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Status of the Lake Ontario Food Web in a Changing Ecosystem: the 2003 Lake Ontario Lower Aquatic Food Web Assessment (LOLA)

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Status of the Lake Ontario Food Web in a Changing Ecosystem:

the 2003 Lake Ontario Lower Aquatic Food Web Assessment (LOLA)

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Executive Summary:
Assessment of the Lake Ontario Lower Food Web

The Lake Ontario Ecosystem

Numerous physical, chemical, and biological stressors have caused profound changes in the Lake Ontario ecosystem and its fish community during the last three decades. In the offshore, cultural eutrophication has been reversed and water quality has improved, but the resulting oligotrophication has lowered the carrying capacity of offshore fisheries. In contrast, the coastal zone remains impaired from point and non-point runoff sources, invasive species, and habitat destruction. The native burrowing amphipod *Diporeia* spp. is at risk of extirpation, likely in response to disruptions to the food web by invasive quagga mussels. Non-native zooplankton, (*Cercopagis pengoi* and *Bythotrephes longimanus*) persist, disrupting zooplankton community dynamics. In the coming decades, Lake Ontario will continue to experience ecosystem stress from the growing demands of a burgeoning human population in the western watershed (e.g. a recent estimate predicts a 47% population increase in the Hamilton/Toronto region, also known as the "Golden Horseshoe", by 2031 [www.pir.gov.on.ca]) and from anthropogenic forces such as invasive species and contaminants. These forces may act synergistically to cause ecological surprises and will continue to plague efforts to restore the lake. Great Lakes scientists and managers must continue to work diligently to assess ecosystem status and to evaluate determinants of ecological change. The success of efforts to maintain recreational fisheries and to restore self-sustaining populations of native species depends on the condition of the lower food web. Long-term assessment of the lower food web is critical to measure the effectiveness of remedial actions, to better understand how stressors manifest themselves across habitats and impact fish communities, and to make recommendations for future actions.

Lake Ontario Lower Aquatic Food Web Assessment (LOLA)

Understanding stressor impacts on ecological processes in Lake Ontario over the last three decades has resulted from a commitment to long-term binational studies by environmental agencies and their dedicated scientists and support staffs in both Canada and the United States. LOLA was initiated at the request of the United States and Canada Lake Ontario Lakewide Management Plan (LaMP) and the Great Lakes Fishery Commission's Lake Ontario Committee with the following two goals: 1) assess the status of and 2) develop recommendations for the long-term comprehensive assessment of the Lake Ontario lower aquatic food web. The 2003 LOLA project incorporated seasonal sampling at a large spatial scale, providing the most comprehensive assessment of the status of Lake Ontario's lower food web since the Lake Ontario Trophic Transfer Program in 1995. Partners from seven government agencies and six universities and colleges participated in the LOLA project. A workshop attended by LaMP representatives, government agencies, and academics was held at Cornell University on November 16-17, 2005. Discussions based on significant findings that were presented at the workshop resulted in seven recommendations for future assessment of the Lake Ontario lower aquatic food web.

Significant Findings

Ecosystem breakdown, native amphipod Diporeia spp. at risk of extirpation. *Diporeia* spp. populations are no longer found in their preferred habitat (30 m to 60 m bottom depth) and are now relegated to bottom depths of >100 m. *Diporeia* spp. is a key organism in the historic Lake Ontario food web and an important high-energy food source for Lake Ontario fish.

Invasive quagga mussels causing food web disruptions. Few zebra mussels remain and quagga mussels now dominate the benthic community in Lake Ontario waters < 90 meters deep. Quagga mussels are expanding into waters >90 meters deep, now considered a fragile refuge for native *Diporeia* spp.

Low offshore phosphorus concentrations. Spring total phosphorus concentrations in offshore waters of Lake Ontario are below the target level of 10 µg/L. The long-term trend at station 41 shows spring TP levels at historic lows. At this site, TP concentrations have been in the 4 – 6 µg/L range for the past five years. This range is slightly lower than the offshore mean (~7 µg/L) obtained from the Canadian Surveillance Program during the same time period.

Impaired food supply for zooplankton. Low phytoplankton biomass has been exacerbated by an increase in the relative biomass of blue-green algae (a poor quality food source for zooplankton) combined with a decrease in biomass of cryptophytes (a preferred food source for zooplankton).

Invasive predatory cladocerans persist. A close watch has been kept on two invasive cladocerans, *Cercopagis pengoi* and *Bythotrephes longimanus*, which typically appear during stratified conditions in late summer. These large zooplankton are major predators of small species and therefore compete with other invertebrates (e.g. *Mysis*) and fish for zooplankton prey. These species accounted for up to 10% of the zooplankton biomass in 2003.

Workshop finding: Impaired water quality in coastal zone due to nutrient enrichment. Although coastal areas were not sampled as part of the LOLA study, it is important to note that, in contrast to offshore areas, environmental integrity and sustainable use of coastal habitats are threatened by anthropogenic forces including rapid population growth in the Greater Golden Horseshoe region (Lake Ontario's western basin). Coastal ecosystem impairments include algal blooms, aquatic weeds, shoreline erosion, invasive species, and habitat destruction. Dreissenids have altered nutrient cycling and increased water clarity resulting in a rebound of the benthic green alga *Cladophora.*

Recommendations to the Lake Ontario Committee (LoC) and Lakewide Management Plan (LaMP) members

- *Establish a Lake Ontario Binational Lower Food Web Task Force*. Improve reporting of lower food web findings to managers through binational participation and leadership.

- *Connect Lake Ontario habitats to the watershed*. Managers need to know how their remediation and restoration decisions in the watershed will impact resources and habitats in the lake.

- *Commit to annual, long-term monitoring of fixed sites combined with less frequent lake-wide condition assessments.* A combination of long-term monitoring and large spatial scale surveys is necessary to measure the efficacy of management decisions, to evaluate future direction, and to link science to policy.

- *Utilize remote sensing technologies* (satellite imagery, buoy systems).

- *Evaluate new survey technologies in lower food web assessment* (optical plankton counter, hydroacoustics, FlowCAM imaging, fluorometry).

- *Incorporate food web bio-markers into monitoring program*. (stable isotopes, fatty acid analysis)

- *Mesh field assessment with experimental studies*. Assessing cause and effect through experimentation is a powerful approach to uncover mechanisms observed in field studies.

The Lake Ontario Lower Aquatic Food Web

Status

*Ecosystem breakdown; native amphipod *Diporeia* at risk of extinction

*Invasive quagga mussels causing food web disruptions

*Total phosphorus concentrations below target levels

*Zooplankton food supply impaired and invasive zooplankton persist

*Impaired water quality in nutrient rich coastal zone

Assessment Needs

*Coordination of monitoring and reporting

*Strategy that links land and water habitats

*Sensitivity to public stakeholder concerns

*Annual assessment of all lower food web components

*An understanding of food web connections and disruptions

*Experimental studies

Next Generation of Assessment Tools

*Optical plankton counter

*Fluorometry

*FlowCAM imaging

*Hydroacoustics

*Satellite imagery

*Buoy monitoring systems

*Food web bio-markers

*Computerized binational data repository

LOLA Recommendations

*Establish a Lake Ontario Binational Lower Food Web Task Force
*Connect lake habitats to the watershed
*Commit to annual, long-term monitoring of fixed sites combined with less frequent lake-wide condition assessments
*Utilize remote sensing technologies (satellite imagery, buoy systems)
*Evaluate new survey technologies (optical plankton counter, hydroacoustics, fluorometry)
*Use food web bio-markers (stable isotopes, fatty acid analysis)
*Mesh field assessment with experimental studies

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I. Introduction.

Establishment of the first European settlement in the Lake Ontario basin in the late 1600s marked the beginning of an era of accelerated ecological change for Lake Ontario. Stressors such as overfishing, cultural eutrophication, land use changes, colonization by non-native species, and eventually, contaminant discharge led to degradation in water quality, loss and change of habitat, and the decline of native fish communities. By the 1970s, Lake Ontario's major native fish stocks had been pushed to near extinction (Christie 1972). Phosphorus is normally the critically limiting nutrient, and high phosphorus levels during the 1950-70s produced dense algal blooms, a general indicator of environmental degradation. The 1972 Great Lakes Water Quality Agreement (GLWQA) (International Joint Commission 1988) between the United States and Canada sought to reverse cultural eutrophication by establishing permissible phosphorus loadings to each of the Great Lakes, marking a new era of ecosystem management and rehabilitation. Phosphorus concentrations began to decline, and by the mid 1980s, the target level of 10 μg/L for Lake Ontario had been achieved (Millard et al. 2003). Habitat and water quality improved, and as expected, the carrying capacity at all levels of the food web declined in step. Lower food web studies in the 1980s and 1990s documented declines in algal abundance and epilimnetic zooplankton biomass and production (Johannsson et al. 1998; Johannsson 2003; Munawar and Munawar 2000, 2003). Data from the late 1990s and early 2000s show that phosphorus concentrations remain well below target levels, and food web structure has been changing with the invasion of exotic species (Lozano et al. 2001; Benoit et al. 2002; Laxson et al. 2003). Sustainable fishery management now requires an understanding of both the carrying capacity of Lake Ontario as well as changes in prey and predator species. An understanding of what influences lower food web productivity coupled with changes in predator and prey species is needed for informed fishery management. Decisions regarding how the Lake Ontario ecosystem will be managed in the future will become more difficult as managers attempt to balance uncertainty and risk with stakeholder desires and expectations.

Despite the success of restorative measures, the return of the Lake Ontario ecosystem to historical conditions has been impeded by unintentional introduction of non-indigenous species to the benthic and planktonic communities. In fact, because eradication of these species is improbable, a return to true historical conditions is highly unlikely. *Dreissena spp.* (zebra and quagga mussels) transformed the benthic habitat during the 1990s. Their efficient grazing of phytoplankton increased water clarity and increased vectoring of lower trophic level production to benthic habitats. Although mussel beds increase benthic biomass and provide shelter to benthic communities, they may also compete with important native species. The native amphipod *Diporeia* declined soon after dreissenid introduction, putting important benthivorous fish species such as native lake whitefish (*Coregonus clupeaformis*) at risk. Another exotic, the predatory cladoceran *Cercopagis pengoi*, had a similar effect on the plankton community in the late 1990s. Its presence has been associated with declines in smaller zooplankton species (*Diacyclops*, bosminids, nauplii) that are prey for young fish (Benoit et al. 2002; Laxson et al. 2003). Because this species is not eaten by the same young fish due to its long tail spine (Bushnoe et al. 2003), first-year growth and therefore over-winter survival of alewife may have declined. New invaders arrive on the scene frequently. The round goby (*Neogobius melanostomus*) is firmly established in Lake Ontario and is anticipated to cause changes in the

benthic community, as has been observed elsewhere (O'Gorman and Schaner, pers obs., Wickett and Corkum 1998, Kuhns and Berg 1999).

Developing a Cooperative Monitoring Approach. Recognizing that the scale of multi-trophic level monitoring needed to fully characterize the status of the lower food web and to assess the impacts of invasive species in Lake Ontario was beyond the resources available to any one organization, the U.S. – Canada Lake Ontario Lakewide Management Plan (LaMP) brought together government and university experts to develop a binational monitoring initiative. This effort, the Lake Ontario Lower Aquatic Food Web Assessment project or LOLA, included whole-lake sampling integrating sampling at a number of historical stations for time-trend comparisons. Project participants include U.S. Environmental Protection Agency in Region 2, Environment Canada, Department of Fisheries & Oceans Canada, National Oceanic & Atmospheric Administration, Cornell University, University of Toronto, SUNY College of Environmental Science & Forestry, SUNY Brockport, Ontario Ministry of Natural Resources, Ontario Ministry of the Environment, New York State Department of Environmental Conservation, U.S. Geological Survey, U.S. Fish & Wildlife Service, Clarkson University, and Western Michigan University.

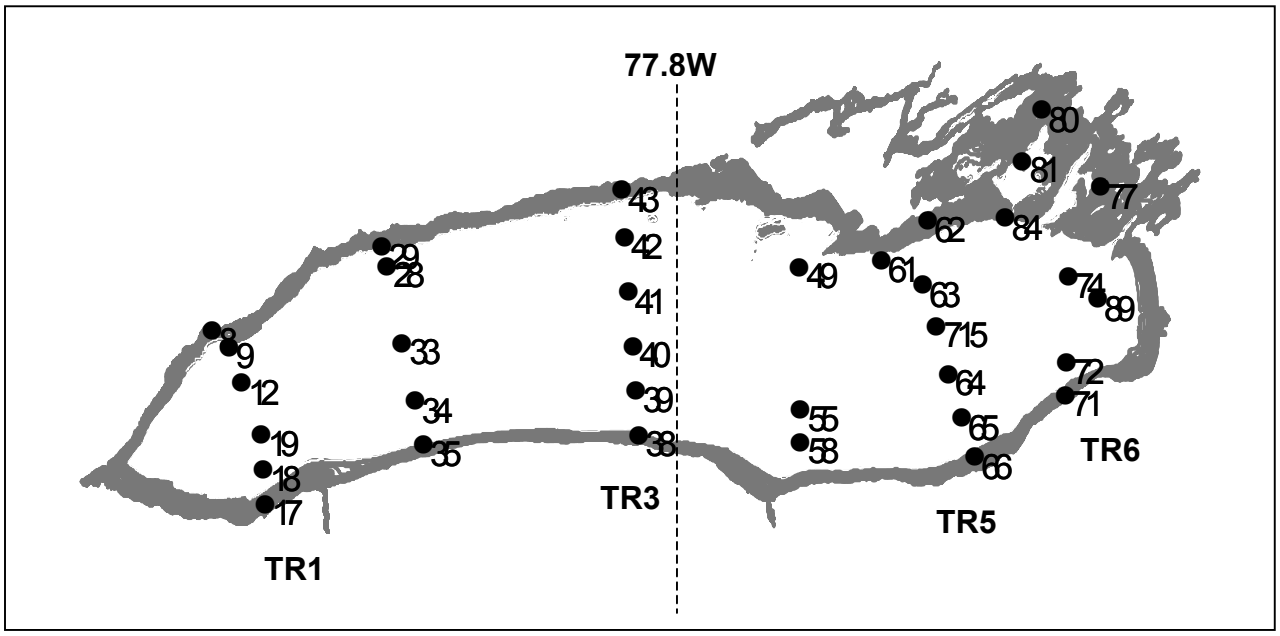
A cooperative agreement with U.S. EPA in Duluth and binational partners (Great Lakes Fishery Commission and the Lake Ontario LaMP group) is an ongoing part of the cooperative model. Four sampling cruises were conducted in Lake Ontario in 2003 using U.S. EPA's vessel *Lake Guardian* and the Canadian Coast Guard's vessel *Limnos*. The data collected in 2003 included: 1) lower food web components including benthos, phytoplankton, bacteria, microzooplankton, zooplankton and mysids; 2) water quality parameters including nutrients [total phosphorus (TP), soluble reactive phosphorus (SRP), and silica (SRS)], chlorophyll *a*, and secchi depth; 3) water column temperature profiles using an electronic bathythermograph (EBT); and 4) zooplankton density using an optical plankton counter for comparison to traditional vertical net hauls. The primary objectives of the study were to: 1) characterize the current status of the lower aquatic food web of Lake Ontario; 2) compare results with historical findings; and 3) conduct a workshop to discuss the findings, evaluate new technologies and sampling designs, and develop recommendations for future assessment.

II. The Status of Lake Ontario

A. The Status of Lake Ontario 2003

Field sampling methods. Three lake-wide cruises were performed to assess both temporal and spatial condition of the lower food web in 2003. Data (see Appendix A) were collected in spring (4/28 – 5/3), summer (8/10-11 and 8/19-21), and fall (9/21 – 9/25), 2003 along four north-south transects (Figure 1) that were selected to overlap with previous studies such as the Lake Ontario Trophic Transfer (LOTT) project of the early 1990s. Additional samples for mysids were collected from October 27-30, 2003. The 30-m bathymetric contour (gray area in Figure 1) was used to delineate nearshore and offshore habitats (nearshore, seasonal n=9; offshore, seasonal n=18). The lake was divided into eastern and western regions by the 77.8°W longitude line (eastern region n=13; western region n=14). See Figure 1 for sampling locations.

Figure 1. LOLA field collection sites in Lake Ontario during April, August, and September 2003 that were also sampled during the LOTT study. Transects 1, 3, 5, and 6 (used for phytoplankton and microbial loop comparisons) are indicated by TR1, TR3, TR5, and TR6. Dashed line represents the 77.8° W longitude line. Light gray shading represents depths of 30 m or less. Site coordinates can be found in Appendix A.



These cruises were planned to coincide with organism life cycles. Spring is the key period for nutrient sampling because the available amounts of nutrients control to a large degree the amount of biological activity that will occur over the year. August and September cruise time frames were selected to characterize the late summer peak in zooplankton production. Mysid production peaks much later, which is why the October cruise was added. The timing of sampling for benthos is less critical, so samples were collected in August and September.

Most parameters were measured on integrated water samples through the epilimnion. An electronic bathythermograph (EBT) or conductivity-temperature-depth (CTD) profile was used

to determine thermocline depth. During spring isothermal conditions, integrated water samples were collected from 20 m depth or two meters above the bottom (for shallow stations) to the surface. In summer and fall, integrated water samples were collected from one meter above the thermocline to the surface. Parameters measured from integrated water samples include total phosphorus (TP), soluble reactive phosphorus (SRP), soluble reactive silica (SRS), chlorophyll *a*, phytoplankton, and microbial food web components. Total phosphorus concentration was determined colorimetrically using the ammonium molybdate – stannous chloride method after preservation with 1 mL 30% H_2SO_4 and persulfate digestion. For SRP and SRS, water was filtered through a 0.45-micron membrane filter. SRP was analyzed in an autoanalyzer using the ammonium molybdate – stannous chloride method. SRS concentration was determined by the autoanalyzer heteropoly – blue method. Chlorophyll *a* was determined by acetone extraction after filtration through 0.45-micron membrane filters.

Thermocline depth was also used to plan sampling of zooplankton populations. Epilimnion samples (following depth protocol above) were collected using a 64-µm mesh, 50-cm diameter metered net. An entire water column sample was collected with a 153-µm mesh, 50-cm diameter metered net from 100 m depth to the surface or from 2 m above the bottom depth to the surface at shallower bottom depths. These samples were collected only if the bottom depth was >10 m below the depth of the 64-µm mesh sample. Zooplankton were only collected during daylight conditions.

Mysids were sampled with a 1-m square net fitted with 1-mm mesh netting and a 253-µm cod end. The net was lowered slowly to 1-2 m above the bottom to sit for 30 seconds, and then raised at a third of a meter a second. Mysids were sampled at night from all the LOTT stations >50 m bottom depth, plus 10 sites through the deep hole and 12 additional sites in the 50 – 100 m bottom depth zone.

Benthic invertebrates were collected with a Ponar (area=0.053 m^2) grab. Triplicate samples were taken at 34 sites. A hard substrate at two sites (29 and 66; Appendix A) permitted the retrieval of only one sample. Triplicates from all sites but six (individually counted for community assessment) were pooled. Mussels were removed prior to sieving to prevent damage to the concentrating net and placed in a sample jar. Pooled or separate triplicates were then placed in an elutriation device and washed through a nylon sieve with a 500-µm mesh.

Data analysis methods. The student's T-test was used to compare group means to identify spatial differences. Significantly different means were identified by a p-value <0.05. Spatial categories include east and west (separated by 77.8˚ W longitude line), referred to hereafter as comparisons between regions, and nearshore and offshore (separated by the 30 m bathymetric contour), referred to hereafter as comparisons between habitats. Analysis of variance (ANOVA) was used to compare means across seasons. Stations that were not sampled on all three cruises were removed from the analysis. Significant differences, identified by a p-value <0.05, were adjusted using the Tukey-Kramer HSD test (JMP IN 5.1.2; SAS Institute). Water quality parameters (TP, SRP, SRS, chl *a*) and zooplankton mean length (ZML) data were not transformed. Zooplankton density and biomass data were not normally distributed and were $\log_{10}$ transformed after adding one.

Results

Water Chemistry and Physical Variables. Monitoring of basic physical and chemical variables has provided critical information for the evaluation of the status of the Lake Ontario food web. Seasonal total phosphorus (TP), soluble reactive phosphorus (SRP), soluble reactive silica (SRS), chlorophyll *a* (unadjusted for phaeophytin), secchi depth, and temperature from 2003 are presented in Table 1.

Table 1. Limnological parameters averaged for all sites in Lake Ontario in spring, summer, and fall 2003. Ranges are in parentheses.

	TP (µg/L)	SRP (µg/L)	SRS (µg/L)	Chlorophyll *a* (µg/L)	Secchi Depth (m)	Epilimnetic Temperature (C)
Spring	7.3 (4.8 – 17.1)	0.9 (0.6 – 2.3)	730 (350 – 870)	1.2 (0.7 – 3.0)	10.3 (6.0 – 17.0)	2.9 (2.0 – 5.9)
Summer	9.6 (1.8 – 26.3)	0.4 (0.2 – 3.8)	260 (100 – 1020)	1.8 (0.8 – 6.8)	7.8 (4.0-11.0)	22.5 (17.7 – 24.6)
Fall	11.5 (7.2 – 28.0)	0.8 (0.2 – 4.9)	340 (130 – 610)	2.7 (1.6 – 4.1)	6.7 (5.0 – 9.0)	17.4 (8.7 – 19.7)

Phosphorus. Total phosphorus is an indicator of ecosystem productivity, and spring TP concentration is the primary determinant of summer algal growth. Therefore, a spring target concentration of 10 µg/L was set for offshore waters of Lake Ontario. Attainment of this target concentration is indicative that the phosphorus loading target (7000 metric tons) set by the Great Lakes Water Quality Agreement had been met. In 2003, the mean spring TP concentration in offshore waters was 6.8 µg/L. Mean lake-wide TP concentrations increased over the course of the sampling season, reaching 11.5 µg/L in the fall. Lake-wide fall TP was significantly higher than spring TP (ANOVA; $p<0.0001$). TP was significantly higher ($p<0.05$) in the western region in summer. There were no significant differences between nearshore and offshore habitats for any season (Table 2) and no significant differences between eastern and western regions for any season/habitat combination.

Table 2. Comparison of nearshore-offshore habitats for TP, SRP, SRS, and chlorophyll *a* in Lake Ontario in spring, summer, and fall 2003.

	Spring	Summer	Fall
TP	ns	ns	ns
SRP	ns	ns	*(nearshore)
SRS	*(offshore)	*(nearshore)	*(nearshore)
Chlorophyll *a*	ns	*(nearshore)	*(offshore)

*t-test (ns=not significant; *=significant at p<0.05); habitat with higher value in parentheses*

Soluble reactive phosphorus is the form of phosphorus that is readily available for use by phytoplankton. Mean seasonal concentrations did not exceed 1.0 µg/L in 2003. There were no significant seasonal lake-wide differences in SRP concentrations, nor were there significant east-west differences for any season. Lake-wide SRP concentrations were significantly higher in the nearshore in fall (Table 2). In September, the nearshore mean was 1.5 µg/L and the offshore mean was 0.5 µg/L. There were no significant differences between eastern and western regions for any season/habitat combination.

Silica. Dissolved silica is used by diatoms for cell wall synthesis, and the availability of dissolved silica can influence the productivity of this group of algae. Mean seasonal SRS concentrations were highest in spring (730 µg/L) and lowest in summer (260 µg/L). Lake-wide SRS levels were significantly higher in spring compared with summer and fall (ANOVA; $p<0.0001$). There were no significant east-west differences for any season. Silica concentrations were significantly higher in the offshore in spring and in the nearshore in summer and fall (Table 2). In September, nearshore habitats had greater concentrations in both the east and the west.

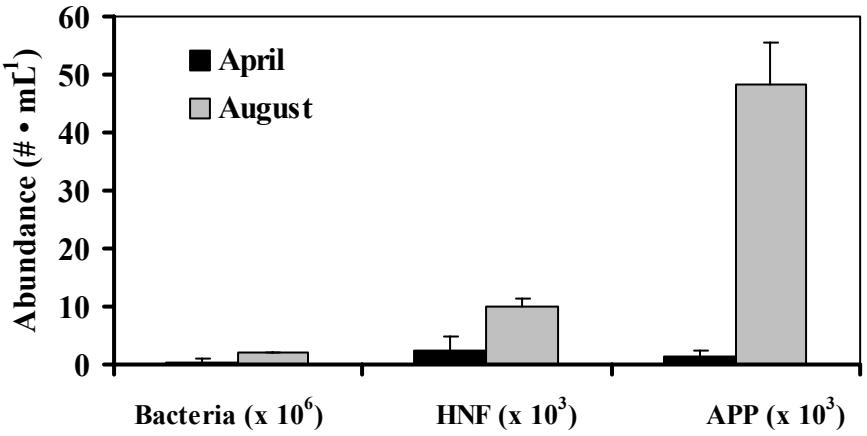
Chlorophyll a. Chlorophyll concentration is a general indicator of algal biomass. Chlorophyll *a* (unadjusted for phaeophytin) concentrations ranged from 0.7 – 6.8 µg/L in 2003. Lake-wide chlorophyll *a* was significantly higher in fall compared with summer, and higher in summer compared with spring (ANOVA; $p<0.0001$). There were no significant east-west differences for any season. Lake-wide chlorophyll concentrations were significantly higher in the nearshore in summer and in the offshore in fall (Table 2). There were no significant differences between eastern and western regions for any season/habitat combination.

Water clarity. One of the most dramatic changes in the Lake Ontario ecosystem over the past two decades has been improved water clarity resulting from both oligotrophication and grazing by *Dreissena* spp. (Mills et al. 2003). Lake Ontario waters exhibited excellent transparency in 2003. Mean secchi disc depth was highest in spring (10.3 m; Table 1) and declined through the summer reaching a mean of 6.7 m in the fall.

***Microbial Loop*.** As the Lake Ontario ecosystem has shifted to a more oligotrophic state, the microbial loop has become the focus of attention due to its increased importance as a pathway of energy transfer to zooplankton (Munawar and Munawar 1999). The microbial loop is composed of bacteria, heterotrophic nanoflagellates (HNF), and autotrophic picoplankton (APP). HNF and bacteria degrade organic material for use by unicellular autotrophs (Blackburn et al. 1997) and are consumed by ciliates.

Microbial loop assessments were performed in April and August 2003. Lake-wide abundances for bacteria, HNF, and APP were significantly higher in August compared with April (t-test; $p<0.05$) (Figure 2). In April, the abundance of bacteria, HNF, and APP was highest on transect 1 (TR1; figure 1). In August, bacteria and HNF were evenly distributed across the lake, but APP abundance was significantly higher in the east (t-test; $p<0.05$)(TR5 & TR6; figure1).

Figure 2. Abundance of microbial loop components in Lake Ontario during April and August, 2003. Error bars represent +1 standard error.



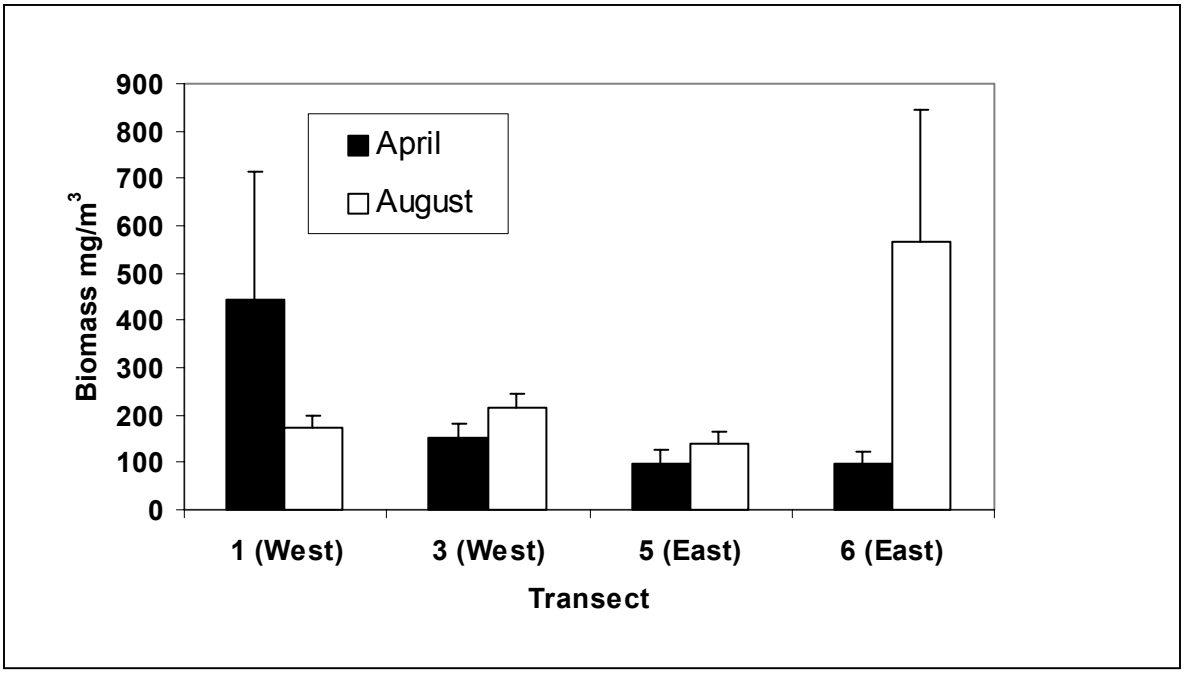
***Phytoplankton*.** Lake-wide phytoplankton surveys in Lake Ontario are scarce (Munawar and Munawar 2003) with the LOLA survey representing one of only four such surveys conducted over the past three decades. With increased N:P ratios, declining phosphorus concentrations, and increased grazing associated with *Dreissena* spp., changes in the phytoplankton community were expected, with respect to both biomass and species composition.

In 2003, of the seven major phytoplankton groups (Cyanophyta, Chlorophyta, Euglenophyta, Chrysophceae, Diatomeae, Cryptophyceae, and Dinophyceae), Chlorophyta accounted for 89% of the abundance in April, and Cyanophyta accounted for 70% of the abundance in August. Total phytoplankton abundance was significantly higher (t-test; $p=0.02$) in August than in April; the abundance of all the groups increased except for the Chlorophyta and Euglenophyta.

Total phytoplankton biomass averaged 213 mg/m^3 in April and 282 mg/m^3 in August. Diatoms and chlorophytes dominated in April accounting for 55% and 19% of the total biomass, respectively. In August, cyanophytes were dominant (42% of total biomass) followed by cryptophytes (17%). Phytoplankton biomass was not significantly higher in August despite significantly higher abundance. No significant differences were found in total phytoplankton abundance or biomass between habitats (nearshore/offshore) or regions (east/west) for either season.

Phytoplankton biomass exhibited high spatial variability (Figure 3). In April, transect 1 (TR1; figure 1) had 3-4 times more biomass than central or eastern areas, but the difference was not significant (ANOVA; $p>0.05$). In August, the reverse was true; the farthest eastern transect (TR6) had 3-4 times more biomass than central or western areas, but again the difference was not significant (ANOVA; $p>0.05$). In April, the high biomass in the west was associated with a dominance by diatoms. The large biomass in the east in August was due primarily to domination by Cyanophyta.

Figure 3. Mean phytoplankton biomass for the four lake-wide transects in Lake Ontario during April and August, 2003. Error bars represent +1 standard error.



Zooplankton. Zooplankton have an intermediate position in the food web and therefore are an important link of primary producers (phytoplankton) and fish. The effects of phosphorus reductions are expected to extend into the food web, leading to lower phytoplankton biomass and therefore lower zooplankton biomass. Zooplankton are the primary food source for important fish species such as alewife. Therefore, the sustainable management of fisheries in Lake Ontario requires an accurate knowledge of zooplankton standing stock. Invasive species also threaten to disrupt the zooplankton community's role in the food web.

The LOLA survey sampled zooplankton using two strategies. Epilimnetic samples were collected using a 64-µm mesh net, and entire water column samples were collected using a 153-µm mesh net. These meshes were selected because of their comparability with historical sampling programs including the Canadian Bioindex (64-µm) and the Cornell Biomonitoring (153-µm) programs. This section focuses on results from offshore (>30 m depth) sites.

Density (#/m^3) and biomass (mg/m^3) are key measures of zooplankton standing stock. The data were not normally distributed and were therefore $\log_{10}$ transformed after adding one prior to calculating lake-wide averages. Density and biomass increased from low levels in spring to much higher levels in summer and fall for both epilimnetic and whole-water column samples (Tables 3 and 4). For example, epilimnetic density (and biomass) increased from 1,600/m^3 (4.2 mg/m^3) in spring to 17,000/m^3 (24.7 mg/m^3) in summer to 40,700/m^3 (66.6 mg/m^3) in fall.

Table 3. Average offshore epilimnion (64-µm mesh net) zooplankton density, biomass, and length in Lake Ontario in spring, summer, and fall 2003. Offshore sites defined by bottom depth > 30 m. Biomass and density data were log_{10} transformed after adding one. Average reported has been backtransformed. Zooplankton mean length is weighted for density of each taxon (veligers not included).

	Biomass (mg/m^3)	Density ($\#/m^3$)	Length (μm)	*Cercopagis* Density ($\#/m^3$)
Spring (n=18)	4.2	1.6×10^3	681	0.0
Summer (n=18)	24.7	17.0×10^3	537	19.3
Fall (n=17)	66.6	40.7×10^3	501	169.1

Table 4. Average offshore entire water column (153-µm mesh net) zooplankton density, biomass, and length in Lake Ontario in spring, summer, and fall 2003. Entire water column nets were towed from 100 m (or 1 m above the bottom for shallower samples) to the surface. Offshore sites defined by a bottom depth > 30m. Biomass and density data were log_{10} transformed after adding one. Average reported has been backtransformed. Zooplankton mean length is weighted for density of each taxon (veligers not included).

	Biomass (mg/m^3)	Density ($\#/m^3$)	Length (μm)
Spring (n=19)	4.4	1.3×10^3	754
Summer (n=17)	32.1	11.5×10^3	596
Fall (n=17)	46.9	18.6×10^3	636

Species composition can reveal interactions within the community as well as the overall role of zooplankton in the lake food web. We assessed change of community composition by dividing epilimnetic zooplankton biomass into six groups: daphnids, bosminids, calanoid copepods, cyclopoid copepods, other cladocera, and invasive predatory cladocerans (Table 5). Cyclopoid copepods were dominant (84% of the total offshore, epilimnetic biomass) in spring 2003. Daphnids (49%) and bosminids (19%) were dominant in the stratified summer period. Both cladoceran and copepod biomass peaked in September, with cladocerans maintaining dominance (70%).

Table 5. Mean relative offshore, epilimnetic zooplankton biomass (percent) and standard deviation (parentheses) from vertical, 64-um mesh net hauls in April, August, and September 2003.

	April	August	September
Daphnids	0.0	49.0 (28.8)	34.8 (13.9)
Bosminids	0.0	19.2 (15.4)	35.9 (19.5)
Calanoids	15.8 (8.8)	1.4 (1.1)	2.4 (1.7)
Cyclopoids	83.8 (9.1)	5.8 (12.4)	19.8 (20.2)
Other Cladocerans	0.0	14.4 (13.2)	3.4 (3.0)
Invasive Predatory Cladocerans	0.0	10.1 (20.7)	3.6 (2.9)

A close watch has been kept on two invasive cladocerans, *Cercopagis pengoi* and *Bythotrephes longimanus*, which typically appear in stratified conditions of late summer. These large zooplankton are major predators of small species and therefore compete with other invertebrates (e.g. *Mysis*) and fish for zooplankton prey. As expected, neither species was observed in April. Epilimnetic offshore density (and biomass) of *Cercopagis* averaged $19/m^3$ ($0.4\ mg/m^3$) in August and $169/m^3$ ($1.9\ mg/m^3$) in September (Table 3) and showed strong regional patterns.

Cercopagis was most abundant in western, offshore Lake Ontario during summer (average density 177/m^3) and most abundant in eastern Lake Ontario in fall (233/m^3). The species made up a large proportion of the total zooplankton biomass (30%) in western Lake Ontario in summer. *Bythotrephes* was only observed in September in the Kingston Basin, with a lake-wide average in fall of 0.6/m^3

Zooplankton mean length (ZML) is an indicator of the relative biomass of piscivores in Lake Ontario. A healthy population of large fish can keep planktivorous fish such as alewife from impacting zooplankton populations. A ZML greater than 800 μm has been suggested to indicate a balanced fish community. The indicator was initially developed using data from 153-μm mesh nets. We present data from both net series because of the different depth intervals sampled. Zooplankton communities in the epilimnion and hypolimnion are very different. Site depth could bias the ZML index in entire water column samples shallower than 100 m because of the changing proportion of the two communities. Also, planktivorous fish such as alewife generally feed in the epilimnion. These averages are calculated from species average lengths after weighting for species density. No transformation of the data was necessary. Our 64-μm epilimnion data may be converted to 153- μm equivalents using regressions developed in Johannsson et al. (1999).

Epilimnetic ZML significantly decreased from 681 μm in spring to 537 μm in summer and 501 μm in fall (Table 3). This size decrease is consistent with the composition shift from copepods (particularly cyclopoids) in spring to generally smaller cladocerans in summer and fall (Table 5). Zooplankton biomass and density increased during the same period. The ZML was also significantly smaller in the west (641 μm) than in the east (713 μm) in the spring (Table 6). Entire water column data had a similar east/west size trend in fall samples.

Table 6. East/west comparison of means for offshore epilimnion (64-μm mesh net) zooplankton biomass, density, and length in Lake Ontario in spring, summer, and fall 2003.

Zooplankton	April	August	September
biomass	ns	ns	ns
density	ns	ns	ns
length	*(east)	ns	ns

*t-test (ns=not significant; *=significant at p<0.05); region with higher value in parentheses*

***Benthic Community*.** A portion of surface production settles to the lake bottom in the form of organic particles, which are then consumed by benthic organisms. Many of these benthic organisms are lipid-rich and the preferred food for fish such as whitefish, sculpins, and lake trout. Therefore, the benthic community represents a critical link between surface production and fish.

Historically, the benthic community of Lake Ontario was dominated by an amphipod (*Diporeia* spp.) which together with fingernail clams (Sphaeriidae), oligochaetes, and chironomids, were the main components of the cold-stenotherm macrobenthic community occupying most of the deeper waters of all the Great Lakes (Cook and Johnson 1974). During the 1990s, the introduction and spread of dreissenid mussels transformed benthic habitats throughout the Great Lakes. Dreissenids include *Dreissena polymorpha* (zebra mussel) and *Dreissena bugensis* (quagga mussel), which are very efficient grazers of phytoplankton and may completely cover the bottom substrate (Mills et al. 1999). Lake-wide surveys during the 1990s documented the spread of dreissenids as well as a decline of native species such as the amphipod *Diporeia* spp (Lozano et al. 2001; Dermott and Geminiuc 2003). The LOLA 2003 survey is the latest lake-wide assessment of Lake Ontario's benthic community.

<u>*Dreissena spp.*</u> Quagga mussels have largely replaced zebra mussels in all benthic habitats of Lake Ontario. The dominance of quagga mussels may be due to several factors including a lower thermal tolerance, ability to colonize soft substrate, and lower nutrient requirement. Zebra mussels were found in only four of 36 samples in 2003, and the species' greatest density ($397/m^2$) was at a shallow site (10 m bottom depth) near the Niagara River input. Meanwhile, *D. bugensis* was abundant (average $8{,}000/ m^2$) in all 24 samples shallower than 100 m bottom depth. This dreissenid has expanded into the deep basin and was even observed at the deepest site (219 m bottom depth). *Dreissena bugensis* density averaged $1100/ m^2$ at sites >100 m bottom depth, occurring in half of the 12 deep sites.

<u>*Diporeia spp.*</u> The native amphipod *Diporeia* historically represented 60%-80% of the benthic community. It is a burrower that depends on organic matter that settles to the bottom from surface production, particularly from diatom blooms. *Diporeia* is an important food source for native benthivorous fish and is therefore considered an important environmental indicator of the benthic community. The 2003 survey indicates that *Diporeia* has disappeared from most of the 30-90 m depth interval, with a population averaging only $63/m^2$. *Diporeia* were only abundant within the deep central basins (>90 m bottom depth), at densities averaging $545/m^2$.

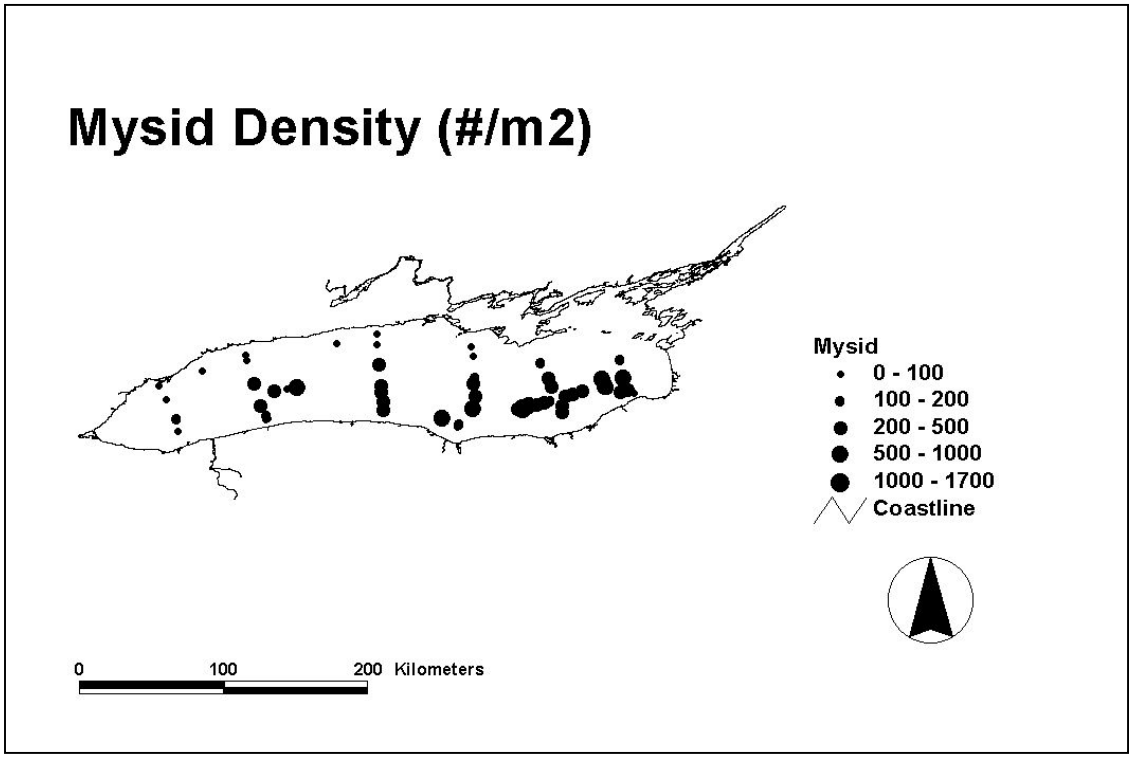
Mysis relicta. The opossum shrimp, *Mysis relicta,* is a large (3-25 mm total body length) native macroinvertebrate that competes with planktivorous fish for zooplankton prey, while being an important prey item for a range of fish species. Its nightly migration from the sediment surface to the thermocline makes it an important link between the benthic and pelagic ecosystems. There has been concern whether oligotrophication or invasive species could impact populations of this important species.

The Department of Fisheries and Oceans (DFO), Canada, runs a monitoring program for mysids in the late autumn when the population is most accurately sampled. We collaborated with the DFO, and the data presented below comes from their November 2003 whole-lake survey which is also modeled on the LOTT station transects from 1990. In autumn 2003, the *Mysis relicta* population was most abundant within the "deep hole" in southeastern Lake Ontario averaging >500/m^2 (Figure 4). Abundances were high (>100/m^2) at sites greater than 100 m water depth and increased with bottom depth over the 100 to 230 m depth range (Table 7).

Table 7. Mean density and standard error (parentheses) of *Mysis relicta* at four bottom depth intervals in Lake Ontario, fall 2003.

Depth Interval	Average Abundance (#/m^2)	Number of Samples
50-100 m	86.5 (30.4)	21
100-150 m	284.3 (53.1)	10
150-200 m	373.5 (54.2)	13
200-230 m	561.0 (129.5)	10

Figure 4. Mysid densities throughout Lake Ontario: November 2003.



B. Historical Trends

The evaluation of long-term change in lower food web components required comparison of the 2003 LOLA data with historical data collected by both Canadian and U.S. sampling programs. We used several Canadian data sets to establish historical trends in water quality, microbial food web, zooplankton, and benthos. The Canadian Lake Ontario Trophic Transfer (LOTT) program (1990 and 1996), the most recent lake-wide study of Lake Ontario's lower trophic levels, was used as a model for the sampling design used in LOLA. This program evolved from the Bioindex Program, a biweekly sampling program from 1981-1995 at an offshore (41) and nearshore (81) station. Environment Canada's Surveillance program included 98 permanent stations throughout the lake from 1969 to 2003. All three sampling programs were instrumental in tracking the long-term decrease of phosphorus and the early impacts of dreissenid mussels on the Lake Ontario ecosystem. Results from the Bioindex Program were published in a technical report (Johannsson et al. 1998). Data from all three programs was published in the State of Lake Ontario volume in 2003 including assessments of water quality (Millard et al. 2003), phytoplankton (Munawar and Munawar 2003), the microbial web (Munawar et al. 2003), zooplankton (Johannsson 2003), mysids (Johannsson et al. 2003), and benthos (Dermott and Geminiuc 2003).

We were also able to gather the monitoring data from the U.S. Environmental Protection Agency (EPA) for water quality and benthic community comparisons. The Great Lakes National Program Office (GLNPO) of the EPA has conducted biological monitoring (water quality, phytoplankton, and zooplankton) of the Great Lakes since 1983. Sampling was expanded to Lake Ontario in 1986 and includes two annual cruises (generally April and August) at up to eight offshore stations. Results of this program for 1998 were presented by Barbiero and Tuchman (2001) and Barbiero et al. (2001) and for 1986 – 1992 by Makarewicz et al. (1995). Annual benthic invertebrate sampling was added in 1997 and was presented by Barbiero at IAGLR 2005. EPA also conducted lake-wide benthic surveys in 1994 and 1997 (Lozano et al. 2001), and 1998-1999, which are all used in our comparison.

Our comparison includes only benthic community analysis (Nalepa and Thomas 1976) from the major binational lake-wide sampling of 1972 for The International Field Year of Great Lakes (IFYGL). Results of several lower food web studies in this program have been published by IAGLR in the 1974 Proceedings of the Seventeenth Conference on Great Lakes Research.

Methods

Field sampling and laboratory

Nutrients (total phosphorus, nitrate + nitrite, and silica). Surveillance nutrient data were collected in spring from surface waters (1 m sampling depth) of open lake stations (sounding depth $\geq$100 m). Bioindex nutrient concentrations were obtained from integrated samples (0 to 20 m) collected biweekly from stations 41 and 81 (spring 1981 – 1995). Spring averages for each year were calculated using values from April 1 to the onset of stratification. LOTT nutrient data (spring 1990 only) were collected from 39 stations; samples were integrated from a depth of 0 to 20 m or 0 to bottom minus 1 m. EPA nutrient data (1986 – 2002) from stations 41 and 81 were

collected in spring and were integrated from a depth of 0 to 20 m. For nutrient comparisons we directly compare the spring cruise of LOLA (April 28-May 2, 2003) to the spring cruises of LOTT in May 22-29, 1990 and April 29-May 8, 1996. Bioindex data from station 41 and 81 are used for the pre-stratified period, defined as April 1 until the water column stratified.

Nutrient analyses for Surveillance, Bioindex, and LOTT were performed by the National Laboratory for Environmental Testing, Environment Canada, Burlington, Ontario (Environment Canada 1997). Soluble nutrients were analyzed onboard ship during Surveillance cruises. Bioindex and LOTT samples were filtered onboard and returned to the lab for analysis. Total phosphorus was analyzed by acid persulfate digestion followed by automated colorimetric molybdate stannous chloride method (Philbert and Traversy 1973). For nitrate and nitrite, the sample was filtered through a 0.45-micron membrane filter and then analyzed by the autoanalyzer cadmium reduction method (Philbert and Traversy 1973). For silica, water was filtered through a 0.45-micron membrane filter and then analyzed by the autoanalyzer heteropoly-blue method (Philbert and Traversy 1973). EPA nutrient data are composites of water samples taken at discrete depths with Nisken bottles (spring: surface, 5 m, 10 m, and 20 m) mounted on a SeaBird Carousel. Sample processing techniques are described in detail by Barbiero and Tuchman (2001).

Phytoplankton and microbial food web. Phytoplankton samples were collected in 1970 (13 cruises), 1978 (8 surveys), 1990 (3 cruises; May, July, and October), and 1981 – 1995 (biweekly; Bioindex Program). Detailed descriptions of sampling methods are published in Munawar and Munawar (1986, 1996, 2003) and in Munawar et al. (1987). All samples were processed using the standard inverted microscope Utermöl technique (Vollenweider et al. 1974; Munawar and Munawar 1996).

Zooplankton and mysids. Zooplankton samples were collected weekly at stations 41 and 81 during the Bioindex Program from 1981-1995. A 64-μm mesh, 50-cm diameter, metered net was towed from 20 m depth (or 1 m above thermocline) to the surface. We compared LOLA densities from May, August and September to Bioindex densities (April 15 – May 15; Aug 1 – Aug 31; Sep 1 – Sep 30). Mysids were collected at station 41 from 1984-1995 with a $1m^2$ net fitted with a 1-mm mesh and 250-μm cod-end. We compare the abundance of mysids at station 41 in October, 2003 to October sampling of station 41 from 1984-1995.

Benthos. The methods used in the several lake-wide benthic sampling programs compared with LOLA are summarized in the Table 8.

Table 8. Historic benthos surveys on Lake Ontario, 1964 - 1999.

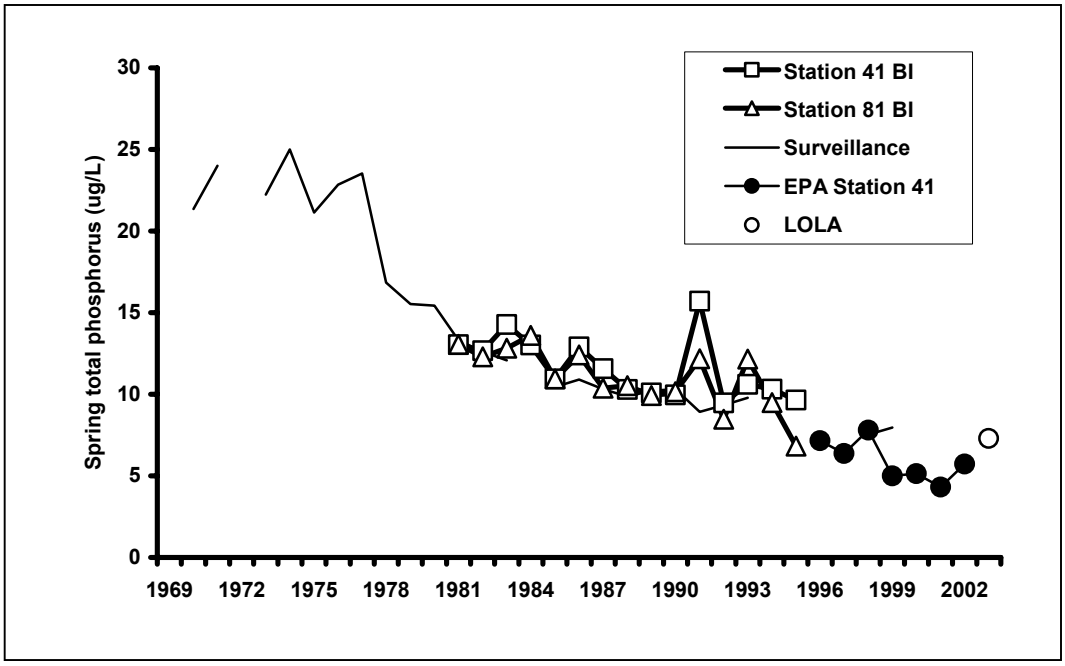
Year	Program	Grab	Mesh	Month	Sites	Grabs	Citation
1999	EPA	Ponar	500-µm	Fall	67	3c	in press
1998	EPA	Ponar	500-µm	Fall	114	3c	in press
1997	EPA	Ponar	500-µm	September	68	3c	Lozano et al 2001
1995	LOTT	Ponar	600-µm[a]	October	41	1	Dermott and Geminiuc 2003
1994	EPA	Ponar	500-µm	August	51	3c	Lozano et al 2001
1990	LOTT	Ponar	600-µm[a]	October	25	1	Dermott and Geminiuc 2003
1977	CCIW	Shipek	153-µm	September	153	1	Golini 1979
1972	IFYGL	Ponar	600-µm	November	55	3i	Nalepa and Thomas 1976
1964	GLFC	Sm/Mc[b]	595-µm	September	24	1	Hiltunen 1969

[a]elutriation device had a 153-µm mesh, but later sieved at 600-µm mesh to separate macrobenthos
[b]Sm/Mc is Smith Mcintyre grab; c=combined; i=individually processed

Results

Total phosphorus, nitrogen, and silica. Open-lake, long-term, spring total phosphorus has been steadily decreasing in Lake Ontario since 1977. Station 41, a mid-lake site with a depth of 128 m, was selected to evaluate the phosphorus trend because long-term data from several programs were available for that site. Figure 5 was created using data from Environment Canada's Surveillance program (1969 – 2003), the Canadian Bioindex Program (1981 – 1995), EPA's Great Lakes Environmental Database (GLENDA) (1996 – 2002), and the LOLA project (2003). Surveillance data are surface (1 m) samples from sites with depths >100 m. Bioindex data are mean values from April 1 until the onset of stratification. EPA data and LOLA data are from single samples collected in April of

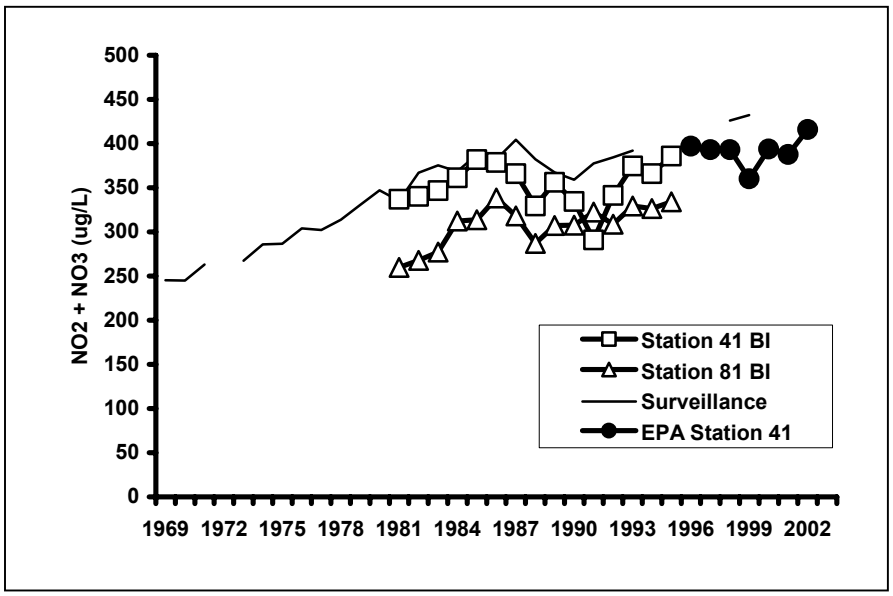
Figure 5. Spring total phosphorus trend in Lake Ontario, 1969-2003.



each year. For EPA data, values are from integrated water column samples from a depth of 0 – 20 m with the exception of 2000 (2 m depth; integrated sample not available). TP concentrations as measured by the Canadian Bioindex Program approached the target level of 10 µg/L in 1985 (Millard et al. 2003) and, with the exception of 1991, remained close to the target until 1995. Since that time, spring TP levels have continued to decline, reaching a low of 4.32 µg/L (USEPA; station 41) in 2001. A lake-wide comparison of spring TP in 1990 (LOTT; Millard et al. 2003) and 2003 (LOLA) shows a similar pattern, supporting the argument that trends in TP at Station 41 reflect whole-lake conditions.

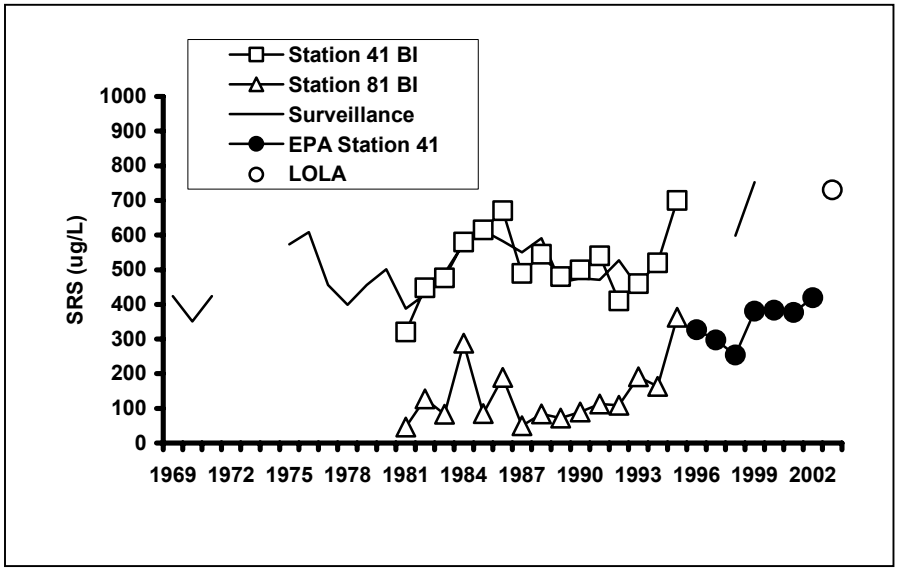
In contrast to phosphorus, spring nitrite plus nitrate concentrations at stations 41 and 81 have been gradually increasing (Figure 6). With the increase in nitrate plus nitrite, and the decrease in TP, the N:P ratios in the system must be increasing. We do not have the total Kjeldahl nitrogen concentrations from recent years to calculate the exact values, but the direction of change is unquestionable.

Figure 6. Mean spring nitrate plus nitrite trend in Lake Ontario, 1969-2003.



Phosphorus enrichment stimulates silica uptake by diatoms. Schelske et al. (1986) contended that TP concentrations in the Great Lakes in the 8.0 – 25.0 µg/L range were required to deplete silica. Open-lake spring TP concentrations have been below 8.0 µg/L since 1996 and have dipped as low as 4.32 µg/L (2001). At the same time, spring open-lake silica concentrations have been gradually increasing (Figure 7).

Figure 7. Mean spring silica trend in Lake Ontario, 1969-2003.



Phytoplankton and microbial food web. Lake-wide spring and summer phytoplankton biomass was low in 2003 compared to previous years (Figure 8). The low biomass in summer 2003 was accompanied by an increase in the relative biomass of Cyanophyta (Figure 9), a poor quality food source for zooplankton. Summer biomass of Cryptophyta, a high quality algal food resource for zooplankton, declined to 0.05 g/m^3, a level less than one-third of that reported in 1995 (Johannsson et al. 1998).

Figure 8. Mean phytoplankton biomass in Lake Ontario, 1970, 1978, 1990, and 2003.

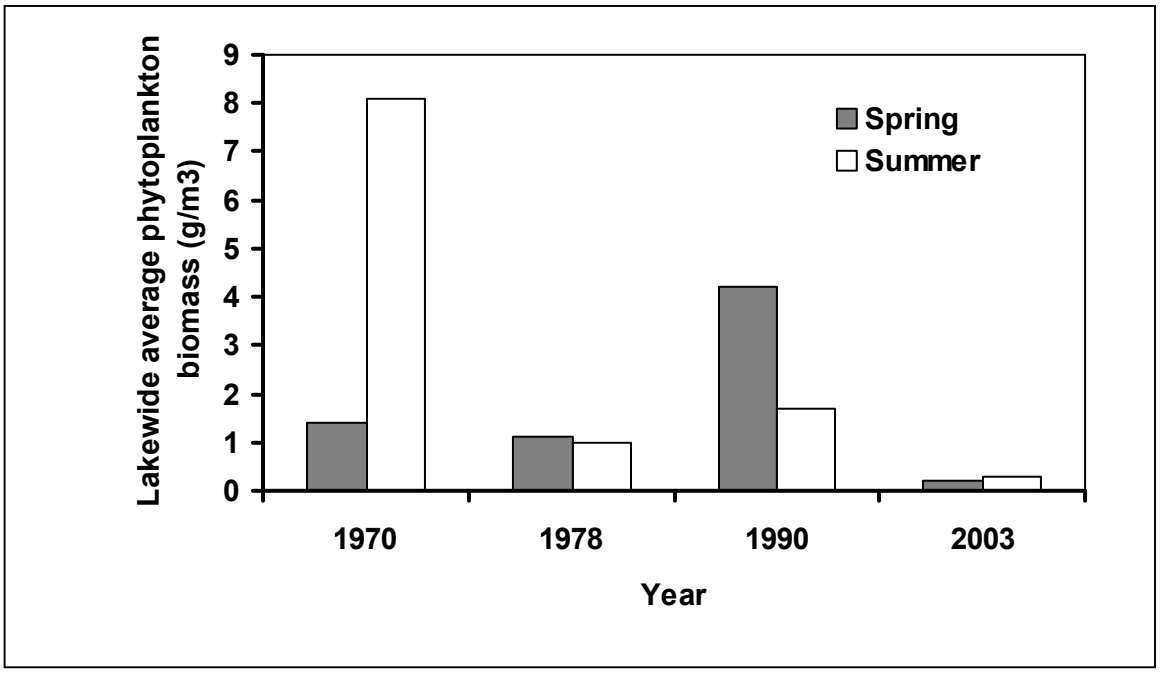
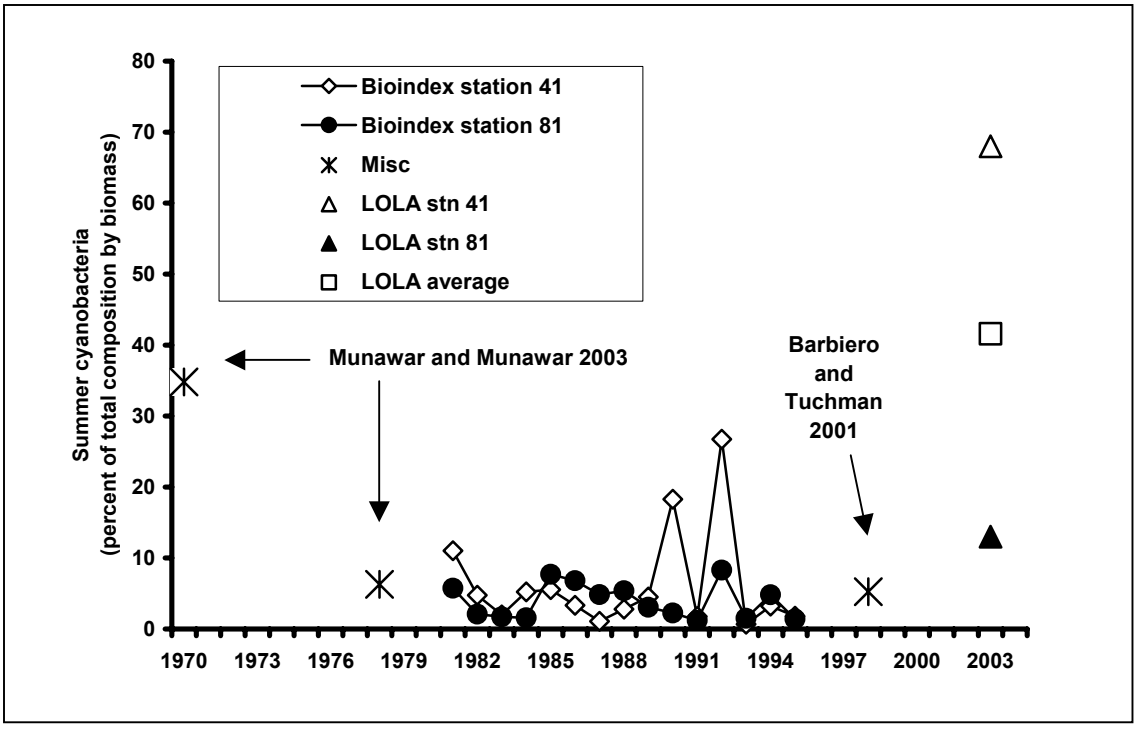


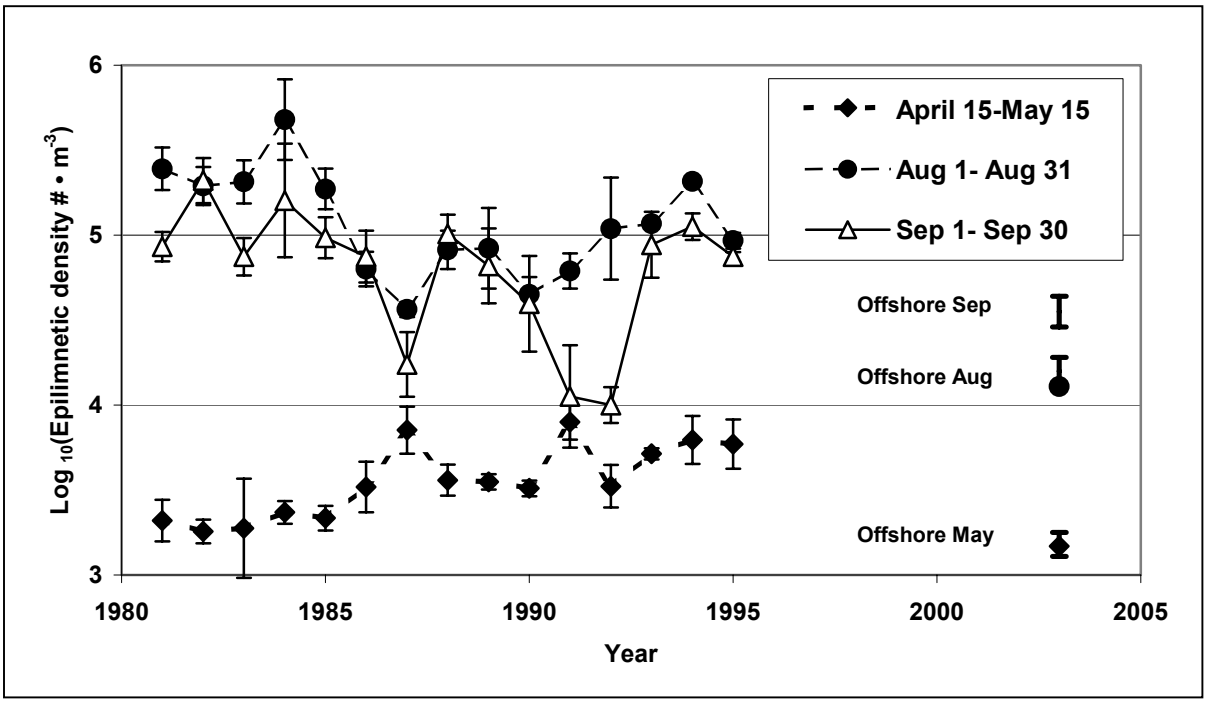
Figure 9. Relative summer biomass of Cyanophyta in Lake Ontario, 1970 – 2003.



In the early 1990s, spring abundances of microbial food web components (APP, HNF, and bacteria) were $9x10^3$, $0.2x10^3$, and $2.3x10^6$ cells/mL, respectively. Sampling in spring 2003 showed a decline in APP to $1.3x10^3$ cells/mL, an increase in HNF to $2.4x10^3$ cells/mL, and a decrease in bacteria to $4.4x10^5$ cells/mL. A comparison of the summer of 1990 to summer of 2003 showed a different pattern. APP abundance was nearly the same ($45x10^3$ cells/L in 1990 and $48x10^3$ cells/L in 2003), HNF had increased from $0.9x10^3$ to $9.8x10^3$, and bacteria had increased from $1.0x10^6$ to $2.0x10^6$ cells/L.

Zooplankton. Epilimnetic zooplankton density and biomass were high in the early 1980s and declined to a relatively stable level by the late 1980s which continued until 1995 (Johannsson 2003). Summer and fall densities are typically an order of magnitude higher than spring densities. In 1987 and 1991, spring densities approached those of fall (Figure 10). In summer of 2003, zooplankton density was as low as 17,000/m^3 and biomass had decreased to 25 mg/m^3. Spring and summer zooplankton densities in 2003 were the lowest recorded for the 1981 to 2003 time period.

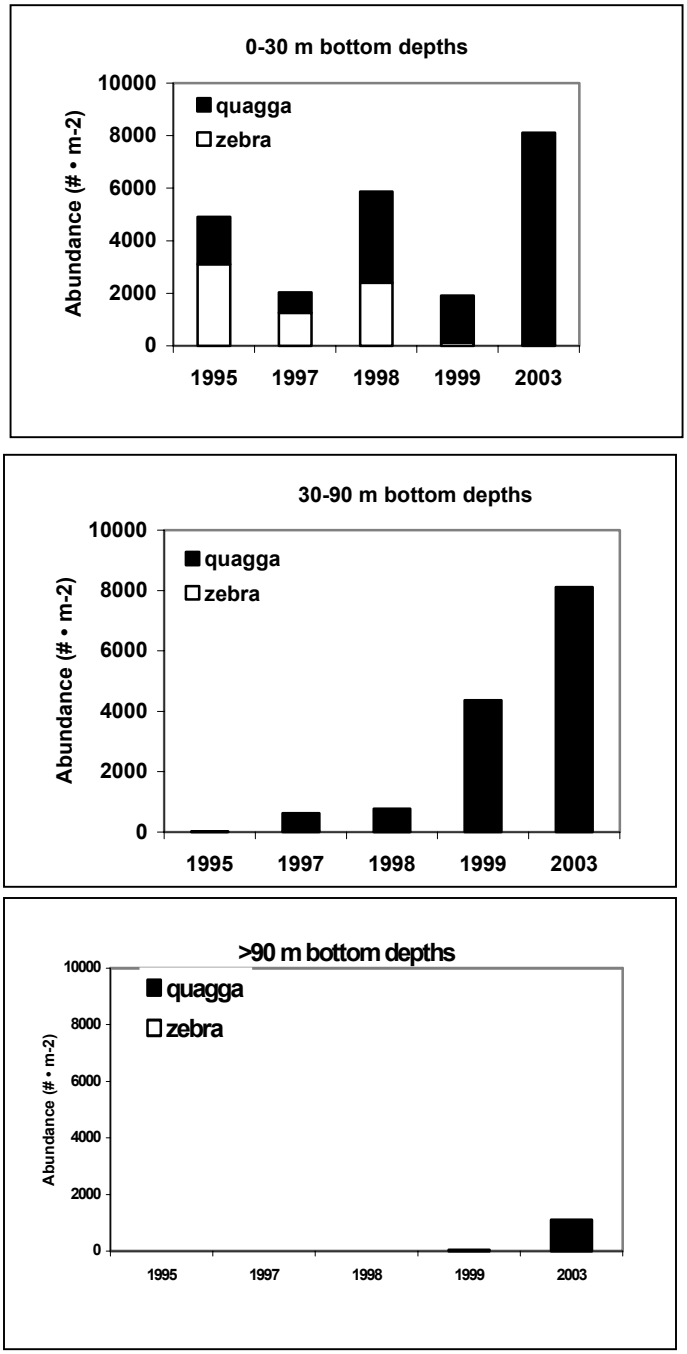
Figure 10. Epilimnetic zooplankton density in Lake Ontario at Station 41, 1981 – 1995 and 2003 and one standard error about mean values from all offshore stations during the LOLA study, 2003. Station 41 was not sampled in September, 2003. Error bars are +/- 1 S.E.



***Dreissena* spp. *and Diporeia* spp.** Quagga mussels (*Dreissena bugensis*) now cover more substrate and have attained higher densities than zebra mussels (*Dreissena polymorpha*) ever did in Lake Ontario, even during the early 1990s when concern for the negative effects of zebra mussels were great. A major expansion in the distribution of *D. bugensis* occurred between 1990 and 1997 (Lozano et al. 2001; Dermott and Geminiuc 2003), and continued through 2003. *Dreissena bugensis* attained very high densities (1,000 – 30,000/m^2) around the entire lake's nearshore by 2003 and has also extended into deeper water (Figure 11). *Dreissena bugensis* was

observed at the deepest site (219 m bottom depth) and was abundant as deep as 174 m bottom depth. In contrast, *D. polymorpha* has decreased in abundance since 1995, particularly on the south shore and the Kingston Basin where large populations were well established.

Figure 11. Dreissenid density in 1995 (October), 1997 (September), and 2003 (August).

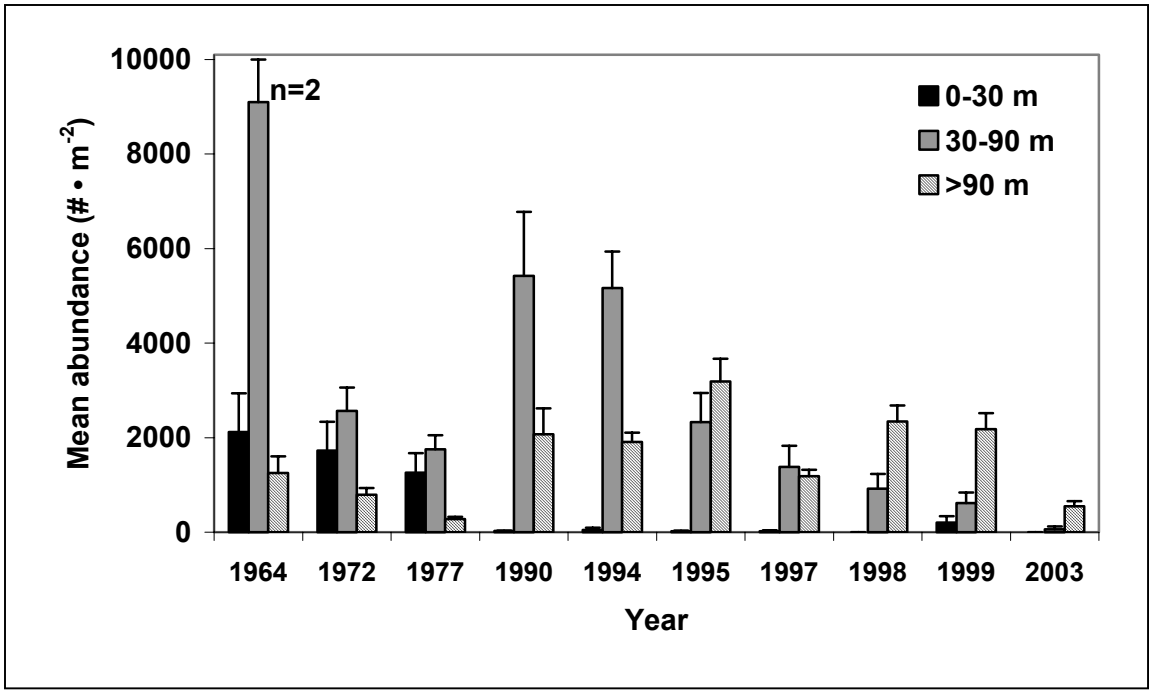


The expansion of *D. bugensis* has accompanied a progressive decline of the native amphipod *Diporeia* spp. During the time period 1964 to 1994, *Diporeia* was most abundant in depths from 30-90 m, averaging densities 2,000 – 5,000 m^2 (Figure 12). A sharp decline in density for this depth interval was reported from 1990 and 1995 (Dermott and Geminiuc 2003) and from 1994 to 1997 (Lozano et al. 2001). By 1997 *Diporeia* density had declined from > 5000/m^2 to 1380/m^2. This density decrease has continued, and by 2003, *Diporeia* was absent from most of the 30-90 m depth interval, with a population averaging only 63/m^2. The deep central basins represent a fragile refuge for *Diporeia*. Even this population is at risk, decreasing from 2000/m^2 in the 1990s to an average of 545/m^2 in 2003. *Diporeia* density exceeded 1000/m^2 at only one deep site. The low density observed in 2003 is significantly lower than high densities observed from 1990-1995, but not significantly different from densities reported in depths >90 m between 1964 and 1977 (Hiltunen 1969; Nalepa and Thomas 1976; Golini 1979).

The decline of *Diporeia* spp. populations has been considered to be a response to direct competition with *D. bugensis* for phytoplankton food resources. However, *Diporeia* populations appear to be declining in deeper habitats in advance of the expansion of *D. bugensis*. For example, the onset in the decline of *Diporeia* in the 30-90 m depth interval observed in 1995 and 1997 occurred prior to the expansion of *D. bugensis* populations into that depth interval.

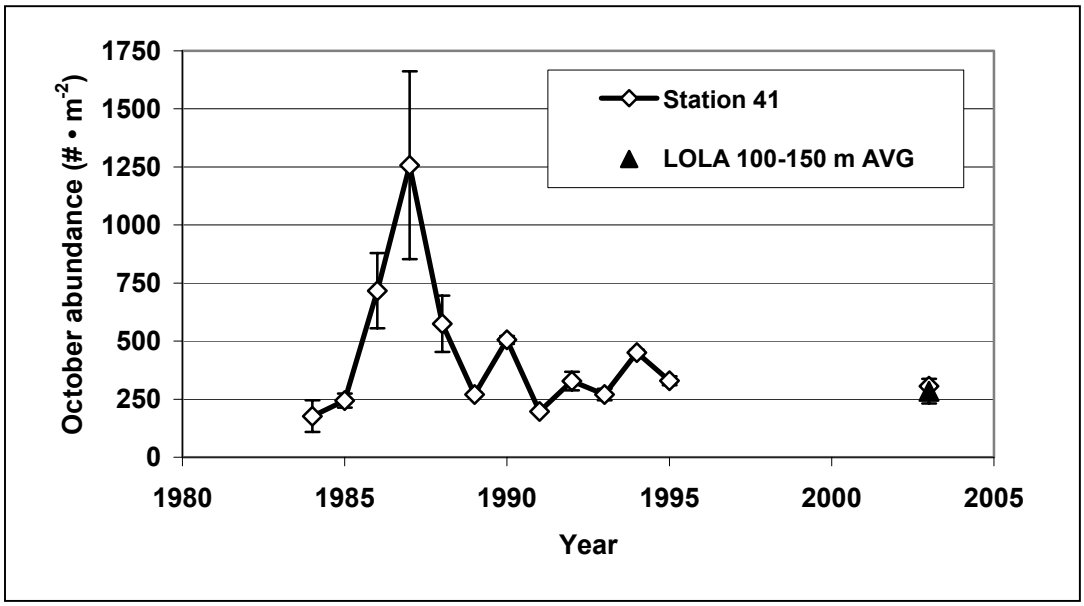
Deep *Diporeia* populations declined in 2003 at many sites in the absence of *D. bugensis*. This pattern suggests that if dreissenids initiated *Diporeia* population decline, they did so from some distance, perhaps via downslope sediment transport. A negative association of *D. bugensis* and *Diporeia* is clear. *Diporeia* rarely occurred at sites where the density of *D. bugensis* surpassed 100/m^2, suggesting little coexistence of these two organisms.

Figure 12. *Diporeia* spp. abundance (#/m^2) for three depth intervals in Lake Ontario: 1964 to 2003. Error bars are +1 SE.



Mysis. The Bioindex Program monitored mysid abundance at station 41 (bottom depth 128 m) from 1984 – 1995 (Figure 13). The abundance at station 41 in October 2003 was 306/m^2, and for all sites in the 100-150 m depth interval was 284/m^2. The abundance is low relative to 1987 but comparable with other years.

Figure 13. October mysid abundance at Station 41, 1984-1995 (from Johannsson et al. 2003), and for all stations in the 100 m to 150 m bottom depth interval, 2003. Error bars are +/- 1 SE.



C. Workshop: Description and Discussion

A workshop was held at the Cornell University Biological Field Station on November 16-17, 2005 (Appendix B). Participants represented 14 agencies and educational institutions in the United States and Canada (Appendix C). The first day's presentations addressed preliminary LOLA findings, management issues, food web structure, habitat definitions, spatial and temporal variability (Appendix D), sampling strategies from a statistical standpoint, and experimental studies (Appendix E). The second day's presentations focused on new technologies such as stable isotopes, fatty acids, hydroacoustics, optical plankton counters, remote sensing, and fluorometry. Detailed descriptions of each of these technologies can be found in Appendix F. The presentations were followed by breakout discussions during which each of three groups was asked to design a sampling program to best assess the lower food web**.** These discussions resulted in the preparation of recommendations regarding a future long-term assessment strategy for Lake Ontario, which is outlined in section IV.

During the workshop, impaired water quality in nearshore areas became a focus of discussion. In contrast to the offshore region, impaired water quality remains an issue in the nutrient-rich coastal zone. Anthropogenic forces including rapid population growth in the Greater Golden Horseshoe (Lake Ontario's western basin) threaten ecosystem integrity and sustainable use of coastal habitats. Coastal ecosystem impairments include algal blooms, aquatic weeds, shoreline erosion, invasive species, and habitat destruction. Filtering activity and selective feeding behavior of dreissenids has increased water clarity and altered nutrient cycling resulting in a rebound of the benthic green alga *Cladophora* and an increase in the relative abundance of pelagic blue-green algae. Although coastal and embayment sampling was not part of the LOLA project, workshop discussions identified these ecosystems as areas of concern from the perspective that future decisions will need to address potentially competing issues: nutrient enrichment in the coastal zone as opposed to "nutrient-starved" offshore waters.

III. Significant Research Findings

Comparison of sampling results from 2003 with historical data has shown that the Lake Ontario lower food web has undergone significant change during the past 10 years. Concentrations of total phosphorus in offshore waters are below the target level of 10 μg/L. The long-term trend at station 41 shows that spring TP levels have been hovering in the 4 – 6 μg/L range for the past 5 years. This range is slightly lower than the offshore mean (~7 μg/L) obtained from the Canadian Surveillance Program during the same time period. Phytoplankton compositional changes, in both spring and summer, between 1995 and 2003 are detrimental to ecosystem productivity. Declines in diatoms in the spring likely impact *Diporeia* spp., *Mysis relicta*, and copepods. The increase in relative biomass of Cyanophyceae (blue-green algae) in summer combined with a reduction in biomass of Cryptophyta further reduces the food resources of zooplankton. Phytoplankton and zooplankton populations are now at historic lows, as must be the carrying capacity of the lake's offshore waters. Few zebra mussels remain and quagga mussels now dominate the benthic community in Lake Ontario waters < 90 m deep. Expansion of the invasive quagga mussel coincides with a decline of the native amphipod, *Diporeia* spp. *Diporeia* spp. populations are no longer found in their preferred habitat (30 m to 60 m bottom depth) and are now relegated to bottom depths of >100 m. *Diporeia* has been a key organism in the Lake

Ontario food web and an important high-energy food source for Lake Ontario fish. Quagga mussels are expanding into waters >90 meters deep, now considered a fragile refuge for native *Diporeia* spp.

IV. Strategy for Long-term Assessment of the Lake Ontario Lower Food Web

Multiple biological, physical, and chemical stressors have caused profound changes in the Lake Ontario ecosystem and its fish community during the last three decades of the twentieth century (Mills et al. 2003). Cultural eutrophication has been reversed and water quality has improved. The resulting oligotrophication lowered the carrying capacity of the lake in the mid-1980s, as expected. However, the food web has changed since that time and offshore oligotrophication continued until the turn of the century. In the last few years (2000 – 2003), it appears to have stabilized, at least from a nutrient perspective. With continued expansion of the quagga mussel and invasion by round goby, additional food web changes are expected. Native species, such as *Diporeia* spp., are at risk of extirpation while non-native zooplankton (*Cercopagis pengoi* and *Bythotrephes longimanus*) persist.

Since 1970, advancements in the understanding of stressor impacts on ecological processes in Lake Ontario were due largely to commitments to long-term assessment studies endorsed by environmental agencies in both Canada and the United States and carried out by dedicated scientists and research support staffs in both countries (cf. State of Lake Ontario, ed. M. Munawar 2003; Johannsson et al. 1998; Mills et al. 2003; Mills et al. 2005). In the coming decades, Lake Ontario will continue to experience ecosystem stress from the growing demands of a burgeoning human population in the watershed (e.g. a recent estimate predicts a 47% population increase in the Hamilton/Toronto/Oshawa region, also known as the "Golden Horseshoe," by 2031 [www.pir.gov.on.ca]) and from anthropogenic forces such as invasive species and contaminants. These forces may act synergistically to cause ecological surprises and will continue to plague efforts to restore and manage the lake. Great Lakes scientists and managers must continue to work diligently to assess ecosystem status and to evaluate determinants of ecological change. Long-term assessment is critical to detect and assess those surprises, to better understand how stressors are manifested across habitats and impact fish communities, to measure effectiveness of remedial actions, and to make recommendations for future actions.

We offer the following recommendations towards developing a long-term assessment plan for facing these challenges:

1) Establish a Lake Ontario Binational Lower Food Web Task Force to improve the reporting of lower food web information to managers. A lower food web task force with binational participation and leadership should be created that reports annually to the Great Lakes Fishery Commission's Lake Ontario Committee, the Lake Ontario Coastal Initiative, and the LaMP group. This task force should develop and maintain a computerized binational data repository and a website that reports activities and findings, provides access to data, and reaches out to the public with coordination through an agency such as the Great Lakes Fishery Commission.

2) Develop a watershed-lake connection for assessing lower food web impacts on Lake Ontario. Management decisions typically consider impacts on single habitats. For example, target phosphorus levels developed under the Great Lakes Water Quality Agreement focused on offshore waters without specific consideration of areas closer to shore. Coastal wetland, embayment, and shore ecosystems, the interface between offshore waters and the surrounding watershed, are first to receive point and non-point source runoff. In turn, nutrient loadings to these habitats likely influence productivity of nearshore and offshore waters. Because shoreline and embayment habitats are highly utilized by the public, remedial efforts that have beneficial impacts on this impaired coastal zone will be more visible as opposed to the "nutrient-starved" offshore waters where phosphorus concentrations have been below target levels for nearly 20 years, and food web disruption has depressed energy flow to higher trophic levels. Managers need to know how their remediation and restoration decisions in the watershed will impact multiple habitats in the Lake Ontario ecosystem. Long-term assessment of Lake Ontario should be sensitive to a watershed-lake connection that includes lower food web comparisons of shoreline, embayment, nearshore, and offshore sites.

3) Maintain a commitment to supporting long-term monitoring. Annual sampling at fixed sites has been critical for assessing ecosystem health, particularly in evaluating the restoration of oligotrophic conditions and monitoring the spread of invasive species. These sites include Canadian Bioindex (Stations 41 and 81), USGS 2 km and 20 km south shore sites, U.S. Biomonitoring of south and east shore sites, Bay of Quinte (Project Quinte, 5 sites), and Hamlin Beach sites on the south shore sampled by J. Makarewicz. Long-term assessment is necessary to measure the efficacy of management decisions, to evaluate past and future direction, and to provide accountability with the public. Annual, long-term trend monitoring at fixed sites should be augmented by less frequent lake-wide condition assessments.

4) Improve the coordination of existing sampling. An impressive array of separate monitoring efforts exists across all Lake Ontario habitats, but unfortunately results are rarely synthesized. Coordination of sampling plans, standardization of units, and interlab comparisons will improve this effort. Lower food web components are clearly important as ecosystem indicators and supporters of fish stocks and therefore merit continued measurement. The primary thread of data collection should include: water chemistry, physical properties such as light extinction and temperature, benthos, microbial food web (MFW), phytoplankton, zooplankton, and *Mysis*. Annual assessments (biweekly for chemistry, MFW, phytoplankton, and zooplankton and seasonally for benthos and *Mysis*) at fixed locations are of highest priority to capture interannual variability coupled with less frequent lake-wide assessments for the determination of spatial variability.

5) Develop buoy monitoring systems in Lake Ontario. These systems could provide a continuous eye on Lake Ontario's ecosystem. Currently Lake Ontario researchers are trailing efforts of other Great Lakes and marine systems in adopting this technology. There is a need to coordinate efforts with funding agencies as well as develop a plan identifying potential sites and desired sensors. The Great Lakes Observing System (GLOS) is coordinating this effort, under leadership of the Integrated Ocean Observing System (IOOS).

6) Use satellite imagery as a monitoring tool and in planning assessment sampling. Existing satellite technology provides lake-wide measurements of surface temperature giving insight into processes such as upwelling and thermal bars. Temperature is a critical factor affecting lower trophic level production. Satellite color imagery provides insight for phytoplankton distributions and biophysical interactions.

7) Incorporate new food web tools into monitoring programs. Food web interactions and nutritional content of food are topics that have been pushed to the forefront in the evaluation of impacts of invasive species. Stable isotopes capture information on food web structure – who eats who and how much. It is important to have an understanding of this structure and to monitor key components to evaluate change. In Lake Ontario, the stable isotope studies by Leggett (1994-1995) provide a baseline, but there is an urgent need to repeat this work and to monitor stable isotopes annually in a few key fish (alewife, whitefish, and lake trout) and lower food web (*Diporeia* spp., dreissenids, and *Mysis*) organisms. We suggest using dreissenids in the nearshore, benthic offshore, and pelagic offshore combined with *Mysis*, *Diporeia*, alewife, whitefish, and lake trout in the annual assessment. Seasonal variation is large, so timing should be coordinated in late spring and late fall.

Growing evidence indicates that not only food quantity, but also the nutritional quality (e.g. relative proportion of elemental components or chemical stochiometry) of the food can be of vital importance. Trophic transfers from phytoplankton to zooplankton and benthic invertebrates determine fatty acid composition and chemical stochiometry of fish. The composition of these essential fatty acids is important for fish health, osmoregulation, and winter survival. We recommend collecting the same animals species at the same time for evaluation of these important food web bio-markers.

8) Apply high-resolution technologies to monitoring programs. New tools such as multiple-frequency hydroacoustics, laser optical plankton counters (LOPC), FlowCAM imaging, and fluorometry provide high-resolution alternatives to traditional net tows and water sampling, and are capable of gathering data on a scale that matches the magnitude of the lake and its inherent gradients. Numerous demonstration projects have shown their feasibility and power, and it is now time to fully adopt these instruments into investigative monitoring programs side-by-side with traditional methods. We suggest a careful comparison for at least five years before eliminating traditional methods or reducing their use. The best application of traditional and advanced methodologies will be sought to provide good information on biodiversity, while minimizing the variance around estimates of biomass that the greater spatial coverage of hydroacoustics, LOPC, and fluorometric technologies can provide.

9) Mesh field assessment with experimental studies. Correlations of parameters within the field assessment data often suggest cause and effect; controlled experiments are needed to help uncover the mechanisms behind the observations. Such experiments could be performed in limno-corrals and mesocosms, and at the bench top/laboratory incubator scale. The binational task force could set priorities for the need of such studies and suggest funding agencies consider these priorities.

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