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ABSTRACT. Round gobies were first discovered in the Duluth-Superior Harbor, Lake Superior, in 1995. Anecdotal sightings by anglers and others suggested that the infestation was growing and expanding; however, direct evidence of the distribution and expansion rate in the harbor was largely unknown. Distribution and range of the round goby, *Apollona melanostoma*, (formerly *Neogobius melanostomus*) was assessed using bottom trawl sampling throughout the Duluth-Superior Harbor, and portions of the lower St. Louis River from 1998 to 2004. Previous to 1998, round gobies only were reported to occupy the harbor between the two shipping entries (river kilometer 1 to 7). By 2004, they expanded throughout the harbor and upstream to river kilometer 13, but remained absent in western Lake Superior. The number of round gobies captured per 5 minutes of trawling (catch per unit effort, CPUE) increased from less than 1 fish in 1998 to an average 5.4 ± 1.2 SE fish in 2004, indicating a large increase in the population. The median yearly fish total length varied from 56.0 to 81.5 mm and wet weight varied from 2.3 to 7.0 g. As nest guarding male round gobies were located in rocky habitats inaccessible to trawling, the initial years were dominated by female round gobies with a 16:1 female to male ratio, but by 2002 the maximum ratio was 2:1. The ratio change may be indicative of the increasing population forcing males from their preferred rocky habitat onto open substrates that were more accessible to trawling.

INDEX WORDS: Aquatic invasive species, round goby, Lake Superior, teleost, *Neogobius melanostomus*.

INTRODUCTION

Resilience of the round goby (*Apollona melanostoma*, formerly *Neogobius melanostomus*; see Stepień and Tumeo 2006) is evidenced by its ability to survive trans-Atlantic voyages in ballast water from its native Caspian Sea (Jude et al. 1992, Charlebois et al. 1997). Within 5 years of the initial sighting in 1990 in the St. Clair River, round gobies had expanded to all the Laurentian Great Lakes (Jude 1997). Commercial ships carrying contaminated ballast water continue to aid the expansion of the round gobies throughout the Great Lakes, leading to widespread colonization and permanent establishment (Weimer and Keppner 2000, Clapp et al. 2001, Hoyle and Schaner 2001, Hensler and Jude 2007). Round goby populations are increasing in many ports, and dispersing from these initial loci into surrounding watersheds (Phillips et al. 2003) and deeper, offshore waters (Schaeffer et al. 2005).

Although direct predation on juvenile and adult native fishes appears uncommon (Shaeffer et al. 2005), round gobies threaten native benthic fish through resource competition and behavioral exclusion (Jude et al. 1995, Jude 1997, Janssen and Jude 2001, Balshine et al. 2005) in the Great Lakes. There is substantial dietary overlap between juvenile round gobies, sculpins (*Cottus*), and darters.

Round gobies prefer crevices among hard substrates, placing them in direct competition with native benthic species for habitat and spawning area (Jude and DeBoe 1996, Charlebois et al. 1997, Jude 2001, Ray and Corkum 2001). High round goby density coupled with aggressive behavior (Jude 2001, Ray and Corkum 2001) has the potential to negatively impact benthic species. Recent reports of round gobies in offshore regions at water depths up to 70 m could potentially impact deeper water species (Schaeffer et al. 2005).

Although the rapid expansion of the round goby throughout the Great Lakes presumably through anthropogenic dispersal is well documented (Clapp et al. 2001, Schaeffer et al. 2005), it is not clear how quickly round gobies will expand from a single locus. Round goby invasion fronts have been noted to shift greater than 20 kilometers over a 3-yr period, with expansion rates of up to 14 kilometers in a single year (Lederer et al. 2006, 2008). Round gobies were captured up to 34 kilometers off shore in Lake Huron with indications they may have migrated this far within 5 years (Schaeffer et al. 2005). Surveys in Lake Michigan found round gobies up to 45 kilometers from their most likely origin (Clapp et al. 2001). However, simultaneous ship introduction can seed large areas with round gobies over a short period of time and makes it difficult to separate natural dispersion from accidental introduction.

The United States Geological Survey (USGS) conducted a long-term monitoring program in the Duluth-Superior Harbor on another invasive fish, the Eurasian ruffe (Gymnocephalus cernuus). Round gobies began to constitute a sizeable by-catch during the Eurasian ruffe project in 1998 and provided a unique opportunity to follow the expansion of a relatively recent aquatic invasive species from a limited point source both upstream into the St. Louis River and potentially into Lake Superior.

MATERIALS AND METHODS

Study Area

The St. Louis River is the second largest tributary to Lake Superior and empties into an approximately 4,800 ha estuary (Breneman et al. 2000). The Duluth-Superior Harbor is situated at the river’s terminus and is separated from Lake Superior by sandbars along Superior and Allouez bays. Two narrow shipping channels connect the harbor to Lake Superior (Fig. 1). Bracketed by these entries, Superior Bay extends to river kilometer 7, and the St. Louis Bay extends to approximately river kilometer 12. Within the lower harbor, shipping channels are dredged throughout ice-free months. Areas

FIG. 1. Map of the lower St. Louis River and the Duluth-Superior Harbor with A) 20 Ha sampling quadrants superimposed and B) River kilometers indicated by solid circles. Scale bar = 2 km.
sampled in the current study included Allouez, Superior, St. Louis, and Pokegama bays, and the southwestern portion of Spirit Lake (approximately river kilometer 20). Bottom substrates in these areas consisted of flats, undredged channels, and dredged channels. The flats (62.5% of the total sampled area) were shallow (< 3 m) and relatively undisturbed by shipping traffic. The undredged channels (17.5%) ranged from 3 to 7.5 m in depth and consisted of natural or former shipping channels. Dredged channels (20%) included manmade channels and large dock slips that were maintained at depths between 6 to 15 m. The shoreline is variable throughout the harbor and estuary, ranging from high anthropomorphic impact (sea walls, breakwaters, pilings) to relatively pristine back bays. The terminal 10 km of the St. Louis River, outside of the shipping lanes, is characterized by large tracts of rocky bottom, active and abandoned dock structures, and large numbers of submerged, manmade objects. Thus there is an abundance of hard substrate to facilitate round goby spawning (Table 1).

**TABLE 1. Aquatic habitat types of the lower St. Louis River.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Major Features</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allouez Bay</td>
<td>Clay-influenced bay</td>
<td>Clay with organic layer</td>
</tr>
<tr>
<td>Duluth-Superior Harbor</td>
<td>Low estuary (industrial harbor)</td>
<td>Variable, high dredging activity, substrates include slag, wood fill and wood slabs</td>
</tr>
<tr>
<td>Superior Entry to Grassy Point (River Kilometer 0 to 11)</td>
<td>Industrial influenced bays</td>
<td>Sand clay bottom cluttered with industrial debris</td>
</tr>
<tr>
<td></td>
<td>Low estuarine dredged river channel</td>
<td>Sand and clay</td>
</tr>
<tr>
<td></td>
<td>Industrial slips</td>
<td>Firm substrate with much debris</td>
</tr>
<tr>
<td>Grassy Point to Spirit Lake (River Kilometer 11 to 20)</td>
<td>Upper estuary flats</td>
<td>Considerable sand with other fine sediment and organic material</td>
</tr>
<tr>
<td></td>
<td>Clay influenced river mouths (Wisconsin shore)</td>
<td>Firm clay with organic material</td>
</tr>
<tr>
<td></td>
<td>Sheltered bays</td>
<td>Variable, some boulders, most have organic layer over firm clay and sand</td>
</tr>
</tbody>
</table>


Bottom Trawls

Bottom trawls were conducted during the spring (mid May to early June), summer (mid July), and fall (mid to late September) from 1998 through 2004. The harbor was sectioned into 20 ha quadrants (n = 216) and a random number program (Fig. 1A) selected 120 (~55%) of these sites for sampling each year. Each selected site randomly was assigned a season (spring, summer, or fall) to be sampled. No quadrant was sampled more than once per year. Eight quadrants were not sampled in the fall of 2004 due to equipment failure. Sampling was conducted with a semi-balloon bottom trawl (5.5 m head-rope and foot-rope, 2.5 cm stretch-mesh body, 6.4 mm stretch-mesh cod end) that was trawled at 2.5 km/hr for approximately 5 minutes per sample. Approximately 50% of the round gobies captured each year were measured (total length) and weighed. The gender of each round goby was determined when possible by examination of the genital papillus, which is pointed in mature males and flat in mature females. The sex of small, immature, or non-reproductive fish usually was not discernable. Catch per unit effort (CPUE) was standardized to the number of round gobies captured per 5 minutes of trawling.

**Statistical Analysis**

All statistical analysis was performed using SigmaStat (Systat Software, Inc. 2004 version 3.10). Round goby size and CPUE each year were tested for normality using the method of Kolmogorov and Smirnov. As both data sets failed the normality test, Kruskal-Wallis One Way Analysis of Variance on
FIG. 2. CPUE of the round goby in the St. Louis River estuary, 1998-2004. Bars represent the sampled quadrants during each year of the study, corresponding to the grid in Figure 1A. Open squares indicate the absence of round gobies in the quadrant and filled squares or bars indicate the catch per unit effort (CPUE: fish per 5 minutes of trawling).
RESULTS

During the first year (1998), round gobies were captured near the Superior Entry of the harbor (river kilometer 1) and south of the Duluth Entry, at river kilometer 7 (Fig. 2A). From 1998 through 2003, round gobies extended their range southeast into Allouez Bay and upstream to river kilometer 11 (Fig. 2B-F). By 2004 round gobies reached river kilometer 13, near the southern portion of St. Louis Bay (Fig. 2G). Although the maximum rate of round goby expansion upstream was approximately 1.0 km/year from 1998 through 2004 based on round goby movement from river kilometer 7 to 13, the population center only shifted 1.5 kilometers (river kilometer 2.5 to 4.0) during this time period (Fig. 3).

The mean CPUE (fish per 5 minutes of trawling) showed a slight, but not statistically significant, increase from 1998 (0.5 ± 0.2 SE) through 2003 (1.8 ± 0.6 SE) before increasing significantly to 5.4 ± 1.2 SE in 2004 (Kruskal-Wallis, $p < 0.001$; $H = 42.5$, $DF = 6$; Fig. 4). The length and weight of fish captured during 1998 and 1999 were significantly larger [Kruskal-Wallis, $p < 0.05$; (length: $h = 129.3$, $DF = 6$), (weight: $h = 87.2$, $DF = 6$)] than succeeding years, (Fig. 5). Size remained relatively steady throughout the remainder of the study except for a significant decrease in 2001 (Kruskal-Wallis, $p < 0.05$; Figs. 4, 5). The ratio of female to male round gobies declined from a high of 16:1 in 1998 to approximately 2:1 by the end of the study (Fig. 6). There was a significant negative correlation between year and percent female ($r = -0.94$, $n = 7$, $p < 0.005$).

DISCUSSION

Invasion of the round goby into the Duluth-Superior Harbor presented a unique opportunity to monitor the spread of an invasive species from a limited point source upstream into the St. Louis River and Estuary. While the number of round goby releases into the harbor is unknown, sampling showed a contiguous spread of the round goby throughout the study. The continual range expansion of the round gobies will put adjacent waterways, including Lake Superior, at risk.

The Duluth-Superior Harbor and lower St. Louis River are bay-like with little sustained current between river kilometer 0 to 22 (Bronte et al. 1998).
As round gobies do not exhibit strong, sustainable swimming abilities (Skora 1996), the relatively calm waters of the harbor and estuary may represent optimal conditions for upstream migration. Although the first physical barrier in the St. Louis River is not until the Fond du Lac dam at river kilometer 32, the river is characterized by relatively high water velocity (St. Louis River Citizens Action Committee 2002) beyond kilometer 22 and will provide an opportunity in future years to examine the effects of current on upstream migration.

However, the leading vanguard of the round goby population only progressed upstream 6 kilometers during the study. The center of the population progressed slower, displaying a 1.5 kilometer shift upstream (river kilometer 2.5 to 4.0). The Duluth-Superior Harbor is characterized by heavy human impact and hard substrate abounds in the form of manmade structures and debris providing ideal round goby habitat. However, near Grassy point (~ river kilometer 11), the industrial landscape gives way to upper estuarine flats, sheltered bays, and clay influenced river mouths that lack high concentrations of hard substrate. The estuarine flats and sheltered bays both contain abundant vegetation which may provide shelter for the round gobies equivalent to Allouez Bay, where round gobies have dispersed. It remains to be determined if sufficient substrate exists to support breeding in Allouez.

![FIG. 5. Length frequency distributions (percentage) of round gobies from 1998 through 2004. Data were binned in 10 mm increments.](image)

![FIG. 6. The proportion of female round gobies per year. Each data point represents the arcsine transformation of the percentage of females capture per year. The solid line represents a linear regression through the data. r² = 0.88](image)
Bay or the upper estuarine flats. Therefore, the relatively slow dispersal of the round goby upstream may be due to lack of suitable habitat. Alternatively, the round gobies may still be colonizing suitable habitat in the harbor and if the population continues to increase, as in other areas of the Great Lakes, upstream expansion may accelerate.

Although the presence of the round gobies in the Duluth-Superior Harbor placed them within meters of expanding into Lake Superior, trawls outside the harbor failed to detect round gobies prior to 2005 (Ashland FRO 2006, unpublished). The abundance of zebra mussels, Dreissena polymorpha, other benthic invertebrates (Breneman et al. 2000), and man-made structures throughout the harbor probably provided more suitable habitat than the oligotrophic lake. Additionally, a reproductive population of zebra mussels has not been documented outside of the harbor (D. Jensen, Minnesota Sea Grant, personal communication) and a lack of food preferred by adult round gobies may limit the round goby spread into the lake.

Despite a decade of remaining within the confines of the Duluth-Superior Harbor, round gobies finally have been detected in western Lake Superior. A single round goby was captured in 2006 in the Amnicon River, Wisconsin (Ashland FRO 2006, unpublished), which is approximately 14 kilometers east of the Superior Entry of the harbor. The southeastern expansion of the round goby range into western Lake Superior is consistent with the prevailing counter-clockwise currents at the western edge of the lake (Beletsky et al. 1999). Whether these currents are responsible for the relatively rapid (7 km/year) egress into Lake Superior perhaps due to round goby larval transport (Hensler and Jude 2007), human transportation (i.e., bait buckets), or they are the vanguard of a very small population that eluded detection for several years remains to be determined. Preliminary sampling along the North Shore of Lake Superior, primarily in Two Harbors, Minnesota, has failed to detect round gobies (Bergstrom and Mensinger, unpublished), suggesting that the currents may impede round goby movement to the northeast.

Clapp et al. (2001) demonstrated angling was more successful at attaining round gobies larger than 70 mm which may often be underestimated in surveys. With large and/or nest guarding males not readily accessible for bottom trawling, our data must be considered as conservative estimates of population size. The large increase in CPUE in 2004 indicates that the population is expanding. As non-reproductive and female round gobies are chased away by nest guarding males from hard substrate (Wickett and Corkum 1998), it was not surprising that the trawls, which were predominantly conducted over soft sediment, found a female to male ratio of 16:1 in the initial year of the study. However, the ratio stabilized around 1:1 (range 51 to 64 % female/male) in the last 3 years of the study. This may be indicative of large males now saturating the optimal habitat and forcing smaller males into the unstructured flats and channels.

The round goby invasion in the Duluth-Superior Harbor provides insight on the expansion of an invasive species from an initial location. This species was presumably brought to the harbor through ballast water discharges, and has been able to colonize the area due to abundant food and habitat. Round gobies exhibited a continual expansion throughout the harbor and estuary from 1998–2004. Once established, round goby populations thrive and challenge resident fish for resources (Thomas 1997, French and Jude 2001, Carman et al. 2006, Lederer et al. 2006), habitat (Jude and DeBoe 1996, Ray and Corkum 2001), and nesting territories (Janssen and Jude 2001). This study provides a foundation for continuous monitoring of an invasive species from a single locus. The rate of expansion is modest and may allow fisheries managers to predict the spread into other similar estuaries or rivers emptying into the Great Lakes.

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