J. Great Lakes Res. 34:690–697
Internat. Assoc. Great Lakes Res., 2008

Impacts of the Introduced Round Goby (*Apollonia melanostoma*) on Dreissenids (*Dreissena polymorpha* and *Dreissena bugensis*) and on Macroinvertebrate Community between 2003 and 2006 in the Littoral Zone of Green Bay, Lake Michigan

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ABSTRACT. *We show that the invasion of round gobies* (Apollonia melanostoma) *in Green Bay, Lake Michigan, has changed the benthic food web in fundamental ways related to their impact on invasive dreissenid mussels. Dreissenid mussels are of specific interest because they are one of the primary dietary items for round gobies. In this study, we collected rocks from each of 10 study sites along approximately 60 km of the eastern shoreline of Green Bay, Lake Michigan, to assess a temporal change in macroinvertebrate abundance related to the northward movement of the round goby invasion front from a point about midway along the shoreline in 2003 to the entire coast in 2006. The pattern of macroinvertebrate abundance in 2003 suggested that round gobies had already caused significant decreases in macroinvertebrate abundances south of the invasion front (interpretation of the data could have been compromised by confounding environmental gradients). In subsequent sampling in 2006 macroinvertebrates were picked off of sampled rocks in the field and underwater transects were videotaped to estimate round goby abundance at each site. Round gobies were collected for stomach analysis to assist in determining which invertebrates would likely be impacted by goby predation. Our results indicated that by 2006, round gobies had become abundant at those sites where they were absent in 2003 and zebra mussels* (Dreissena polymorpha), *quagga mussels* (Dreissena bugensis), *isopods, amphipods, trichopterans, and gastropods in the newly invaded sites had significantly decreased at the newly invaded sites.*

INDEX WORDS: *Round goby, macroinvertebrates, Green Bay, invasive species, benthic.*

INTRODUCTION

Species native to Eurasia have invaded the Laurentian Great Lakes since the beginning of European settlement. The incidence of invasions accelerated in the 1840s with completion of the first passages by ocean-going vessels into the Great Lakes (Mills *et al.* 1993). Many recent invasive species were introduced to the Great Lakes by ballast water from transoceanic Eurasian freighters. The most significant of these ballast water invasives are probably the zebra mussel (*Dreissena polymorpha*), discovered in 1988, which was followed by a second dreissenid, the quagga mussel (*Dreissena bugensis*) in 1989 (Mills *et al.* 1993, Bailey and MacIsaac 2000). The invasion of a predator on dreissenids, the round goby, (*Apollonia melanostoma*), was likely facilitated by the abundance of dreissenid mussels in the Great Lakes (Ricciardi 2001).

Round gobies, native to the Black and Caspian seas, spread rapidly in the Great Lakes basin after they were first reported in the St. Clair River during 1990 (Jude *et al.* 1992). They were present in all five Great Lakes a few years later (Charlebois *et al.*

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1997). Since their introduction to the Great Lakes, round gobies have also spread into several Great Lakes tributaries, three inland rivers in Michigan, an inland river in Ontario, and down the Chicago Sanitary and Shipping Canal en route to the Mississippi River (Charlebois *et al.* 2001).

It is likely that the round goby has been able to expand its range so rapidly because of its tolerance for a wide range of environmental conditions, diet, aggressive behavior, ability to spawn repeatedly throughout the spring and summer, parental care by males, and large body size compared with similar native species (Charlebois *et al.* 1997).

Round gobies have negatively impacted native fishes, dreissenids, and other benthic invertebrates. Round goby adults generally prefer rocky habitat (Ray and Corkum 2001) and have probably extirpated mottled sculpins (*Cottus bairdi*, Janssen and Jude 2001) and johnny darters (*Etheostoma nigra*) Lauer *et al.* 2004), two native species that also prefer rocky habitat. Djuricich and Janssen (2001) concluded that round gobies altered the size distribution of zebra mussels, but there were sufficient refugia from predation in crevices so that they would not eradicate them from the Great Lakes. Lederer *et al.* (2006) showed a negative relationship between round gobies and dreissenids and other invertebrates across the round goby invasion front in Green Bay, Lake Michigan.

If round gobies have a significant impact on dreissenids, they have the potential for community-wide impacts because the establishment of dreissenids in the Great Lakes has coincided with increases in water clarity, depth of light penetration, and amounts of submerged and emergent vegetation including the benthic alga *Cladophora* spp. (Lowe and Pillsbury 1995, MacIsaac 1996, Hecky *et al.* 2004). Dreissenid driven changes in energy flow from primarily pelagic to benthic have influenced benthic algal food resources and benthic invertebrate community structure (Stewart and Haynes 1994, Ricciardi *et al.* 1997, Stewart *et al.* 1998).

Lederer *et al.*'s (2006) conclusion that round gobies reduced abundances of benthic macroinvertebrates was consistent with an interpretation that round goby predation impacted the macroinvertebrates, but the research did not explicitly demonstrate cause and effect. They found that round gobies could significantly decrease benthic invertebrate densities within a 24 hour period and concluded that the negative impact on mussels was probably due to direct predation while the negative impact on the other invertebrates may be a combination of direct predation and indirect effects due to the loss of the microhabitat or food that zebra mussels provide.

Coincident with the round goby invasion, quagga mussels have become established in Green Bay (Lederer *et al.* 2006). Elsewhere they are slowly displacing zebra mussels and becoming the dominant dreissenid in the lower Great Lakes (Mills *et al.* 1999).

Studies by Barton *et al.* (2005) and Wilson *et al.* (2006) also report a decline of macroinvertebrate populations at Great Lakes sites. Wilson *et al.* (2006) examined spatial variation in Lake Ontario and Green Bay respectively, and Barton *et al* (2005) examined temporal change in northeast Lake Erie. Both temporal and spatial comparisons have potential weaknesses. For a spatial difference, the impact attributed to round gobies is confounded with other known or unknown physical and biological differences among the habitats. For example, Wilson *et al.* (2006) noted that there were also spatial differences in upwelling frequency and rocky habitat. For temporal changes, unexplained interannual variations in populations are common features of aquatic communities (Dodson 2005).

A useful aspect of the Lederer *et al.* (2006) study is that, while a spatial comparison, the round gobies appeared to have an invasion front that was moving along the eastern shore of Green Bay. This allowed us to repeat the sampling done in 2003, 3 years later, after the invasion by round gobies appeared to be complete. The objectives of this study were to re-evaluate the Green Bay, Lake Michigan, study sites used in Lederer *et al.* (2006) to examine if round gobies had invaded sites that were not invaded in 2003 and to examine changes in round goby impacts on the benthic macroinvertebrate abundances since 2003.

METHODS

Study Area

We sampled ten sites (Fig. 1) along a "peninsula transect" extending from Sturgeon Bay to the north end of the Door Peninsula along the east shore of Green Bay, Lake Michigan. This coast is rocky with dolomite talus derived from the Niagaran escarpment's west side cliffs. These were the same sites sampled in 2003 by Lederer *et at.* (2006) and cover a distance of approximately 60 km. Site 1 was at the mouth of Sturgeon Bay; the other sites were selected based on access and spatial distribution. Sites 1–4 were categorized as southern sites and Sites

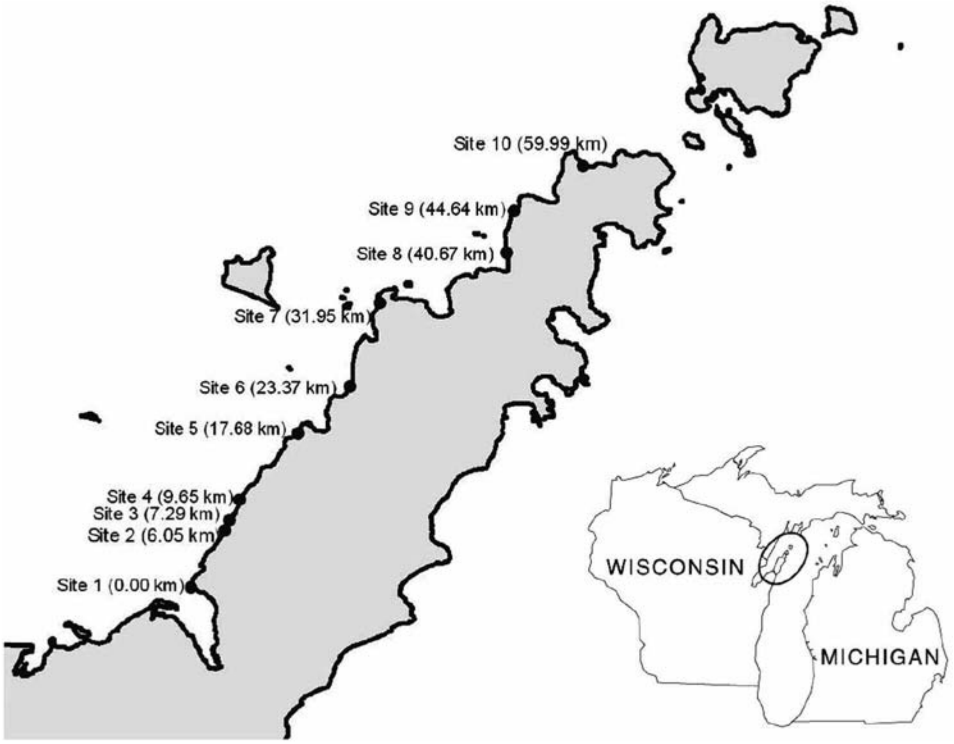

FIG. 1. Sampling sites along the northern Door Peninsula, which borders the east side of Green Bay, Lake Michigan. Southern sites (1-4) had high densities of round gobies in 2003 and 2006 while northern sites (7–10) had high round goby densities only in 2006. The invasion front in 2003 occurred at Sites 5 and 6 so these sites were excluded from the 2003 vs. 2006 comparative analyses.

7–10 were categorized as the northern sites. For comparison of changes in round goby and macroinvertebrate abundance in the northern vs. southern sites between the 2003 and 2006 data, Sites 5 and 6 were omitted because this was where the invasion front was occurring in 2003.

Round Goby Abundance

Our methods are consistent with the previous study in 2003 (Lederer *et al.* 2006). Underwater video (Sony TRV 900 digital camcorder with a Light & Motion Stingray II housing) transects were videotaped at all sites to estimate round goby relative abundance. Transect locations were chosen by measuring the total distance of shoreline at each site (50 m) and dividing that distance by the number of transects (1 transect every 10 m). For each transect, a snorkeler swam with the camera facing straight down 60–80 cm from the bottom. Round goby abundance for each site was calculated as the total number of round gobies recorded on video for all transects at that site.

Round Goby Diet Analysis

Round gobies collected from Sites 2, 5, and 10 were used for diet analysis. Total length and weight of all round gobies and abundance of other fish caught were recorded. All round gobies were preserved in 95% ethanol and taken back to the laboratory. Thirty randomly chosen round goby stomachs were examined for diet analysis. Zebra and quagga mussel shells found in the stomachs were hard to distinguish due to their small size (< 2 mm) and fragmentation. Hence, they were pooled as “dreissenids.” All other invertebrates found in round goby stomachs were identified to family. Our intent was not to detail the diet of round gobies nor compare their diets in 2003 vs. 2006, but to use the samples to find out what the fish were eating qualitatively to help determine which invertebrates on the rocks were likely impacted by the round gobies.

Macroinvertebrate Abundance

These methods are also consistent with the 2003 study (Lederer *et al.* 2006). Invertebrates were collected from all 10 study sites over 2 days (5–6 July 2006). On each of the 2 sampling days, five sites per day (randomly selected) were sampled between 11:00 a.m.–3:00 p.m. A 4-hour sampling window was allowed to control for possible variability in invertebrate spatial distribution throughout the day. At each site, snorkelers collected two rocks from a depth of 1.5–2 m. Rock selection was somewhat randomized by collecting rocks while the snorkeler's eyes were closed. Collected rocks were generally flat and a size that would fit into a 3.8-L zippered plastic bag. After each rock was collected, it was immediately placed into a plastic bag (one rock per bag) underwater and sealed to minimize sample loss. Once collected, rocks were field processed so that dreissenids were removed, placed into individual jars identified by site and sample, and preserved in 95% ethanol. Rocks (with remaining invertebrates) were preserved in 95% ethanol in the field for removal of remaining invertebrates in the laboratory.

In the laboratory, rocks were rinsed over a 212 µm sieve, and invertebrates were preserved in 95% ethanol. All samples were dyed with rose bengal to separate invertebrates from debris effectively. Chironomids and water mites were identified to family, dreissenids and all other invertebrates were identified to the lowest possible taxonomic level using standard keys (Merritt and Cummins 1996, Hilsenhoff 1995). Rock size was measured as the area of the top surface by photocopying the rock, cutting out the image, and weighing the paper image and remaining piece of paper. The area was then estimated as the percent of the total paper weight times the paper's initial area.

Statistical Analysis

Data from 2006 were compared to the data collected by Lederer *et al.* (2006) in 2003. The statistical analysis proceeded in two stages. First we compared the round goby abundance for 2003 vs 2006 along the 10-site peninsula transect to confirm that the round goby invasion front had migrated to the north tip of the peninsula. In the second analysis we compared the abundance of dreissenids and non-mussel lithophilic invertebrates at the sites deemed "round goby absent" (sites 7–10) and round goby established (sites 1–4) in 2003 (Lederer *et al.* 2006). In 2003 sites 5 and 6 were considered to be the invasion front because round gobies were absent there the previous year, but abundant at more southern sites.

To test for homogeneity in round goby abundance from Sturgeon Bay to the most northern sampling site for 2003 and 2006 we performed linear regressions (one for each year) with ln(N+1) as the dependent variable and distance from Sturgeon Bay as the dependent variable. We then compared the slopes of the two regressions using a t-test (Zar 1994).

Changes in macroinvertebrate abundance from 2003–2006 were analyzed using two-factor ANOVAs with interaction. Year (2003 vs. 2006) was one factor and the second factor was site (northern vs. southern). The dependent variables were the abundances of round gobies, dreissenids, amphipods, isopods, trichopterans, gastropods, and chironomids. As in Lederer *et al.* 2006, dreissenid, amphipod, isopod, trichopteran, gastropod, and chironomid data were densities (number per square meter) log (ln) normalized. Water mites were excluded from the comparison analysis because water mites were not collected in round goby stomachs nor enumerated from samples in 2003.

RESULTS

Round Goby Abundance

Round gobies were seen in the underwater transect surveys at all 10 study sites in 2006. In 2006, round gobies were seen within seconds of exploratory snorkeling at all sites unlike in 2003 where no round gobies were recorded on video at sites north of Site 7. In 2003 occasional small round gobies were seen during more extensive snorkeling at Sites 7 and 8, and no round gobies were seen at sites 9 and 10 (Lederer *et al.* 2006). Round goby densities are probably underestimated because some fish may have hidden under large boulders and masses of *Cladophora*.

Statistical analyses of the regressions of ln(N+1) vs distance from Sturgeon Bay indicated that, between 2003 and 2006, the distribution of round gobies had changed from one of a decrease in abundance with distance to a statistically homogenous distribution. The regression equations for round goby abundance for the 2 years were:

TABLE 1. Results of 2-way ANOVAs examining the effects of years (2003 vs. 2006), locations (north vs. south) and the location x year interaction on abundance of individuals in the respective taxon. Shown are F (P), degrees of freedom for each F ratio are 1,27.

Taxon	Rock Area	Location	Year	Location × Year
Dreissena spp.	0.05 (> 0.8)	6.6 (< 0.016)	23.6 (< 0.001)	12.5 (< 0.001)
Amphipoda	0.68 (> 0.4)	3.9 (> 0.05)	10.1 (< 0.004)	20.4 (< 0.001)
Isopoda	1.2 (> 0.28)	5.9 (< 0.025)	6.0 (< 0.025)	12.5 (< 0.002)
Trichoptera	0.16 (> 0.6)	5.7 (< 0.025)	27.7(< 0.001)	8.2 (< 0.008)
Gastropoda	0.1 (> 0.7)	23.8 (< 0.001)	20.5 (< 0.001)	15.5 (< 0.001)
Chironomidae	1.7 (> 0.2)	0.3 (> 0.5)	11.2 (< 0.002)	2.3 (> 0.1)

2003 $\ln(N+1) = 4.174 - 0.087*\text{Distance}$; $r = 0.918$, 8 df, $P < 0.001$

2006 $\ln(N+1) = 3.719 - 0.001*\text{Distance}$; $r = 0.058$, df, $P > 0.8$

The t-test comparing the two slopes was highly significant ($t = 5.84$, 16 df, $P < 0.001$). Because the slopes were statistically distinguishable, no test was made of the elevations (Zar 1994).

Round Goby Diet Analysis

The 33 round gobies collected from three sites for stomach analysis ranged from 60–109 mm total length. Site 2 averaged the smallest round gobies (n = 8, mean 66.0 mm, range 62–70 mm), and the largest round gobies were found at Site 5 (n = 24, mean 76.2 mm, range 60–109 mm). One round goby was collected from Site 10 (71.0 mm).

The number of prey items found in the stomachs ranged from 0–51 (mean = 15). Three round goby stomachs (from Site 2) did not contain prey items and were excluded from the analysis. Prey items were partly digested. However, macroinvertebrate exoskeletons were identifiable. The most common prey items were: chironomids (51.4% of total prey items found), amphipods (21.2% of total prey items found), isopods (13.0% of total prey items found), dreissenids (5.1% of total prey items found), trichopterans (6.5% of total prey items found), diptera (0.4% of total prey items found), and gastropods (0.4% of total prey items found).

Round Goby and Macroinvertebrate Abundance: 2003 vs. 2006

The two-way ANOVA's for all of the invertebrate taxa except chironomids had highly significant year x site interactions (Table 1). Rock areas ranged from 6220 to 13776 cm^2 with no statistically detectable differences among locations or years ($F_{1,29} = 0.73$, $P > 0.4$ for location and $F_{1,29} = 0.2.1$, $P > 0.15$ for year). There was no effect of rock area on numbers of individuals for any of the taxa (Table 1). For chironomids, there was a significant difference between years with abundances higher in 2006 than in 2003 (Table 1). The means for both zones (north and south) were pooled over the two years. In 2003, the mean for chironomids was 12.0 (south = 9.2, north = 15.7). In 2006, the mean was 33.5 (south = 24.5; north = 45.6). Significant interactions for the other taxa mean that interpretation of the main effects is not meaningful (Zar 1994) and the individual year × site cells must be compared via a post-hoc test. The results of the Tukey tests indicated significantly greater abundances of each taxon at the 2003 northern (round goby free) cell compared to the other cells (2003 south, 2006 south, and 2006 north, all of which had high densities of round gobies (Table 2).

DISCUSSION

The round goby abundance gradient observed in 2003 was no longer evident by 2006 (Fig. 2). Round gobies had moved into and established significant numbers in all ten study sites such that their densities along the 60 km transect were now spatially statistically uniform. This expansion may have been accelerated by decreases in prey items, specifically dreissenids, at the previously invaded southern sites. As round goby populations increased at these sites, the amount of food may have decreased, resulting in migration or expansion into the northern sites.

Diggins *et al.* (2002) found that round gobies selected amphipods over mussels on physically simple substrate in the laboratory, and total consumption increased when amphipods were offered. Round goby stomach contents at our study

TABLE 2. Comparison of means for invertebrates on rocks. Location × year cells that were not statistically distinguishable are underlined. For those invertebrates with a significant location x year interaction (Table 1) a post-hoc Tukey test was used. For Chironomidae the location × year interaction was not significant while the year effect was significant (Table 1). Mean number of animals per rock (mean + se, mean-se) are reported. Means and (+) and (–) standard errors were first calculated using log transformed data, these statistics were the n detransfomed for reporting. Underlining indicates no significant difference (P > 0.15). For Dreissena, *Amphipoda, Isopoda, Trichoptera, and Gastropoda the North 2003 cell was significantly greater than the other three cells (P < 0.004 or less) while South 2003, North 2006, and South 2006 are statistically indistinguishable. For Chironomidae only the year effect was significant (P < 0.002, Table 1).*

Taxon	North 2003	South 2003	North 2006	South 2006
Dreissena spp.	15.3 (12.0, 19.4)	1.6 (1.3, 2.1)	0.6 (0.4, 0.9)	1.1 (0.7, 1.7)
Amphipoda	2.0 (1.4, 2.7)	0.25 (0.19, 0.32)	0.16 (0.13, 0.19)	0.39 (0.26, 0.57)
Isopoda	4.6 (3.4, 6.4)	0.33 (0.25, 0.44	0.37 (0.22, 0.62)	0.54 (0.34, 0.86)
Trichoptera	1.46 (1.2, 1.8)	0.44 (0.34, 0.56)	0.17 (0.13, 0.22)	0.26 (0.21, 0.34)
Gastropoda	0.60 (0.46, 0.80)	0.13 (0.11, 0.15)	0.11 (0.10, 0.13)	0.12 (0.11, 0.13)
Chironomidae	16.5 (16.5, 20.5)	8.7 (6.6, 11.4)	2.9 (2.0, 4.3)	3.8 (3.0, 4.8)

sites are comparable to those reported by Barton *et al.* (2005) in Lake Erie, where prey consisted of fewer *Dreissena* and more non-dreissenid species in 2004 than in 2001.

Our comparison between 2003 and 2006 indicated that as round gobies invaded new sites, there were significant declines in macroinvertebrates. In this system, and others, round gobies are associated with significant decreases in most invertebrate populations (Lederer *et al* 2006, Barton *et al.* 2005). When round goby abundances are high, invertebrate abundances tend to be low. Our between-year results are comparable to Barton *et al.* (2005) who found that zebra and quagga mussels, and two types of amphipods (*Gammarus fasciatus* and *Echinogammarus ischnus*), decreased significantly over 4 years in Lake Erie. Barton *et al.* (2005) also concluded that round gobies reduced the dreissenid population and consequently increased the vulnerability of other prey items to round goby predation.

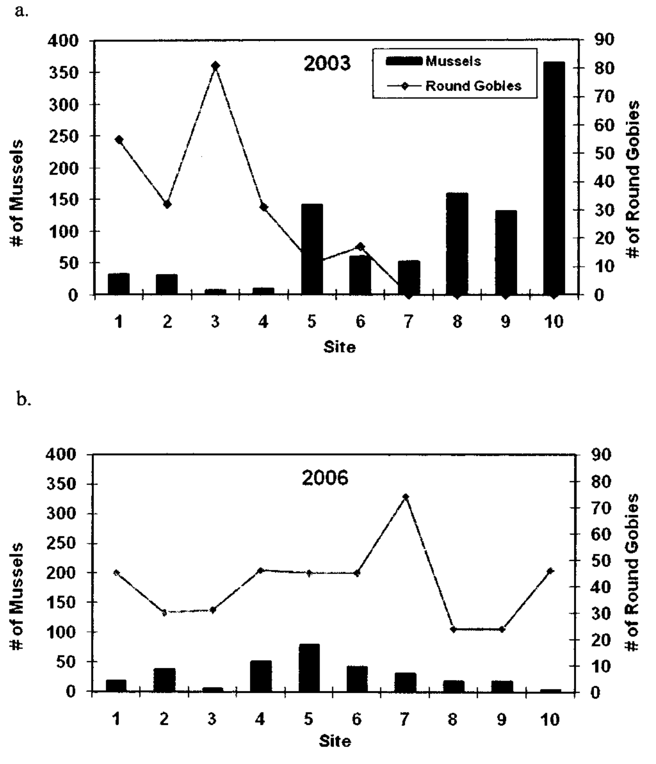

FIG. 2. Round goby and dreissenid abundance at study sites in 2003 (a) and 2006 (b).

The results of our work are consistent with our hypothesis that as round gobies invade areas they have negative impacts on the benthic macroinvertebrate populations. These negative impacts result from predation but also from indirect effects. For example dreissenid populations declined significantly between 2003 and 2006. Decreases in zebra and quagga mussels in all study sites decreased habitat complexity for other invertebrates that inhabit the crevices around dreissenids. Also decreases in this type of habitat may allow mobile organisms to become more vulnerable to predation by round gobies. Clearly no single impact of round goby invasion controls macroinvertebrate populations. Diggins *et al.* (2002) found that added substratum complexity reduced round goby predation on mobile amphipods which sought refuge in crevices and other irregular microhabitats. Similarly, Gonzalez and Downing (1999) reported that habitat complexity provided by zebra mussels could reduce amphipod predation risk. Reduced substrate complexity, due to elimination of zebra and quagga mussels, reduced opportunities for refuge for many types of mobile macroinvertebrates. Indeed, our findings are consistent with the findings of Barton *et al.* (2005) that predation by round gobies on dreissenid mussels was correlated with reduced abundances of non-dreissenid macroinvertebrates in eastern Lake Erie over 4 years.

This study complements work done Lederer *et al.* (2006) and Barton *et al.* (2005) and provides further evidence that the invasion of round gobies into Lake Michigan, as well as other lakes, has the potential to change trophic interactions of littoral benthic communities. Changing the benthic trophic structure by the introduction of round gobies alters amphipod, isopod, dreissenid, trichopteran, and other taxa group abundances in an ecosystem like that of Green Bay, Lake Michigan, and other Laurentian Great Lakes. Our study investigates the long-term effects of round gobies on macroinvertebrate abundances after invasion, and is an approach that can be applied to other studies attempting to examine long-term effects of similar invasive species.

ACKNOWLEDGMENTS

This work was funded by the University of Wisconsin Sea Grant Institute under grants from the National Sea Grant College Program, National Oceanographic and Atmospheric Administration, U. W. Department of Commerce, and from the State of Wisconsin, Federal grant number #144-NR79, project numbers #R/AI-1 and #R/LR-93. I would like to thank Zach Zopp, David Bloomstrad, and Chris Malinowski for assistance in data collection in addition to the Great Lakes WATER Institute for supplying technical equipment.

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Submitted: 23 September 2007
Accepted: 7 May 2008
Editorial handling: Thomas F. Nalepa