Status of benthic macroinvertebrates in southern nearshore Lake Superior, 1994-2003

J. Scharold[1*], S. J. Lozano[2], T.D. Corry[1]

[1]U.S. Environmental Protection Agency, Mid-continent Ecology Division, 6201 Congdon Blvd., Duluth, MN, 55804, USA. [2] National Oceanic and Atmospheric Agency, Great Lakes Enviromental Reserarch Laboratory, 2205 Commonwealth Blvd., Ann Arbor, MI, 48105, USA.
**Corresponding author: Scharold.Jill@epamail.epa.gov*

Keywords: Diporeia, Oligochaeta, Chironomidae, Sphaeriidae, abundance, depth distribution

Introduction

Benthic macroinvertebrate communities are useful indicators of ecological condition for the Great Lakes (Cook and Johnson, 1974; Wiederholm, 1980). Benthic macroinvertebrates are closely associated with lake sediments, and are impacted by changes in physical and chemical characteristics of the sediments and of the overlying water. Benthic organisms play an important role in the ecosystem by influencing sediment-water interactions and by mediating the flow of energy and material between decomposers, primary producers, and higher trophic levels. Because of the sedentary nature and relatively stable population characteristics of benthic communities, their responses integrate environmental conditions in a local area over extended periods of time (Cook and Johnson, 1974).

State of Lake Superior
Edited by M. Munawar & I.F. Munawar

In this study, we examined the benthic macroinvertebrate community of the nearshore U.S. waters of Lake Superior in 1994, 2000, and 2003 to assess the condition of the region and to evaluate changes in abundance and measures of community composition over time. For purposes of assessment, we focused on two indicators of biotic integrity for the lake: 1) abundance of the amphipod *Diporeia*, a species-level measure of ecological condition, and 2) an oligochaete trophic index, a community-level measure of productivity and organic enrichment. To examine changes in composition, we used two indicators of community similarity: 1) coefficient of Jaccard, which is based on presence/absence data and 2) percent similarity, which is based on quantitative data.

Abundance of the amphipod *Diporeia* has been selected by the Great Lakes Water Quality Agreement (GLWQA) as an indicator of ecological condition for the Great Lakes (IJC, 1978). *Diporeia* is the dominant member of the benthic macroinvertebrate assemblage in profundal sediments of the Great Lakes, in terms of both numbers and biomass (Cook and Johnson, 1974; Nalepa, 1989). It is primarily associated with the sediment-water interface, where it feeds on freshly-deposited phytoplankton and serves as an important food item for many species of fish (Nalepa and Robertson, 1981; Quigley and Vanderploeg, 1991; Gardner et al., 1985; Wells and Beeton, 1963; Wojcik et al., 1986; Elrod, 1983; Fratt et al., 1997). Because of its prominence and its role in benthic-pelagic coupling and trophic
Abundance of the amphipod *Diporeia* has been selected by the Great Lakes Water Quality Agreement (GLWQA) as an indicator of ecological condition for the Great Lakes (IJC, 1978). *Diporeia* is the dominant member of the benthic macroinvertebrate assemblage in profundal sediments of the Great Lakes, in terms of both numbers and biomass (Cook and Johnson, 1974; Nalepa, 1989). It is primarily associated with the sediment-water interface, where it feeds on freshly-deposited phytoplankton and serves as an important food item for many species of fish (Nalepa and Robertson, 1981; Quigley and Vanderploeg, 1991; Gardner et al., 1985; Wells and Beeton, 1963; Wojcik et al., 1986; Elrod, 1983; Fratt et al., 1997). Because of its prominence and its role in benthic-pelagic coupling and trophic
interactions, *Diporeia* abundance is expected to be a good indicator of condition for the Lake Superior ecosystem. Since the late 1980s, *Diporeia* populations in the lower Great Lakes have undergone severe reductions (Dermott and Kerec, 1997; Nalepa et al., 1998; Dermott. 2001; Lozano et al., 2001), followed by negative effects on fish

their environment. The oligochaete trophic index (OTI) is calculated by the formula:

$$OTI = (\sum n_1 + 2\sum n_2) / (\sum n_0 + \sum n_1 + \sum n_2),$$

where $\sum n_0$ is the total number of oligochaetes belonging to species limited to oligotrophic conditions, $\sum n_1$ is the total number of oligochaetes characteristic of mesotrophic or slightly enriched environments, and $\sum n_2$ is the total number of worms belonging to species that are tolerant of eutrophic conditions or extreme organic enrichment. The OTI ranges from 0, indicating extremely oligotrophic conditions, to 2, indicating highly eutrophic conditions. We used only mature, identifiable specimens to calculate OTI, as recommended by Milbrink (1983).

Indices of similarity provide a measure of the stability of benthic communities. The coefficient of Jaccard is a simple similarity index that uses presence/absence data (Jaccard, 1912; Krebs, 1999). Jaccard's coefficient is calculated by the formula:

$$S_j = a / (a + b + c),$$

where a is the number of species in sample A and sample B, b is the number of species in sample A but not in sample B, and c is the number of species in sample B but not in sample A. Percent similarity is a useful measure of similarity for quantitative data on communities (Renkonen, 1938). This index is calculated from percentages for each site. Values range from 0 (no similarity) to 100 (complete similarity). Percent similarity is calculated by the formula:

that uses presence/absence data (Jaccard, 1912; Krebs, 1999). Jaccard's coefficient is calculated by the formula:

$$S_j = a / (a + b + c),$$

where a is the number of species in sample A and sample B, b is the number of species in sample A but not in sample B, and c is the number of species in sample B but not in sample A. Percent similarity is a useful measure of similarity for quantitative data on communities (Renkonen, 1938). This index is calculated from percentages for each site. Values range from 0 (no similarity) to 100 (complete similarity). Percent similarity is calculated by the formula:

$$P = \sum (\text{minimum} (p_{1i}, p_{2i})),$$

where P is percent similarity between samples 1 and 2, p_{1i} is the percentage of species i in community sample 1, and p_{2i} is the percentage of species i in community sample 2. The two similarity indices were used to compare nearshore benthic communities between 1994, 2000, and 2003, using sites as replicates. Both indices provide

Program (EMAP-GL) (US EPA 1992, US EPA 1993, Stevens 1997). The nearshore was defined as U.S. waters of Lake Superior between the shoreline and the 150 m contour, as determined using bathymetric maps digitized on a 4 km grid. A three-fold enhancement of the EMAP base grid (US EPA 1993) was applied to the target area. Sampling sites were located at the intersections of the resulting hexagons. The point to point distance on the grid was 13.3 km, resulting in a density of one point per 155 km^2. Each site's sampling coordinate was verified using a differential global positioning system (DGPS). Sampling was limited to the portion of the nearshore within U.S. waters and with depths between 10 and 110 meters, resulting in 27 sampling locations (Fig. 1). In 1994, the depths of stations ranged from 22 to 110 m, with a mean of 59 m. In 2000, depths were 18 to 137 m, with a mean of 62 m. Depths in 2003 were 18 to 120 m, with a mean of 59 m.

At each station, benthic macroinvertebrates were collected following the methods of Nalepa (1987). Sediment was collected using a Ponar grab with a sampling area of 0.05 m^2. Each sample consisted of three replicate grabs. The contents of each grab were placed into an elutriation device and rinsed through a 500-µm mesh sleeve. The organisms retained were preserved in 5% formalin containing rose bengal stain.

In the laboratory, organisms were picked from the sample and sorted into major taxa using a dissecting microscope. Oligochaetes

18 to 137 m, with a mean of 62 m. Depths in 2003 were 18 to 120 m, with a mean of 59 m.

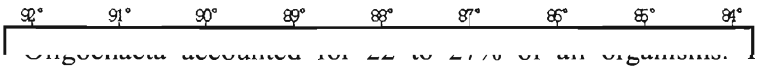
At each station, benthic macroinvertebrates were collected following the methods of Nalepa (1987). Sediment was collected using a Ponar grab with a sampling area of 0.05 m^2. Each sample consisted of three replicate grabs. The contents of each grab were placed into an elutriation device and rinsed through a 500-µm mesh sleeve. The organisms retained were preserved in 5% formalin containing rose bengal stain.

In the laboratory, organisms were picked from the sample and sorted into major taxa using a dissecting microscope. Oligochaetes
and chironomids were mounted on glass slides and identified to the lowest feasible taxa. Amphipods, clams, and other organisms were identified using a dissecting microscope. The abundance for each sample was obtained by averaging the three replicate counts. Mysids, nematodes, and ostracods were not included in analyses, as the methods used did not adequately sample these groups. Statistical

Total macroinvertebrate abundance did not vary among years (ANOVA, df = 80, F=2.84, p=0.06) (Fig. 2). Abundances of Oligochaeta, clams, and Chironomidae also did not vary significantly among years. Only abundance of *Diporeia* varied between years (ANOVA, df=80, F=3.97, p=0.02). The abundance of *Diporeia* in 2000 was significantly lower compared to abundance in 1994 and 2003 (Fig. 2; Tukey's multiple comparison test, p<0.05).

The dominant component of the benthic macroinvertebrate community was *Diporeia*, the only amphipod collected. Annual mean relative abundance of this amphipod ranged from 50 to 61%. *Diporeia* was present at 99% of sites, and occurred over the entire depth range sampled (18 to 139 meters).

Oligochaeta accounted for 22 to 27% of all organisms. The dominant oligochaete species was the lumbriculid *Stylodrilus heringianus*, which accounted for 56 to 60% of oligochaetes. *Stylodrilus heringianus* was the only member of the family Lumbriculidae collected. It was found at 85% of sites and at all depths. The remainder of the Oligochaeta was made up of the families Enchytraeidae (29 to 36%), Tubificidae (5 to 11%), and Naididae (1 to 4%). No Enchytraeidae were identified to genus. Enchytraeids



dominant oligochaete species was the lumbriculid *Stylodrilus heringianus*, which accounted for 56 to 60% of oligochaetes. *Stylodrilus heringianus* was the only member of the family Lumbriculidae collected. It was found at 85% of sites and at all depths. The remainder of the Oligochaeta was made up of the families Enchytraeidae (29 to 36%), Tubificidae (5 to 11%), and Naididae (1 to 4%). No Enchytraeidae were identified to genus. Enchytraeids

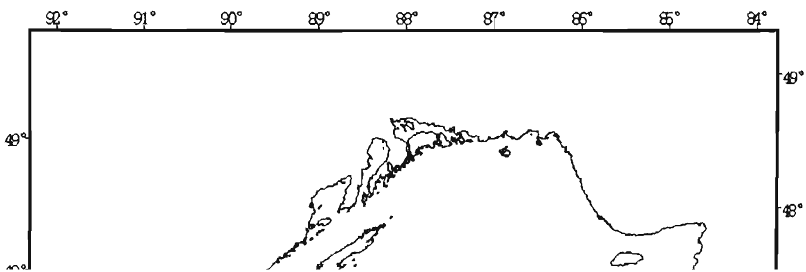


Table 1. Taxa found in benthic samples from U.S. nearshore waters of Lake Superior. Planktonic organisms, nematodes, and ostracods are excluded.

Class	Order	Family	Genus and species
Bivalvia	Veneroidea	Sphaeriidae	*Pisidium* sp.
Malacostraca	Amphipoda	Pontoporeiidae	*Diporeia* spp.
Clitellata	Lumbriculida	Lumbriculidae	*Stylodrilus heringianus*
	Haplotaxida	Enchytraeidae	
		Naididae	*Arcteonais lomondi*
			Chaetogaster diaphanus
			C. limnaei
			Chaetogaster sp.
			Nais communis
			N. simplex
			N. variabilis
			Piguetiella michiganensis
			Pristina aequiseta
			Pristina sp.
			Slavina appendiculata
			Stylaria lacustris
			Uncinais uncinata
			Vejdovskyella intermedia
			Nais communis
			N. simplex
			N. variabilis
			Piguetiella michiganensis
			Pristina aequiseta
			Pristina sp.
			Slavina appendiculata
			Stylaria lacustris
			Uncinais uncinata
			Vejdovskyella intermedia
		Tubificidae	*Aulodrilus limnobius*
			Limnodrilus hoffmeisteri
			Limnodrilus sp.
			Quistadrilus multisetosus
			Rhyacodrilus coccineus
			R. sodalis

Table 1. Contd.

Class	Order	Family	Genus and species
Aphanoneura	Aeolostomatida	Aeolosomatidae	
Insecta	Diptera	Chironomidae	*Chironomus* sp.
			Cladotanytarsus mancus gr.
			Cryptochironomus sp.
			Demicryptochironomus sp.
			Dicrotendipes sp.
			Kloosia sp.
			Micropsectra sp.
			Pagastiella sp.
			Paratanytarsus sp.
			Paracladopelma camptolabis
			P. doris
			P. nigritula
			P tuberculatum
			P. undine
			P. winnelli
			Paracladopelma sp.
			Paratendipes sp.
			Phaenopsectra sp.
			Pagastiella sp.
			Paratanytarsus sp.
			Paracladopelma camptolabis
			P. doris
			P. nigritula
			P tuberculatum
			P. undine
			P. winnelli
			Paracladopelma sp.
			Paratendipes sp.
			Phaenopsectra sp.
			Polypedilum laetum
			Polypedilum sp.
			Robackia sp.
			Saetheria sp.
			Stempellina sp.

Table 1. Contd.

Class	Order	Family	Genus and species
			Pseudodiamesa sp.
			Coryoneura sp.
			Cricotopus sp.
			Heterotrissocladius changi
			H. maeaeri
			H. marcidus
			H. oliveri
			H. subpilosus
			Heterotrissocladius sp.
Insecta	Diptera	Chironomidae	
			Orthocladius sp.
			Parakiefferiella sp.
			Psectrocladius psilopterus
			Psectrocladius sp.
			Monodiamesa tuberculata
			Monodiamesa sp.
			Coelotanypus sp.
			Procladius sp.
			Thienemannimyia gr.
Insecta	Diptera	Chironomidae	
			Orthocladius sp.
			Parakiefferiella sp.
			Psectrocladius psilopterus
			Psectrocladius sp.
			Monodiamesa tuberculata
			Monodiamesa sp.
			Coelotanypus sp.
			Procladius sp.
			Thienemannimyia gr.
		Ceratopogonidae	*Probezzia* sp.
	Ephemeroptera	Ephemeridae	*Ephemera* sp.
	Trichoptera	Apataniidae	*Apatania* sp.

were found at 93% of sites and all depths from 22 to 139 meters. Among the family Tubificidae, the dominant genus was *Spirosperma* (25 to 99% of Tubificidae). Of the 18 genera of oligochaetes identified, most (10) were found at only one or two sites.

Clams accounted for 14 to 16% of total abundance. They consisted entirely of the family Sphaeriidae (fingernail clams), with *Pisidium* being the only genus identified. Sphaeriids were found at 93% of sites, and at all depths greater than 20 meters.

Chironomids accounted for 3 to 5% of total organisms. The dominant chironomid genus was *Heterotrissocladius*, which accounted for 54 to 70% of chironomids. *Heterotrissocladius* was present at 91% of sites and at all depths sampled. Other important chironomids included *Paracladopelma* (4 to 18% of chironomids) and *Micropsectra* (4 to 10%). These two genera were present at about 33% of sites, at depths from 20 to 110 m. Of the 34 genera of chironomids identified, most (25) were present at only one or two sites.

To examine depth distributions of major taxa, abundances for all three years were averaged in 10-meter depth classes (Fig. 3). *Diporeia* exhibited two peaks in abundance, at 30 to 40 meters and 60 to 70 meters. Oligochaete abundance increased from low values at depths less than 30 m to a maximum at 50 to 60 m, then declined to low values in the 70 to > 110 m range. Abundance of clams was

Micropsectra (4 to 10%). These two genera were present at about 33% of sites, at depths from 20 to 110 m. Of the 34 genera of chironomids identified, most (25) were present at only one or two sites.

To examine depth distributions of major taxa, abundances for all three years were averaged in 10-meter depth classes (Fig. 3). *Diporeia* exhibited two peaks in abundance, at 30 to 40 meters and 60 to 70 meters. Oligochaete abundance increased from low values at depths less than 30 m to a maximum at 50 to 60 m, then declined to low values in the 70 to > 110 m range. Abundance of clams was
greatest between 30 and 70 m. Chironomidae were most abundant at the shallowest depths sampled (18 to 30 m) and at 50 to 60 m.

The abundance of *Diporeia* within the area sampled can be summarized by a cumulative frequency distribution (Fig. 4), which shows the proportion of sites with values at or below a given value. In 1994, *Diporeia* abundance exceeded the ecosystem objective of at least 300 *Diporeia* m^{-2} established by the GLWQA at all sites, mean *Diporeia* abundance during 1994 to 2003 was five to eight times greater than that reported for 1973 (Cook, 1975).

The cumulative frequency distributions of the oligochaete trophic index (OTI) were similar for 1994, 2000, and 2003 (Fig. 5). None of the U.S. nearshore region of Lake Superior exceeded an OTI value of 1.0. In 1994, 88% of the sites had an OTI value of 0, representing extremely oligotrophic conditions, and only 7% of the region (two sites) had an OTI greater than 0.5. In 2000, 75% of the nearshore had an OTI value of 0, and again 7% had a value of 0.5 or greater. In 2000, 62% of the sites had an index value of 0, and 11% exceeded 0.5. No differences in the mean value of the trophic index were detected among years (ANOVA, df=74, F=0.44, p=0.65).

Indices of community similarity as measured by Jaccard's coefficient and percent similarity between 1994, 2000, and 2003 were remarkably similar in values between years. The Jaccard's coefficient ranged from 0.55 to 0.61 and percent similarity ranged from 72 to 83% (Table 2). The high values for the coefficients of Jaccard and percent similarity are the result of three dominant species or taxa including *Diporeia*, *Pisidium*, and *Stylodrilus heringianus*. The least overlap between species or taxa were found at shallow sites, i.e. less than 30 meters, in 1994. A comparison of average values (Table 3) calculated for sites less or greater than 30 meters revealed that the mean coefficients for the 1994 comparisons at shallow sites (< 30 m) were 43 to 55% smaller than mean coefficients calculated from
coefficient and percent similarity between 1994, 2000, and 2003 were remarkably similar in values between years. The Jaccard's coefficient ranged from 0.55 to 0.61 and percent similarity ranged from 72 to 83% (Table 2). The high values for the coefficients of Jaccard and percent similarity are the result of three dominant species or taxa including *Diporeia*, *Pisidium*, and *Stylodrilus heringianus*. The least overlap between species or taxa were found at shallow sites, i.e. less than 30 meters, in 1994. A comparison of average values (Table 3) calculated for sites less or greater than 30 meters revealed that the mean coefficients for the 1994 comparisons at shallow sites (< 30 m) were 43 to 55% smaller than mean coefficients calculated from
deeper sites (> 30 m).

Discussion

The composition of the benthic macroinvertebrate community in this

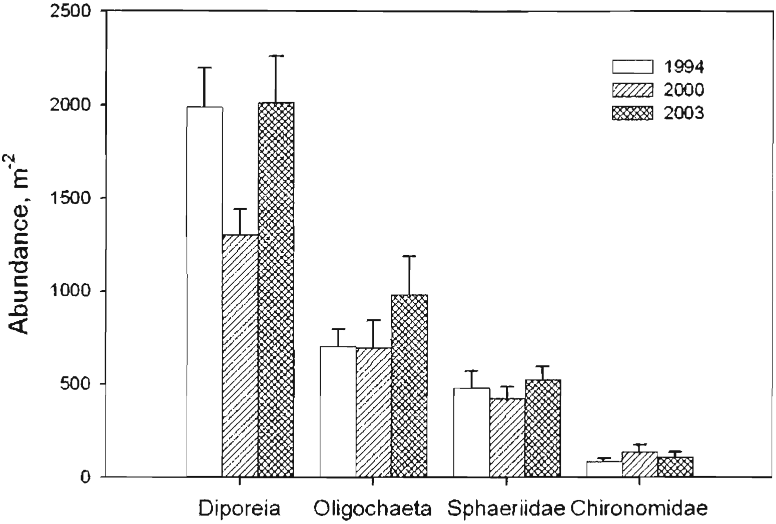


Fig. 2. Abundance of major benthic macroinvertebrate taxa in the U.S. nearshore region of Lake Superior during 1994, 2000, and 2003. Error bars are standard error of the mean.

Table 2. Mean and standard errors (SE) for Jaccard's coefficient and percent similarity across 27 sites between 1994, 2000, and 2003. Pearson correlations were calculated between similarity indices and depth at each site.

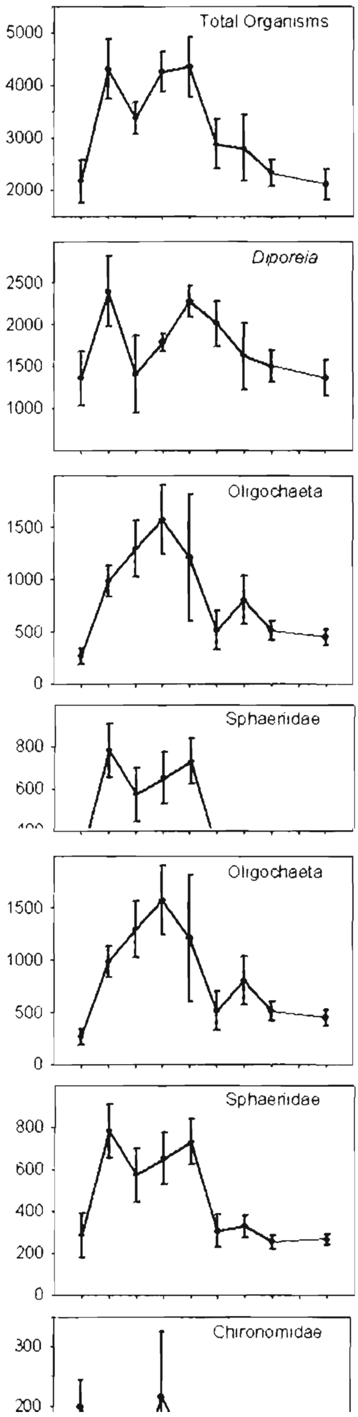
Years Jaccard's Coefficient Pearson Correlation Percent Similarity Pearson Correlation
0
Diporeia Oligochaeta Sphaeriidae Chironomidae

Fig. 2. Abundance of major benthic macroinvertebrate taxa in the U.S. nearshore region of Lake Superior during 1994, 2000, and 2003. Error bars are standard error of the mean.

Table 2. Mean and standard errors (SE) for Jaccard's coefficient and percent similarity across 27 sites between 1994, 2000, and 2003. Pearson correlations were calculated between similarity indices and depth at each site.

Years	Jaccard's Coefficient (SE)	Pearson Correlation	Percent Similarity (SE)	Pearson Correlation
1994-2000	0.61 (0.04)	0.55 **	72.2 (4.1%)	0.48 *
1994-2003	0.55 (0.04)	0.50 **	74.3 (4.1%)	0.46 *
2000-2003	0.60 (0.3)	0.42 *	82.6 (1.9%)	0.62 **

* $p < 0.05$


Total Organisms
5000
4000
3000
2000
Diporeia
2500
2000
1500
1000
Oligochaeta
1500
1000
500
0
Sphaeriidae
800
600
Oligochaeta
1500
1000
500
0
Sphaeriidae
800
600
400
200
0
Chironomidae
300
200

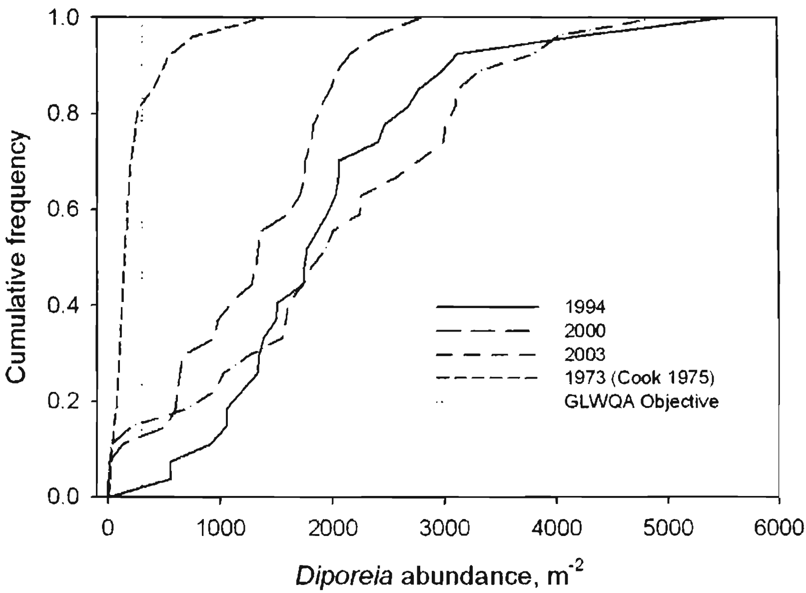


Fig. 4. Cumulative frequency distributions of abundance of *Diporeia* spp. in the U.S. nearshore region of Lake Superior during 1994, 2000, and 2003.

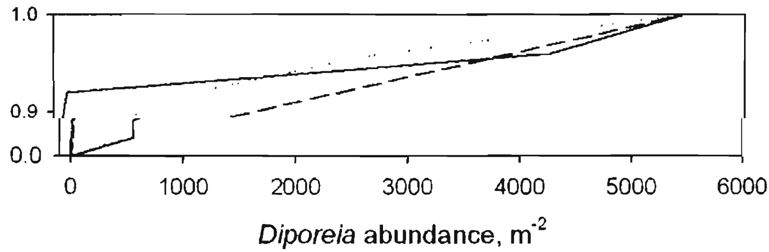


Fig. 4. Cumulative frequency distributions of abundance of *Diporeia* spp. in the U.S. nearshore region of Lake Superior during 1994, 2000, and 2003.

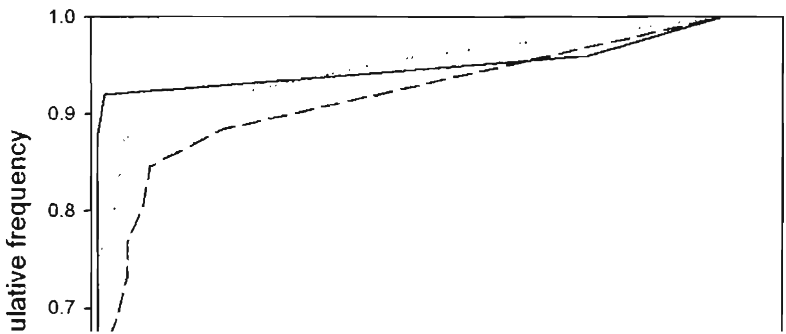


Table 3. Mean Jaccard's coefficient and percent similarity across sites that were grouped by two depth categories (10 - 30 m, > 30 m) between 1994, 2000, and 2003.

	Jaccard's Coefficient		Percent Similarity (SE)	
Years	10-30 m	> 30 m	10 - 30 m	> 30 m
1994-2000	0.29	0.68	42 %	79 %
1994-2003	0.30	0.60	45 %	81 %
2000-2003	0.50	0.62	72 %	85 %

the study period. Only *Diporeia* showed a significant decline in 2000, but by 2003 abundance had returned to levels similar to those in 1994. During all three years sampled, less than 15% of the nearshore was below the GLWQA objective for *Diporeia* abundance. Thus, there is no indication of an ongoing reduction in *Diporeia* populations of Lake Superior, as has occurred in the lower Great Lakes (Dermott and Kerec, 1997; Nalepa et al., 1998; Dermott, 2001; Lozano et al., 2001).

The changes observed in abundance of *Diporeia* between 1994, 2000, and 2003 are small compared with the increase from 1973 (Cook, 1975) to the present study. Although some of the difference in abundance may be due to changes in methodology, the observed increase appears greater than can be explained by differences in

sampling equipment or season of sampling alone, as discussed by
was below the GLWQA objective for *Diporeia* abundance. Thus, there is no indication of an ongoing reduction in *Diporeia* populations of Lake Superior, as has occurred in the lower Great Lakes (Dermott and Kerec, 1997; Nalepa et al., 1998; Dermott, 2001; Lozano et al., 2001).

The changes observed in abundance of *Diporeia* between 1994, 2000, and 2003 are small compared with the increase from 1973 (Cook, 1975) to the present study. Although some of the difference in abundance may be due to changes in methodology, the observed increase appears greater than can be explained by differences in
sampling equipment or season of sampling alone, as discussed by Scharold et al. (2004). Some of the increase in abundance of *Diporeia* may be due to decreased predation pressure by benthivorous fish. During the early 1980s, biomass of slimy sculpins (*Cottus cognatus*), spoonhead sculpins (*Cottus ricei*), deepwater sculpins (*Myoxocephalus thompsoni*), nine-spined stickleback (*Pungitius*

recovering populations of lake trout (*Salvelinus namaycush*) as the cause (Bronte et al., 2003).

Abundances of all major taxonomic groups were lower in 1973 (Cook, 1975) than in our study. The three-year mean abundances of oligochaetes and clams in our study were twice those reported for 1973. Chironomid abundance was three times greater. It appears that some factor lowered *Diporeia* abundance in 1973 relative to other benthic taxa. Similarly, only *Diporeia* showed significant differences in abundance during the period of our study. *Diporeia* populations appear to exhibit greater variability than the other major taxa.

Although *Diporeia* is clearly numerically dominant in Lake Superior's benthic assemblage, it is even more important when biomass is considered. The mean biomass per individual is higher for *Diporeia* spp. than for oligochaetes, clams, and chironomids (Cook, 1975). Furthermore, the higher lipid content of *Diporeia* spp. relative to other major taxa enhances its importance in the storage and transfer of energy (Gardner et al., 1985).

Depth distributions of major taxa were similar to those observed in previous studies of Lake Superior. Along the western edge of the Keweenaw Peninsula, Auer and Kahn (2004) reported maximum abundance of oligochaetes and chironomids at 50 to 60 m, sphaeriids at 40 to 70 m, and *Diporeia* at 50 to 140 m. At the 26 sites of Cook (1975) that we compared with our study, *Diporeia* showed maximum

abundances between 50 and 80 m, and clams between 30 and 80 m.
spp. than for oligochaetes, clams, and chironomids (Cook, 1975). Furthermore, the higher lipid content of *Diporeia* spp. relative to other major taxa enhances its importance in the storage and transfer of energy (Gardner et al., 1985).

Depth distributions of major taxa were similar to those observed in previous studies of Lake Superior. Along the western edge of the Keweenaw Peninsula, Auer and Kahn (2004) reported maximum abundance of oligochaetes and chironomids at 50 to 60 m, sphaeriids at 40 to 70 m, and *Diporeia* at 50 to 140 m. At the 26 sites of Cook (1975) that we compared with our study, *Diporeia* showed maximum
abundances between 50 and 80 m, and clams between 30 and 80 m. Oligochaetes and chironomids had more variable abundance, but also exhibited peaks in the 60 to 80 m range. These peaks in abundance of benthic macroinvertebrates at intermediate depths have been observed in Lake Michigan (review by Cook and Johnson, 1974; Nalepa et al. 1989) and have been attributed to focusing of high

Similarly, the US EPA Great Lakes National Program Office reported three-year (1997 to 1999) mean abundances of 212 m^{-2} at six offshore sites with depths of 150 to 228 m, and 920 m^{-2} at five nearshore sites with depths of 56 to 113 m (R. Barbiero, CSC, Chicago, IL, pers. comm.).

The oligochaete trophic index was uniformly low for all years of the study. This corresponds with the oligotrophic character of most of Lake Superior, the deepest, coldest, and least productive of the Laurentian Great Lakes. Howmiller and Scott (1977) reported values of 1.53 to 1.92 for Green Bay, Lake Michigan. They found that this index was more sensitive at discriminating between their sites than were several other indices, including species diversity, which did not consider the ecological characteristics of the species measured. However, they noted that the other indices would be equally good at distinguishing between sites at opposite extremes of condition. Our study of nearshore Lake Superior encompassed an area at the lower extreme of productivity, yet a few sites could be identified as having higher index values. At one of these sites, the higher score resulted from the presence of *Tubifex tubifex*, a member of the organic enrichment-tolerant Group 2 (Howmiller and Scott, 1977). Milbrink (1983) pointed out that although this species is tolerant of sewage, it is also found in oligotrophic environments, and suggested that *T. tubifex* be assigned to the eutrophic group (Group 2) only when present in high numbers or with *Limnodrilus hoffmeisteri*, and consider the ecological characteristics of the species measured. However, they noted that the other indices would be equally good at distinguishing between sites at opposite extremes of condition. Our study of nearshore Lake Superior encompassed an area at the lower extreme of productivity, yet a few sites could be identified as having higher index values. At one of these sites, the higher score resulted from the presence of *Tubifex tubifex*, a member of the organic enrichment-tolerant Group 2 (Howmiller and Scott, 1977). Milbrink (1983) pointed out that although this species is tolerant of sewage, it is also found in oligotrophic environments, and suggested that *T. tubifex* be assigned to the eutrophic group (Group 2) only when present in high numbers or with *Limnodrilus hoffmeisteri*, and assigned to Group 0 when found with other oligotrophic species. The latter would be the case with our site, changing the score from 0.8 to 0.

Both measures of taxa similarity support our view that the macroinvertebrate community is in a relatively stable state. Between

Conclusions

Both the species-level indicator of *Diporeia* abundance and the community-level indicator of oligochaete community composition showed the U.S. nearshore waters of Lake Superior to be in good condition during 1994 to 2003. The abundance of *Diporeia* was above the GLWQA objective for 85% of the nearshore, with no sign of progressive reduction. Trophic status, as indicated by the oligochaete community, was very oligotrophic in 70 to 80% of the nearshore, with only 7% classed as mesotrophic. Measures of community similiarity also showed the benthic macroinvertebrate assemblage to be stable during the study period. Further research will help to elucidate the temporal and spatial variability of these indicators and to evaluate their utility in detecting trends.

Summary

Recent changes to benthic communities in the lower Laurentian Great Lakes raise concerns about the status of benthic macroinvertebrates in Lake Superior. This lakewide study was conducted to ascertain their status in nearshore waters of Lake Superior. Benthic macroinvertebrates were collected from 27 sites representing the temporal and spatial variability of these indicators and to evaluate their utility in detecting trends.

Summary

Recent changes to benthic communities in the lower Laurentian Great Lakes raise concerns about the status of benthic macroinvertebrates in Lake Superior. This lakewide study was conducted to ascertain their status in nearshore waters of Lake Superior. Benthic macroinvertebrates were collected from 27 sites representing the U.S. nearshore waters (20 to 110 m) of Lake Superior in 1994, 2000, and 2003. No significant differences in total benthic macroinvertebrate abundance, or abundances of oligochaetes, clams, or chironomids were detected among years. Abundance of the amphipod *Diporeia* was lower in 2000 than in 1994 or 2003. The oligochaete trophic

Acknowledgements

The authors thank T. Olsen and D. Stevens for assistance with EMAP site selection, the helpful crew members of the research vessels *Lake Explorer*, *Lake Guardian*, and *Prairie Sounder* for assistance with field collections, and T. Angradi, K. Schmude, and M.A. Starus for comments on the manuscript. Taxonomic identifications were performed by NOAA-GLERL on samples collected in 1994 and by SoBran, Inc. on samples collected in 2000 and 2003.

References

Adams, C.E., Kregear, R.D, 1969. Sedimentary and faunal environments of eastern Lake Superior. p 1-20. In: Proc. 12th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., 1969 May, Ann Arbor, MI.

Auer, N.A., Kahn, J.E., 2004. Abundance and distribution of benthic invertebrates, with emphasis on *Diporeia*, along the Keweenaw Peninsula, Lake Superior. J. Great Lakes Res. 30 (Supplement 1), 340-359.

Bronte, C.R., Ebener, M.P., Schreiner, D.R., DeVault, D.S., Petzold, M.M., Jensen, D.A., Richards, C., Lozano, S.J., 2003. Fish community change in Lake Superior, 1970-2000. Can. J. Fish. Aquat. Sci. 60, 1552-1574.

Cook, D.G., Johnson, M.G., 1974. Benthic macroinvertebrates of the St. Lawrence Great Lakes. J. Fish. Res. Bd. Can. 31, 763-782.

Cook, D.G, 1975. *A preliminary report on the benthic macroinvertebrates of Lake*

Adams, C.E., Kregear, R.D, 1969. Sedimentary and faunal environments of eastern Lake Superior. p 1-20. In: Proc. 12th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., 1969 May, Ann Arbor, MI.

Auer, N.A., Kahn, J.E., 2004. Abundance and distribution of benthic invertebrates, with emphasis on *Diporeia*, along the Keweenaw Peninsula, Lake Superior. J. Great Lakes Res. 30 (Supplement 1), 340-359.

Bronte, C.R., Ebener, M.P., Schreiner, D.R., DeVault, D.S., Petzold, M.M., Jensen, D.A., Richards, C., Lozano, S.J., 2003. Fish community change in Lake Superior, 1970-2000. Can. J. Fish. Aquat. Sci. 60, 1552-1574.

Cook, D.G., Johnson, M.G., 1974. Benthic macroinvertebrates of the St. Lawrence Great Lakes. J. Fish. Res. Bd. Can. 31, 763-782.

Cook, D.G, 1975. *A preliminary report on the benthic macroinvertebrates of Lake Superior.* Environment Canada, Fisheries and Marine Service, Burlington, ON. Technical Report No. 572.

Dermott, R., 2001. Sudden disappearance of the amphipod *Diporeia* from eastern Lake Ontario, 1993-1995. J. Great Lakes Res. 27, 423-433.

Dermott, R., Kerec, D., 1997. Changes to the deepwater benthos of Lake Erie since the invasion of *Dreissena*: 1979-1993. Can. J. Fish. Aquat. Sci. 54, 922-930.

Elrod, J.H., 1983. Seasonal food of juvenile lake trout in U.S. waters of Lake Ontario. J. Great Lakes Res. 9, 396-402.

Griswold, B.L., Smith, L.L. Jr., 1973. The life history and trophic relationship of the nine-spine stickleback, *Pungitius pungitius*, in the Apostle Islands area of Lake Superior. Fish. Bull. 71, 1039-1060.

Hiltunen, J.K., 1969. Invertebrate macrobenthos of western Lake Superior. Mich. Acad. 1, 123-133.

Howmiller, R.P., Scott, M.A., 1977. An environmental index based on relative abundance of oligochaete species. J. Water Poll. Cont. Fed. 49, 809-815.

IJC, 1978., Great Lakes Water Quality Agreement of 1978. Agreement, with annexes and terms of reference, between the United States of America and Canada signed at Ottawa November 22, 1978. International Joint Commission, Windsor, ON.

Jaccard, P., 1912. The distribution of flora in the alpine zone. The New Phytologist 11(2), 37-50.

Krebs, C.J., 1999. *Ecological Methodology*, 2nd ed. Benjamin/Cummings imprint, New York, NY.

Lozano, S.L., Scharold, J.V., Nalepa, T.F., 2001. Recent declines in benthic macroinvertebrate densities in Lake Ontario. Can. J. Fish. Aquat. Sci. 58, 518-529.

Milbrink, G., 1983. An improved environmental index based on the relative abundance of oligochaete species. Hydrobiol. 102, 89-97.

Nalepa, T.F., 1987. Long-term changes in the macrobenthos of southern Lake Michigan. Can. J. Fish. Aquat. Sci. 44, 515-524.

Nalepa, T.F., 1989. Estimates of macroinvertebrate biomass in Lake Michigan. J. Great Lakes Res. 15, 437-443.

Nalepa, T.F., Hartson, D.J., Fanslow, D.L., Lang, G. A., Lozano, S.J., 1998. Declines in benthic macroinvertebrate populations in southern Lake Michigan, 1980-1993. Can. J. Fish. Aquat. Sci. 55, 2402-2413.

Nalepa, T.F., Mohr, L.C., Henderson, B.A., Madenjian, C.P., 2005. Lake whitefish and *Diporeia* spp. in the Great Lakes: an overview. p 3-20. In: L.C. Mohr and T.F. Nalepa (Eds.), Proceedings of a workshop on the dynamics of lake whitefish *(Coregonus clupeaformis)* and the amphipod *Diporeia* spp. in the Great Lakes
macroinvertebrate densities in Lake Ontario. Can. J. Fish. Aquat. Sci. 58, 518-529.

Milbrink, G., 1983. An improved environmental index based on the relative abundance of oligochaete species. Hydrobiol. 102, 89-97.

Nalepa, T.F., 1987. Long-term changes in the macrobenthos of southern Lake Michigan. Can. J. Fish. Aquat. Sci. 44, 515-524.

Nalepa, T.F., 1989. Estimates of macroinvertebrate biomass in Lake Michigan. J. Great Lakes Res. 15, 437-443.

Nalepa, T.F., Hartson, D.J., Fanslow, D.L., Lang, G. A., Lozano, S.J., 1998. Declines in benthic macroinvertebrate populations in southern Lake Michigan, 1980-1993. Can. J. Fish. Aquat. Sci. 55, 2402-2413.
Nalepa, T.F., Mohr, L.C., Henderson, B.A., Madenjian, C.P., 2005. Lake whitefish and *Diporeia* spp. in the Great Lakes: an overview. p 3-20. In: L.C. Mohr and T.F. Nalepa (Eds.), Proceedings of a workshop on the dynamics of lake whitefish *(Coregonus clupeaformis)* and the amphipod *Diporeia* spp. in the Great Lakes, 2002 February. Great Lakes Fish. Comm. Tech. Rep. 66, Ann Arbor, MI.

Nalepa, T.F., Robertson, A., 1981. Vertical distribution of the zoobenthos in southeastern Lake Michigan with evidence of seasonal variation. Freshwat. Biol. 11, 87-96.

Quigley, M.A., Vanderploeg, H.A., 1991. Ingestion of live filamentous diatoms by the Great Lakes amphipod, *Diporeia* sp.: a case study of the limited value of gut contents analysis. Hydrobiol. 223, 141-148.

Renkonen, O., 1938. Statisch-okologische Untersuchungen uber die terrestiche kaferwelt

Wells, L., Beeton, A.M., 1963. Food of the bloater, *Coregonus hoyi*, in Lake Michigan. Trans. Amer. Fish. Soc. 92, 245-255.

Wiederholm, T., 1980. Use of benthos in lake monitoring. J. Wat. Poll. Cont. Fed. 52, 537-547.

Wilkinson, L., 1999. *SYSTAT 9.0 for Windows*. SPSS Inc., Chicago, IL.

Wojcik, J.A., Evans, M.S., Jude, D.J., 1986. Food of deepwater sculpin, *Myoxocephalus thompsoni*, from southeastern Lake Michigan. J. Great Lakes Res. 12, 225-231.

State of Lake Superior

Editors:
M. Munawar and I. F. Munawar

Publishers:
Aquatic Ecosystem Health and Management Society
Canada

Photo credits

Front Cover:
Foreground: Lake Superior water surface temperature 08/30/2007, 12:00 GMT (courtesy of the National Oceanic and Atmospheric Administration (NOAA) Coast Watch, AVHRR Imagery)
Back Cover:
Background: Lake Superior (©Chris J. Benson, www.chrisjbenson.com)
Foreground: Maps of Lake Superior:
1656: Sanson, Nicolas. Le Canada ou Nouvelle France &c., National Archives of Canada.
1719: Châtelain, Henri Abraham. Carte du Canada ou de la Nouvelle France &c., The W. H. Pugsley Collection of Early Canadian Maps, McGill University Libraries
1755: Bellin, J.N. Partie Occidentale de la Nouvelle France ou Canada, National Archives of Canada
1835: Bradford, Thomas Gamaliel. Michigan and the Great Lakes. Barry Lawrence Ruderman Antique Maps Inc.
2005: Schmaltz, Jeff. The Great Lakes. Taken by Terra/MODIS Sensor. (Courtesy of Nasa. Image available at http://visibleearth.nasa.gov/)

Printed by: Gopsons Papers Ltd., Noida
Goodword Books
1, Nizamuddin West Market, New Delhi 110013
Tel. (9111) 2435 5454, 2435 6666, 2435 5729
Fax (9111) 2435 7333
e-mail: info@goodwordbooks.com
Websites: www.goodwordbooks.com, www.goodword.net

ISBN: 978-81-7898-592-3

First published 2009