island (283) is to the south of the AOC. Sturgeon Bay (285), a coastal station to the east, was not sampled in 1999

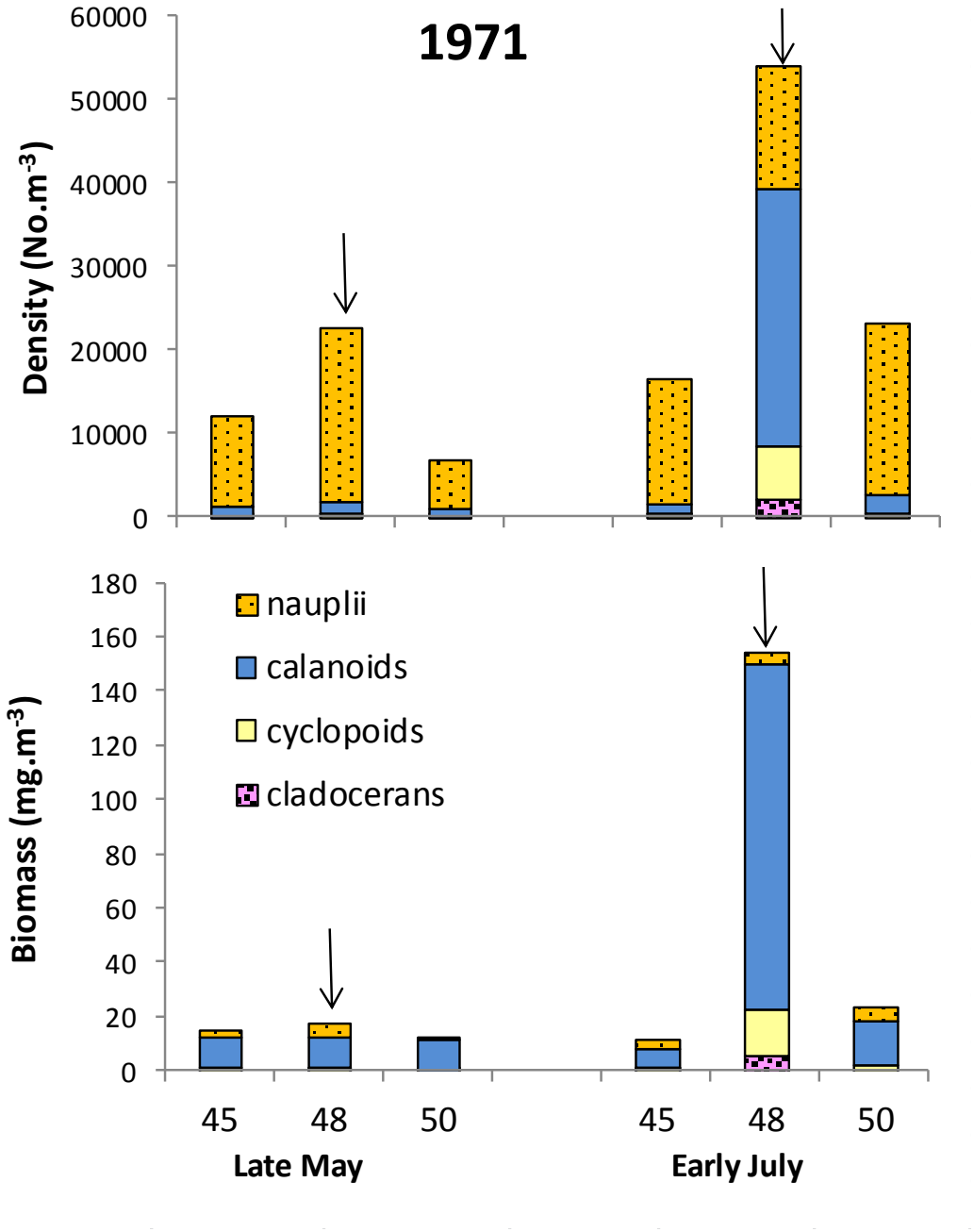

Figure 8: Density and biomass of dominant zooplankton groups at stations in the Thunder Bay area during the 1971 surveys by Watson and Carpenter. Station 48 indicated by the arrow is located in the outer AOC.

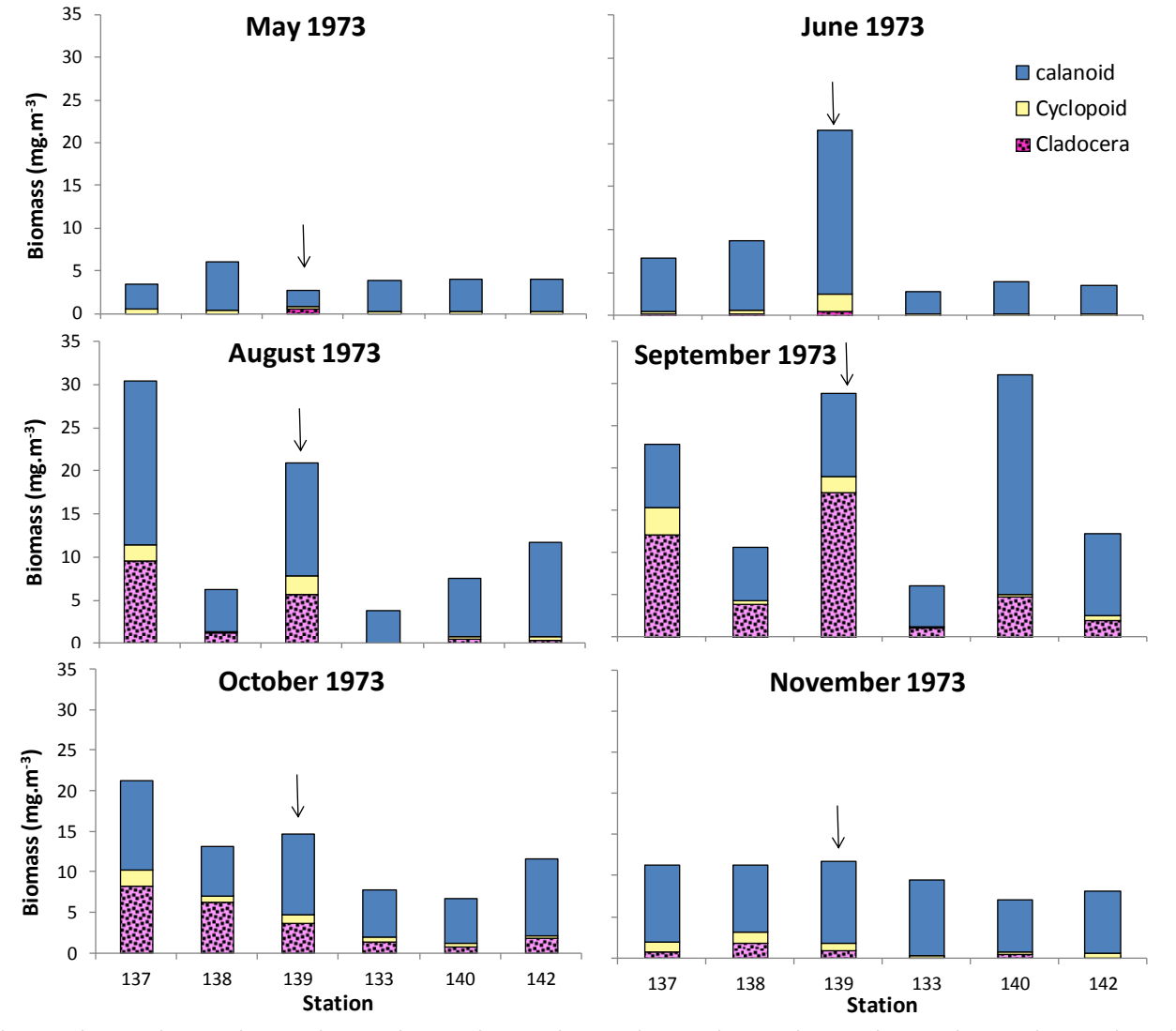

Figure 9: Biomass of dominant zooplankton groups at stations in the Thunder Bay area during the 1973 surveys by Watson and Carpenter. Station 139 indicated by the arrow is located in the outer AOC. Copepod nauplii were not counted during this survey.

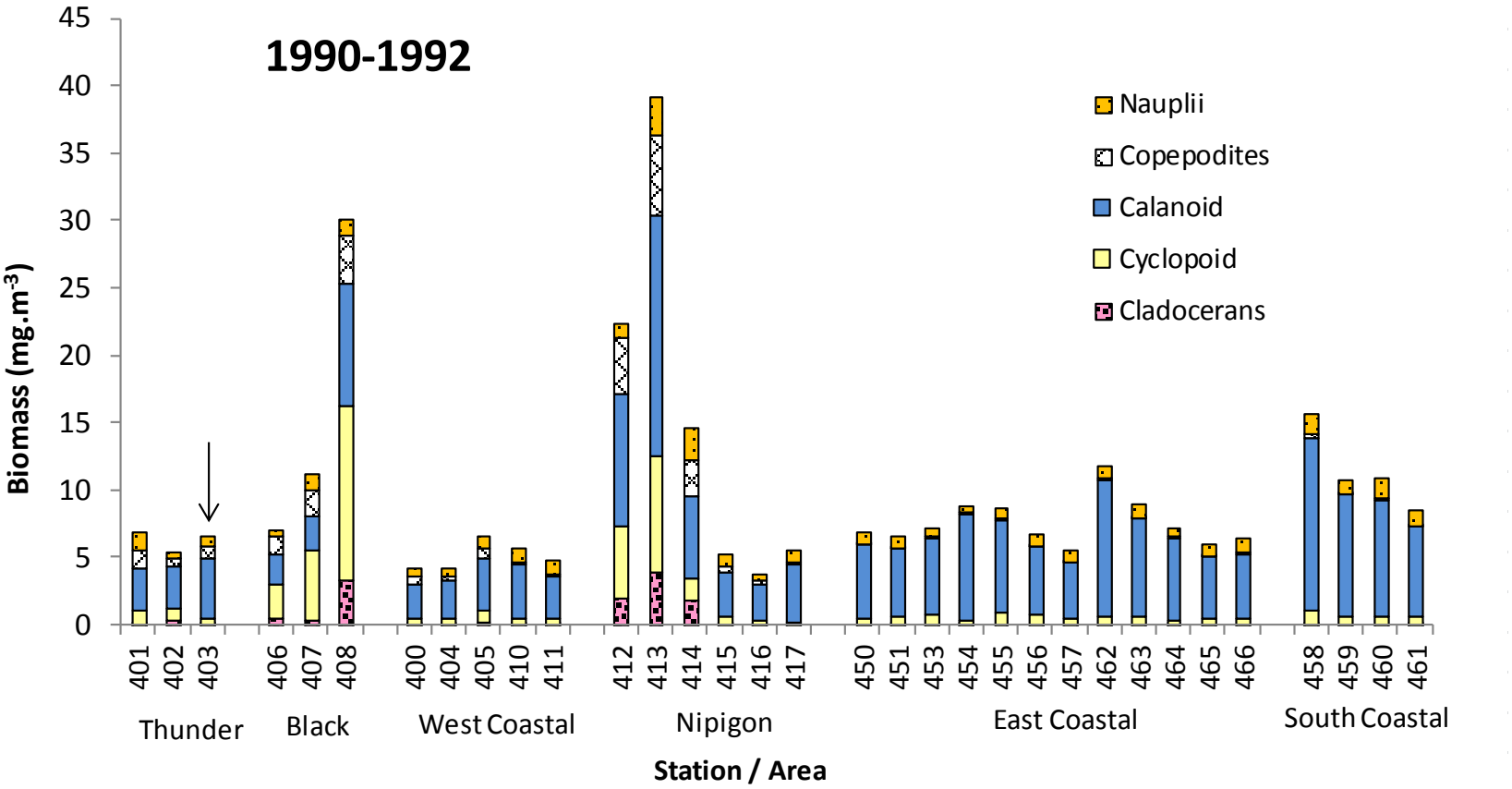

Figure 10: Mean biomass of dominant zooplankton groups found in June at nearshore USGS stations along the Canadian Lake Superior coast, averaged over the 1990-1992 period.

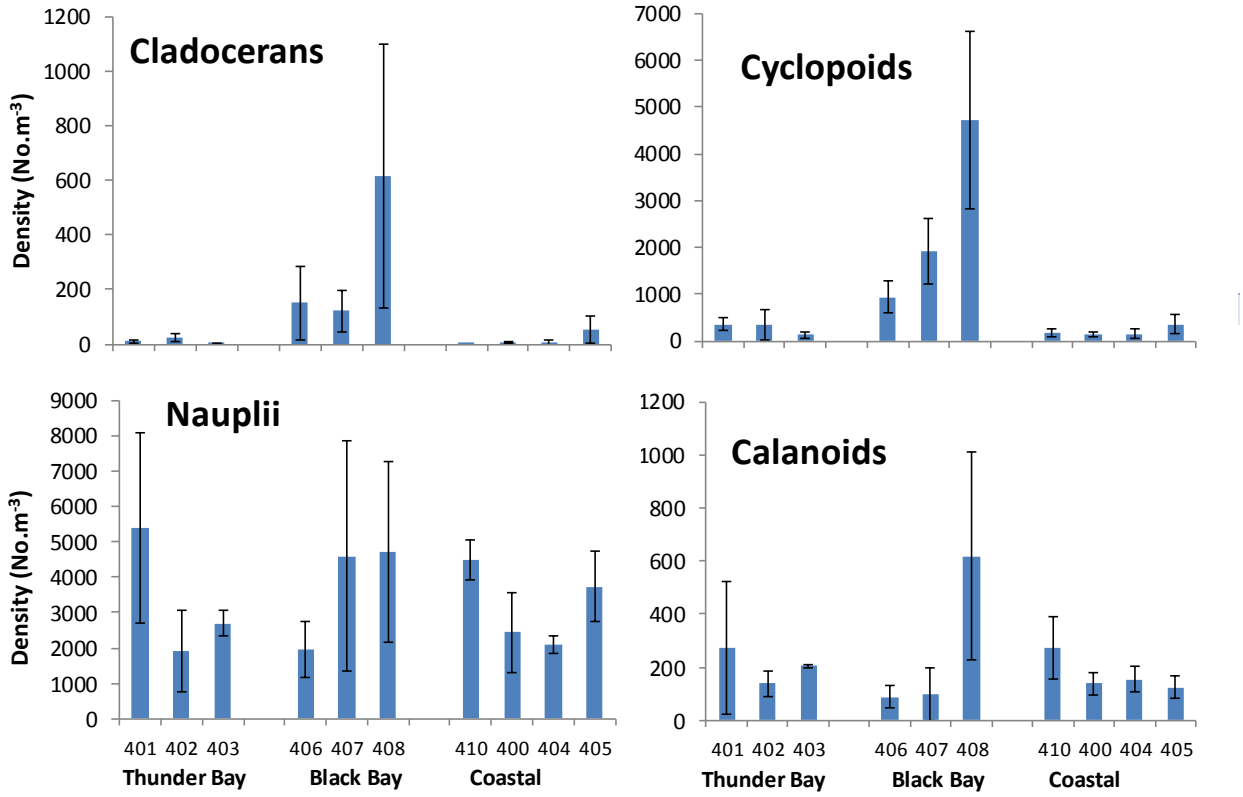

Figure 11: Mean densities (±SE) of dominant zooplankton groups found in June at nearshore USGS stations in the vicinity of Thunder Bay, averaged over the 1990-1992 period.

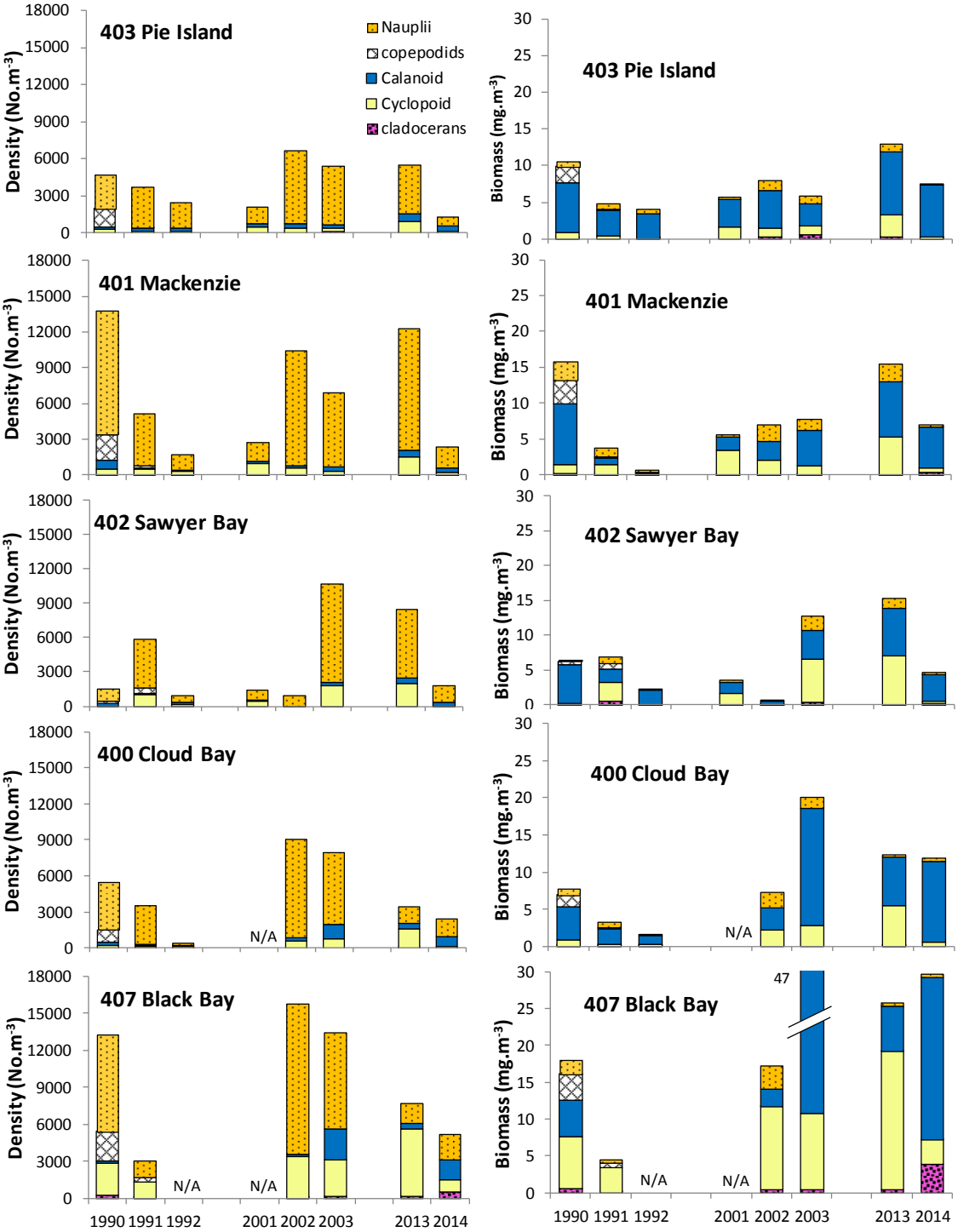

Figure 12: Mean densities and biomass of dominant zooplankton groups found in June at nearshore USGS stations in the vicinity of Thunder Bay, from 1990-1992, 2001-2003 and 2013-2014. Years marked NA were not sampled. Biomass in 2003 at Black Bay was off the scale, reaching 47 mg m^{-3}.

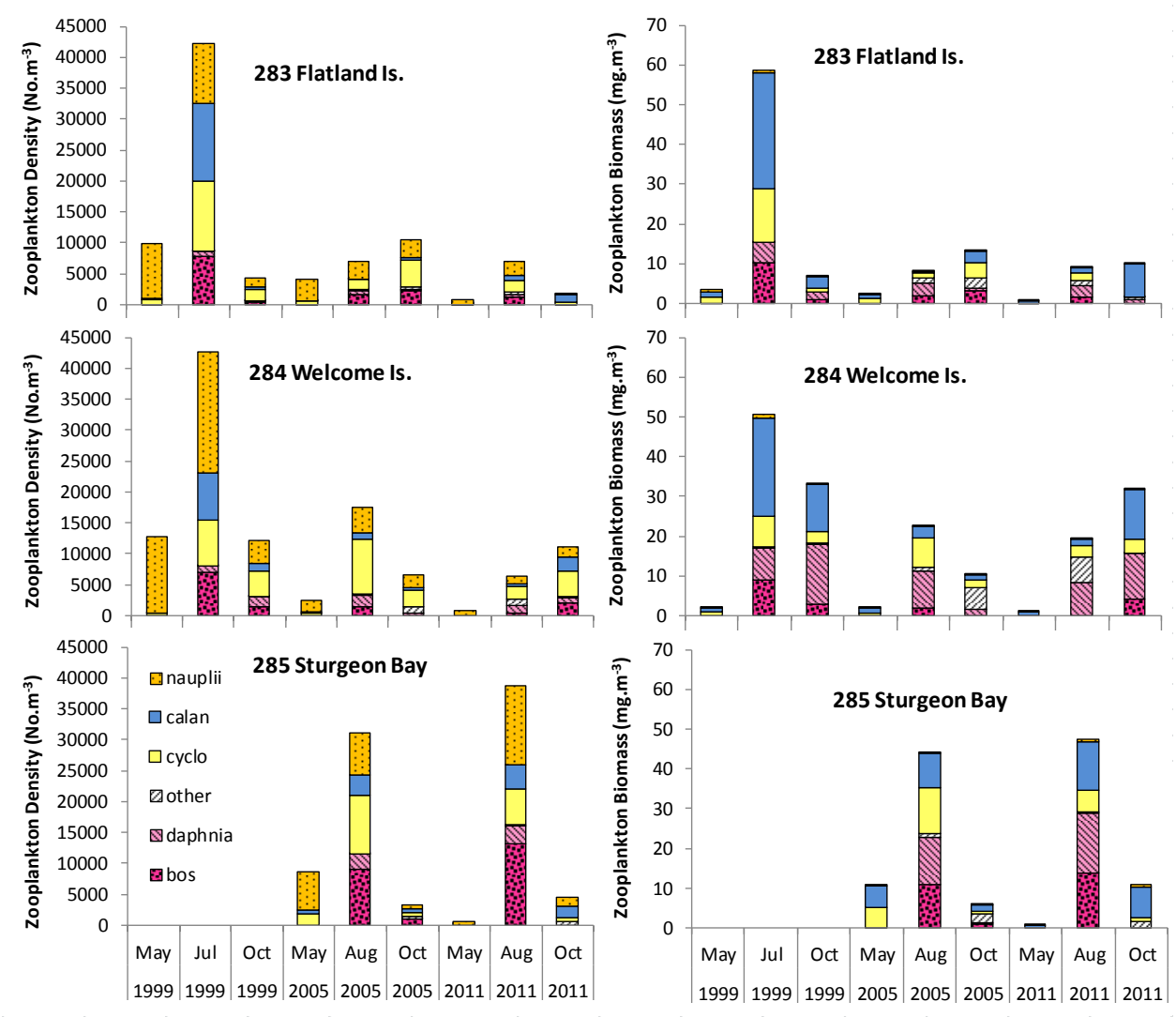

Figure 13: Density and biomass of dominant zooplankton groups during the seasonal OMOE Index surveys in the Thunder Bay area in 1999, 2005 and 2011. The Welcome Island station is located in the outer AOC, and Flatland Island is to the south of the AOC. Sturgeon Bay, a coastal station to the east, was not sampled in 1999.

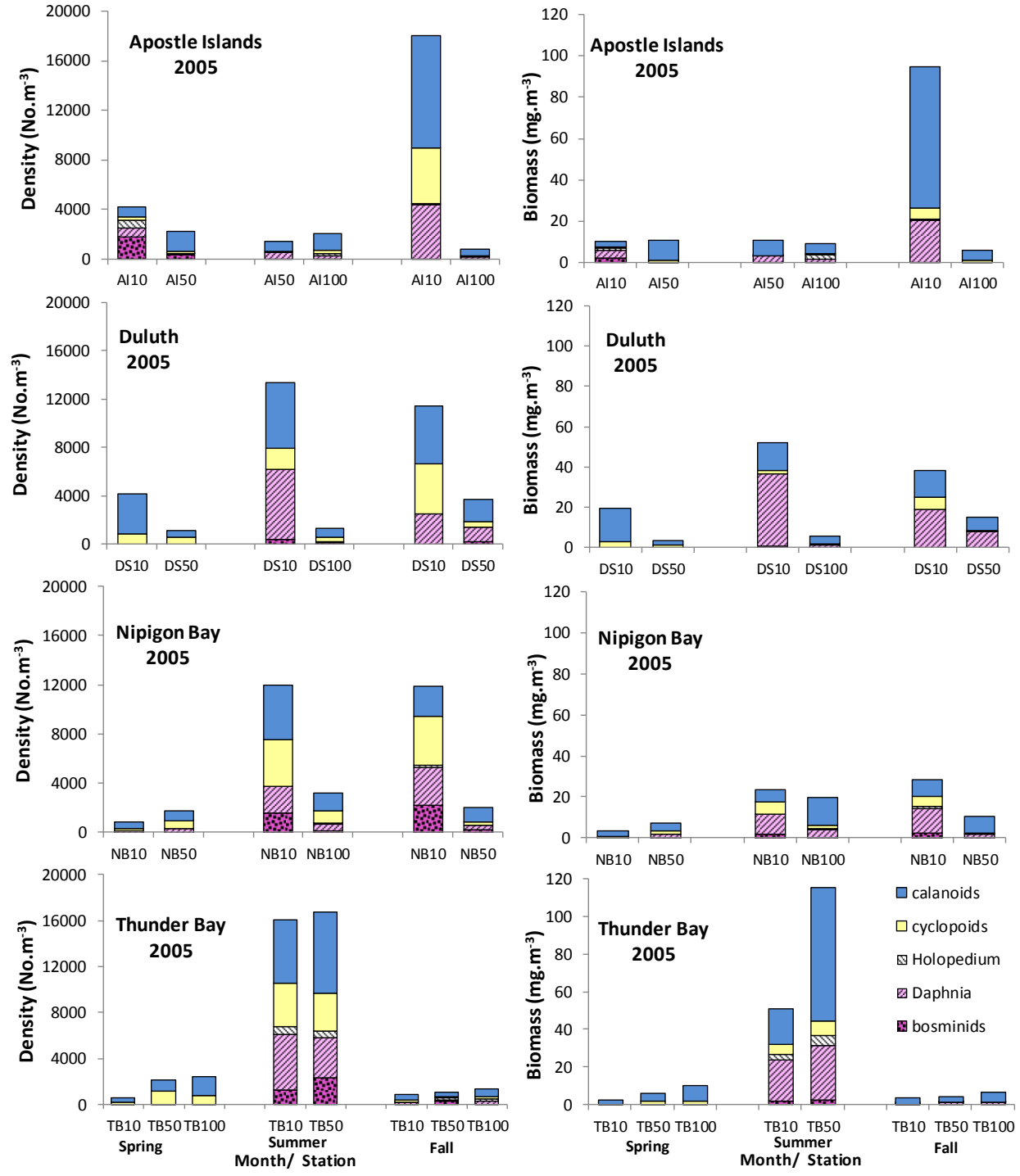

Figure 14: Density and biomass of dominant zooplankton groups during the seasonal OMNR surveys in Lake Superior embayments in 2005. Nauplii were abundant but not included as they were not consistently sampled due to differences in net mesh size.

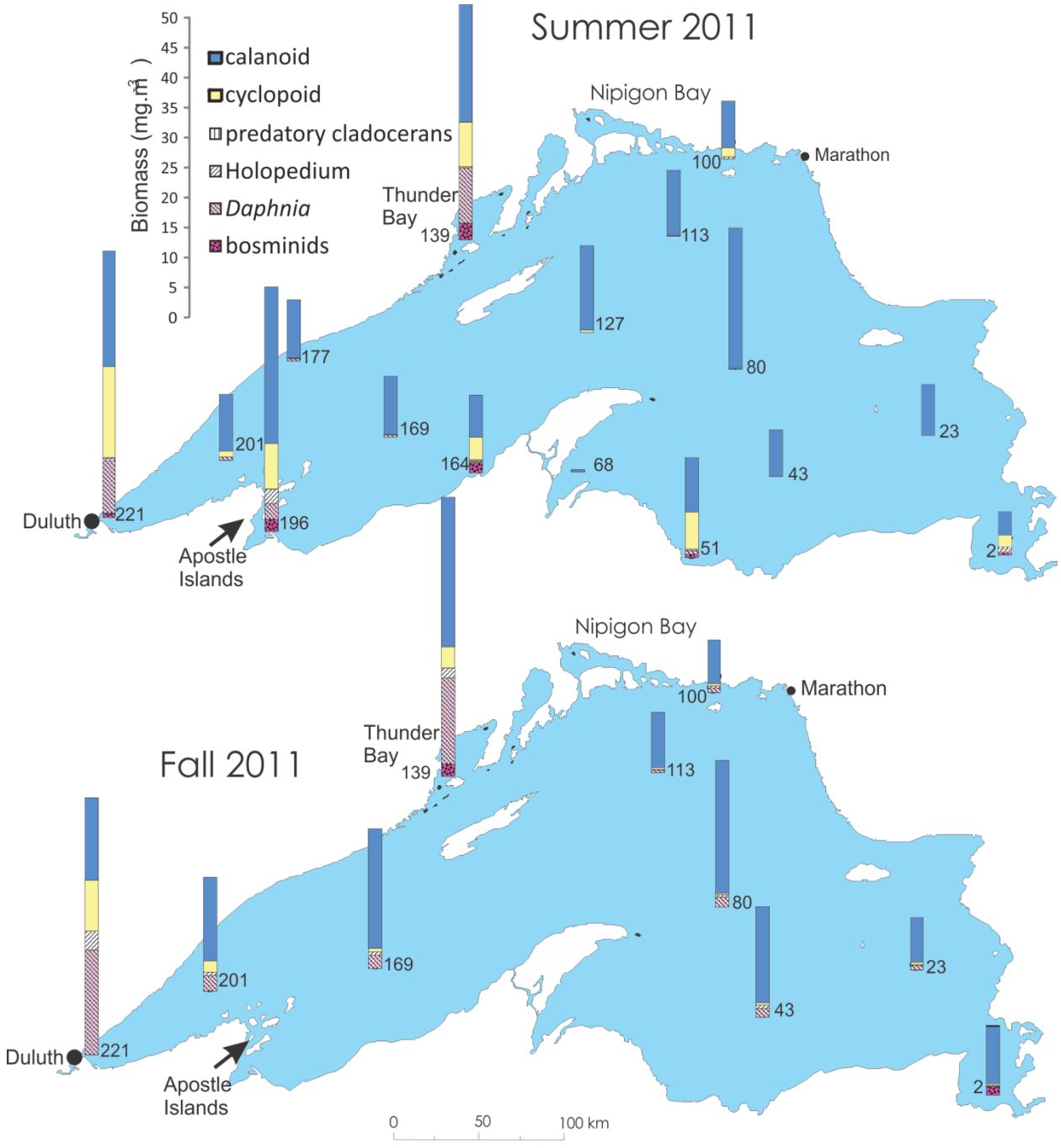

Figure 15: Total water column biomass of dominant zooplankton groups during the summer 2011 and fall 2011 CSMI surveys completed by DFO. Samples were collected using a 153 µm net, so nauplii and veligers were not sampled effectively.

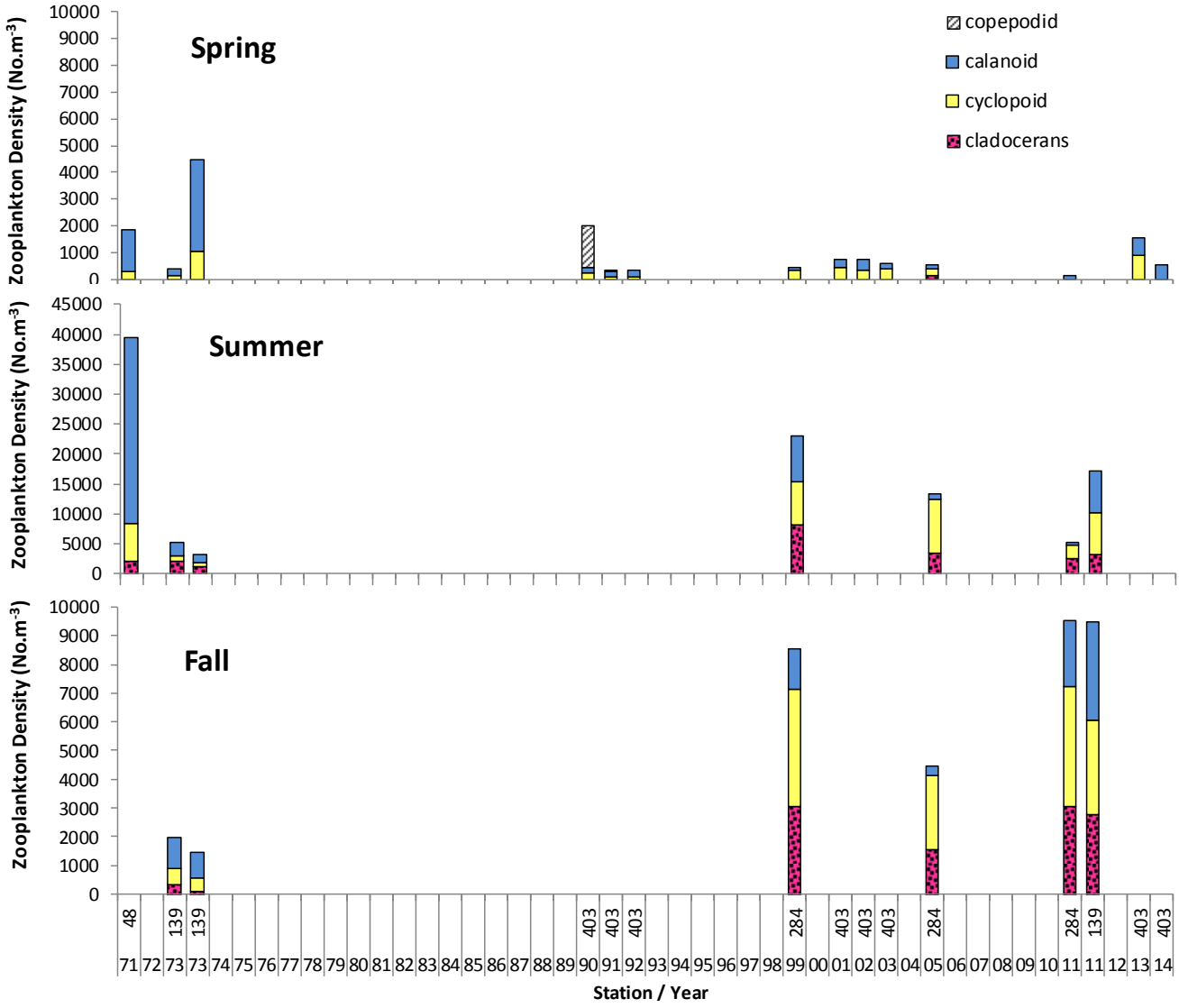

Figure 16: Densities of zooplankton groups at stations within the outer Thunder Bay AOC between 1971 and 2014. Note that the scale for the summer densities is different. Station 403 was only sampled in June. Copepod nauplii, though numerically dominant, are not included as they were not counted consistently.

PHYTOPLANKTON AND ZOOPLANKTON POPULATIONS: CONCLUSIONS

While information on plankton populations is scarce for both Toronto Region AOC and Thunder Bay AOC, all available historical information including results from the DFO's 2010 Ecosystem Research Initiative (ERI), OMOECC Index sampling, and the 2013 GLLFAS survey of Toronto is documented in this report.

Section 1:
The Toronto Region planktonic ecosystem study was a lone survey during the week of Sept 9-13, 2013 from Etobicoke to Pickering, the boundaries of the AOC. The purpose was to determine the distribution of zooplankton, chlorophyll and physical water characteristics using DFO's towed SHRIMP sensor array, but to enhance this spatial survey (for the 2013 CSMI), station sampling was included for physical characteristics, water chemistry, and collection of phytoplankton, microbial loop and zooplankton for taxonomy, which are made available.

During the survey, the entire Toronto coastline experienced a strong, widespread upwelling which greatly affected the distribution of physical characteristics, chlorophyll, and zooplankton densities. In particular, the area near Ashbridges Bay along the scarp was highly affected by the upwelling making any determination of impact by factors such as the sewage treatment outfall difficult for this survey. Though much reduced in intensity, Humber Bay, the source water for Toronto Harbour, was also influenced by the upwelling. Humber Bay also showed weak stratification for all of 2013, likely due to its orientation to the northwest, the dominant prevailing wind direction. Frequent upwelling forces combined with the internal seiche of the lake is likely to create very specific physical mixing conditions in Humber Bay unique to Lake Ontario, so comparisons to other embayments will be difficult.

Toronto Inner Harbour was very different from surrounding habitat in physical water characteristics with elevated values for temperature, turbidity and chlorophyll but much reduced primary production, densities of zooplankton and phytoplankton and differing composition. Phytoplankton composition was highly variable between stations although there was a preponderance of flagellated forms capable of self-directed movement. Primary production was depressed in the Harbour except at the Don River mouth, which also had higher chlorophyll-*a*, turbidity and total phosphorus. Driven in part by river discharges, bacterial production was elevated within the Harbour and in Humber Bay. Zooplankton particle densities were highly reduced in the Harbour compared to other coastal and other embayment habitats, especially for the eastern portion of the AOC which had much higher densities. This was unexpected since zooplankton should be able to retain themselves in the Harbour, even during an upwelling event. This, added to low counts found during other past surveys, and the lack of change in rotifer densities, suggests the possibility that Toronto Harbour may not be a suitable habitat for plankton populations. A single snapshot spatial survey is however not adequate to properly assess the zooplankton and phytoplankton BUI of the Toronto AOC. Further sampling should involve at least monthly sampling of zooplankton and phytoplankton from May-Oct to determine population structure over the spring-fall period and possibly population growth studies using incubations, in addition to tracking the effect of planktivory from fishes.

Section 2:
The use of the Ontario Ministry of the Environment (and Climate Change) Nearshore Index archived plankton samples, in of themselves, were found to be insufficient to determine the status of BUI 13 with regards to densities or composition of zooplankton or phytoplankton. The sampling program of three times per year, every three years for Toronto Harbour is too sparse to account for the underlying variability within plankton populations and determine differences

between sites. A power analysis indicated that at least 50-60 samples would be needed from each site to resolve differences between 2 locations (within AOC to a reference site), and the years of sampling has not been the same for each Index site, so pairing sites is additionally difficult. An additional difficulty is in the timing of the early sample in April, which was chosen to target the freshet runoff and resulting increased chloride inputs. Zooplankton composition is generally limited to overwintering juvenile copepod stages at this time of the year so is not comparable to any other studies. The “fall” sample in November is also very late in the year, leaving only a single sample in August per year for comparison to other sampling programs. Lastly, the taxonomist notes that that the other nearby coastal Index sites have different planktonic species compositions than Toronto making them unsuitable reference conditions.

A comparison of DFO to MOECC sampling frequency in Hamilton Harbour for two sampling years indicated that the three samples taken per year by MOECC is insufficient to account for changes in species composition and density over the sampling season. In particular, the dominant genus *Bosmina*, is almost completely absent from the Index sampling due to lack of sampling during June and July. Furthermore, estimated zooplankton densities were only half of that found by DFO biweekly sampling. It is recommended that a minimum of monthly sampling is necessary for zooplankton resulting in at least 6 samples per sampling year. Phytoplankton populations have higher variability so are likely to require even more frequent samples to accurately sample species composition.

Section 3:
All available plankton and coinciding physical-chemical data from the Thunder Bay area is documented from DFO, MOECC Index, MNRF and USGS programs, along with other embayment, coastal and offshore areas in Lake Superior. Data contained in this report could be used as a baseline for lake-wide changes over time or reference for any new studies.

Some governmental program sampling takes place during less ideal periods early in the year, since they are not targeting plankton (e.g. USGS since 1990 in June and MOECC in May), when zooplankton consists of only copepods and their nauplii stages, which are undersampled by the use of large-mesh nets. Most differences among areas develop through the summer as cladocerans and other taxa preferring warmer temperatures appear, which occurs earlier in protected embayments. However, most previously sampled Thunder Bay area stations are either located outside of the AOC boundaries or are at the southern, lake-mixed, coastally influenced portion of the AOC. In order to properly assess whether phytoplankton and zooplankton populations within the Thunder Bay AOC are impacted, it is necessary to sample the areas where impacts are most likely to occur (e.g. turbidity, contaminated sediment). The Thunder Bay RAP identified the Kaministiquia River, the inner Thunder Bay Harbour and Chippewa Beach as the areas of highest degradation, with impacts radiating out from the river’s delta. Sampling should be carried out at several stations along a gradient away from the most impacted areas. Sampling would ideally be done six times per year with emphasis on the July to September period when the zooplankton community is most developed. This would provide data on spatial variability within Thunder Bay harbour, and determine if a trophic gradient exists.