Age and growth of round gobies in Lake Huron: implications for food web dynamics

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Abstract: Although the round goby (*Neogobius melanostomus*) has become established throughout the Laurentian Great Lakes, information is scarce on spatial variation in round goby growth between and within lakes. Based on a sample of 754 specimens captured in 2014, age, growth, and mortality of round gobies at four locations in Lake Huron were assessed via otolith analysis. Total length (*TL*) of round gobies ranged from 44 to 111 mm for Saginaw Bay, from 45 to 115 mm for Rockport, from 50 to 123 mm for Hammond Bay, and from 51 to 118 mm for Thunder Bay. Estimated ages of round gobies ranged from 2 to 5 years for Saginaw Bay, from 2 to 6 years for Rockport, and from 2 to 7 years for Hammond Bay and Thunder Bay. Sex-specific, body-otolith relationships were used to back-calculate total lengths at age, which were then fitted to von Bertalanffy growth models. For each sex, round goby growth showed significant spatial variation among the four locations within Lake Huron. At all four locations in Lake Huron, males grew significantly faster than females and attained a larger asymptotic length than females. Annual mortality rate estimates were high (62 to 85%), based on catch-curve analysis, suggesting that round gobies may be under predatory control in Lake Huron.

Index words: Age structure; Mortality; Round goby; Spatial variation in growth; Top-down control

Introduction

Not only do species invasions motivate extensive concern over their effects on native species and ecosystem function, but invasive species can become important components of the Laurentian Great Lakes food webs (Charlebois et al., 2001).

Invasive species can influence food web dynamics by competing with native fauna for space or by interfering with natural reproduction of native species (Charlebois et al., 1997; MacInnis and Corkum, 2000a; Ruiz et al., 1997). Although negative effects of aquatic invaders are often highlighted in the scientific literature (Charlebois et al., 1997; MacInnis and Corkum, 2000a; Rodriguez, 2006), aquatic invaders may also become an important food resource for native fauna (Crane et al., 2015). Once a new species becomes established, it is essential to attempt to understand its complex role within the ecosystem as changes in the abundance of the new species can have a variety of ecosystem effects (Zavaleta et al., 2001). Additionally, research on established populations of non-native species can answer fundamental questions in ecology and guide future control methods and effective maintenance management (Simberloff, 2003).

The first record of the round goby (*Neogobius melanostomus*) invasion of the Laurentian Great Lakes basin was the capture of round gobies in the St. Clair River in 1990 (Jude et al., 1992). Since that time, the invasive round goby has become well established in four of five Laurentian Great Lakes and has become a significant component of their food webs (He et al., 2015; Johnson et al., 2005; Kornis et al., 2012). Predicted ecological effects induced by the round goby invasion include the exclusion of native benthic fish species due to competition for spawning space,

habitat and dietary resources (French and Jude, 2001; Janssen and Jude, 2001; Jude et al., 1995; Jude, 1997), predation on eggs and fry of native fishes (Chotkowski and Marsden, 1999; Phillips et al., 2003; Steinhart et al., 2004), support of piscivore biomass by providing an alternative energy source (Dietrich et al., 2006; He et al., 2015; Madenjian et al., 2011; Pothoven and Madenjian, 2013; Truemper and Lauer, 2005), and serving as a conduit to funnel dreissenid energy production to upper trophic levels of the food web (Johnson et al., 2005). Nevertheless, much more research is needed to fully determine the extent of these and other predicted ecological impacts of round gobies on food webs of the invaded aquatic ecosystems.

Knowledge of life-history variables, such as age composition, growth and mortality rate, is essential for predicting long-term effects of nonindigenous species on food webs and for establishing practical management policies to control non-native species (Veitch and Clout, 2002). Previous studies on round goby age and growth within invaded ecosystems indicated that size within an age group was highly variable and males grew faster and attained a larger maximum size than females (French and Black, 2009; Gümüs and Kurt, 2009; MacInnis and Corkum, 2000a, 2000b; Phillips et al., 2003; Sokołowska and Fey, 2011; Taraborelli et al., 2010). Moreover, life-history characteristics were found to vary over time and space. With regard to time, Grul'a et al. (2012) reported that round gobies in the middle Danube River allocated energy resources to reproduction and offspring care in newly established populations, which were characterized by negative allometric growth. However, in longer established populations there was positive allometric growth which resulted in a shift in allocation

towards somatic growth. Lynch and Mensinger (2013) determined that round gobies in Duluth Harbor of Lake Superior demonstrated maximum growth in July and August and almost no growth between October and March. With regard to space, Huo et al. (2014) reported that round goby growth showed significant spatial variation within Lake Michigan. Round gobies at Sleeping Bear Dunes and Waukegan grew significantly faster than those at Sturgeon Bay.

Available information on round goby mortality rates in the Laurentian Great Lakes is limited. Round gobies experienced an annual mortality of 0.33 in the Duluth Harbor, while estimated annual mortalities ranged from 0.26 to 0.44 in Hamilton Harbour of Lake Ontario (Lynch and Mensinger, 2013; Vélez-Espino et al., 2010). Bunnell et al. (2005) reported that the annual mortality rate of round gobies in open waters of the central basin of Lake Erie was 0.62, while Huo et al. (2014) showed that estimated annual mortality rates of round gobies in three locations of Lake Michigan varied from 0.79 to 0.84. To date, growth rates and mortality rates for round gobies in Lake Huron have not been investigated.

The primary goal of our study was to determine whether round goby growth showed significant spatial variation among four different locations of Lake Huron. The secondary goal of our study was to estimate round goby mortality rates for Lake Huron. Our specific objectives were to: (1) age round gobies from four different locations of Lake Huron using otoliths, (2) establish a back-calculation formula and then back-calculate total lengths at age for use in growth analyses, (3) compare growth among the four locations, (4) compare growth between the sexes, and (5)

estimated mortality rates at the four locations using catch-curve analysis.

Materials and methods

We primarily relied on routine annual sampling to obtain round gobies from Saginaw Bay, Thunder Bay, and Rockport in Lake Huron during 2014, but we also conducted some supplementary sampling at Hammond Bay to obtain additional round gobies (Fig. 1). The Michigan Department of Natural Resources conducts a bottom trawl survey of Saginaw Bay and Thunder Bay each year, whereas the U. S. Fish and Wildlife captures round gobies from Rockport each year using minnow traps. Round gobies were captured using minnow traps deployed at depths ranging from 3 to 20 m at Rockport and Hammond Bay during August and September 2014, while round gobies were caught using bottom trawl towed at depths ranging from 20 to 27 m in Thunder Bay during July and August 2014 and at depths between 11 and 12 m in Saginaw Bay during September 2014. All bottom trawling was conducted over soft bottom areas of the lake. At Rockport, minnow traps were placed over silty or sandy areas adjacent to large boulders used to construct the pier. In Hammond Bay, the bottom substrate consisted of a mix of silt, sand, rock cobble, and a few large rocks. All fish were immediately frozen and transported back to the laboratory. After specimens were thawed, total length (*TL*) was measured to the nearest 1 mm. All individuals were sexed based on shape of the urogenital papilla (Kornis et al., 2012).

Both sagittal otoliths were extracted from each fish, washed with ethanol, air-dried, and then stored in labeled test tubes. Typically, left otoliths were prepared for age estimation by cutting, grinding, and polishing according to the method of Huo

et al. (2014). Age was estimated by counting annuli on the otolith using a microscope at $\times 100$ magnifications under transmitted light. Three readers with no prior knowledge of the length, sex, or time of capture of the fish participated in age estimation. All ages were determined by two of the three readers. If both readings were in agreement, the agreed-upon age was assigned to the round goby. If the two readings differed, then the otolith was read by the third reader. If the third reading did not agree with either of the other readings, then no age assignment was made for that fish. If the third reading agreed with one of the previous two readings, the age for which there was agreement was assigned to that fish.

A digital picture of each otolith was taken using an Olympus BX51 photo-microscope, and then otolith radius (OR) was measured as described by Huo et al. (2014). Measurements to the nearest 0.001 mm were carried out using Image Pro Plus V6.0 software on a personal computer. The relationship between $\log_{10}$ -transformed total length (TL) and $\log_{10}$ -transformed otolith radius was characterized using simple linear regression, and we refer to this relationship as the body-otolith relationship in discussions below.

We used back-calculation based on the body proportional hypothesis (Francis, 1990) to reconstruct the growth history of each round goby. The ratio of the otolith radius at one age to the otolith radius at another age is a function of the fish length at these two ages, and this function could be linear or nonlinear (Francis, 1990).

Preliminary analysis of total length-otolith radius data revealed that logarithm of total length was linearly related to logarithm of otolith radius. Thus, we

back-calculated round goby total length using the following relationship:

$$\log_{10}(TL_n) = \log_{10}(TL) + a \times (\log_{10}(OR_n) - \log_{10}(OR))$$

where TL_n , total length at annulus n ; TL , observed total length; OR_n , otolith radius at annulus n ; OR , otolith radius; a , the slope of the linear function between logarithm of total length and logarithm of otolith radius. To avoid the potential for autocorrelated growth increments of an individual fish, we only back-calculated total lengths at the ages corresponding to the two most recent annuli on the otolith for each fish. In addition, Francis (1990) recommended that total lengths be back-calculated under both the body proportional and structure size proportional hypotheses, and results be compared to check on the robustness of the back-calculation procedure. Following the advice of Francis (1990), we back-calculated total lengths for the round gobies under both hypotheses, although we present only the results from the body proportional hypothesis in this paper. Growth curves and inferences regarding differences in growth between sexes and locations were similar for both hypotheses, indicating that our conclusions were robust to the back-calculation procedure. Our back-calculation procedure was based on the implicit assumption that the proportional relationship between total length and otolith radius was consistent throughout the fish's lifetime, including its embryonic development phase. Thus, the biological intercept, as defined by Campana (1990), was assumed to occur at total length equal to zero and otolith length equal to zero. Measurements of total lengths and otolith lengths by Azour et al. (2015) of round gobies from the Baltic Sea, over a wide range of round goby sizes, suggested that this assumption was valid.

For each combination of location and sex, simple linear regression was used to estimate the slope of the body-otolith relationship. In addition, we used analysis of covariance (ANCOVA) to determine if slopes of the body-otolith relationship differed between sexes at each of the four locations. For each sex, we also used ANCOVA to determine if slopes of the body-otolith relationship differed among the four locations. For each ANCOVA model, $\log_{10}(TL)$ was the dependent variable, sex or location was the treatment effect, $\log_{10}(OR)$ was the covariate, and the interaction between the treatment effect and the covariate was also included in the model. The F test for significance of the interaction term was equivalent to the F test for equality of slopes. Analyses were carried out using SPSS 16.0 (Chicago, IL) and Lab Origin pro 8.0 (Originlab, Northampton, MA). We set $\alpha = 0.05$ for all of our statistical testing.

If, for a given sex, the above-mentioned testing for equality of slopes indicated that the slopes did not significantly differ among the four locations, the interaction term was eliminated from the ANCOVA model. We then used the F test for significance of the location effect as a test for equality of the intercepts among the four locations. If intercepts significantly varied among the four locations, the ANCOVA model with location as the treatment effect and $\log_{10}(OR)$ as the covariate was used to estimate the value of the slope, a , and this value was used to back-calculate total lengths for round gobies from all four locations. On the other hand, if testing for equality of intercepts revealed that the intercepts did not significantly vary among the four locations, data from all four locations were pooled, and simple linear regression analysis was applied to $\log_{10}(TL)$ as a function of

$\log_{10}(OR)$. The estimate of the slope, a , was then used to back-calculate total lengths for round gobies from all four locations. If the above-mentioned testing for equality of slopes indicated that the slopes did significantly vary among the four locations, we applied simple linear regression analysis to $\log_{10}(TL)$ as a function of $\log_{10}(OR)$, by location, to estimate a for each location. Then, the estimate of a was used to back-calculate total lengths.

For each combination of location and sex, a von Bertalanffy growth model was fitted to total lengths calculated from the above equation. A Gauss-Newton nonlinear regression algorithm was used to estimate parameters in the von Bertalanffy growth model. The likelihood ratio test, as described by Quinn and Deriso (1999), was used to determine whether fitted von Bertalanffy growth models differed significantly between sexes for each of the four locations. In addition, for each sex, we tested for pairwise differences in fitted von Bertalanffy growth models among the four locations of Lake Huron using likelihood ratio tests, and a Bonferroni correction was applied to these six pairwise comparisons among locations.

Catch-curve analysis was used to estimate round goby mortality rates at the four locations of Lake Huron (Ricker, 1975). We first determined age at which round gobies were fully recruited to the sampling gear by examining the catch curves for each location (Quinn and Deriso, 1999; Ricker, 1975), and then we used the right truncation method to exclude old age groups, with catches less than 5 from the data sets of each location due to the extreme variation that could be introduced by the collection of, or failure to collect, a few individuals (Smith et al., 2012; Van Den

Avyle and Hayward, 1999). Simple catch curves were used for the four locations because round gobies were sampled for just 1 year (2014) in all four locations (Ricker, 1975). If sufficient data were available, simple linear regression was used to fit a regression line to $\log_e$ -transformed catch-at-age as a function of age. Simple linear regression yielded an estimate of instantaneous mortality rate Z , and annual survival S is equal to e^{-Z} . However, if only two data points were available on the descending limb of the catch curve, we simply calculated the ratio of catch at the older age to peak catch to estimate annual survival. Annual mortality is equal to $1 - S$. Variance of the annual survival estimate was calculated by the delta method (Seber, 1982). For a particular location, variance(σ^2) and standard error (SE) for the annual survival estimate were equal to σ^2 and SE, respectively, for the annual mortality estimate. When only two data points were available on the descending limb of the catch curve, variances of survival and mortality estimates could not be estimated. Due to low sample sizes of the older ages, especially for the females, we pooled catches of males and females to estimate mortality rates for both sexes pooled. Similarly, Huo et al. (2014) pooled catches of males and females to estimate mortality rates of Lake Michigan round gobies for both sexes pooled.

Results

Length composition

The size distribution of round gobies was unimodal at all four locations of Lake Huron (Fig. 2). For males, total lengths of Saginaw Bay round gobies varied from 44 to 111 mm, with modal size from 50 to 65 mm; total lengths of Rockport round gobies

varied from 46 to 113 mm, with the most dominant classes from 65 to 85 mm; total lengths of Hammond Bay round gobies varied from 52 to 123 mm, with the most frequent classes from 65 to 85 mm; total lengths of Thunder Bay round gobies ranged from 51 to 118 mm, with the most frequent classes from 65 to 80 mm (Fig. 2).

For females, total lengths of Saginaw Bay round gobies varied from 51 to 90 mm, with the modal size from 60 to 70 mm; total lengths of Rockport round gobies varied from 45 to 115 mm, with the most dominant classes from 55 to 65 mm; total lengths of Hammond Bay round gobies varied from 50 to 87 mm, with the most frequent classes from 55 to 70 mm; total lengths of Thunder Bay round gobies ranged from 52 to 106 mm, with the most frequent classes from 65 to 80 mm (Fig. 2).

Age composition

We were able to assign an age to all but 4 of 754 otoliths by agreement from multiple readings. For males, age estimates ranged from 2 to 7 years for Hammond Bay and Thunder Bay, from 2 to 5 years for Saginaw Bay, and from 2 to 6 years for Rockport (Fig. 3). For females, age estimates ranged from 2 to 4 years for Saginaw Bay, from 2 to 6 years for Rockport, from 2 to 5 years for Hammond Bay, and from 2 to 7 years for Thunder Bay (Fig. 3). Thus, both sexes of round gobies attained an age of 7 years in Lake Huron.

Body-otolith relationship

For both sexes, slopes of the body-otolith relationships did not significantly differ among four locations of Lake Huron (Fig. 4; Table 1). However, slope for males was significantly greater than slope for females at Saginaw Bay, whereas slopes did not

significantly differ between sexes at Rockport, Hammond Bay, or Thunder Bay (Table 2). Because the slopes did not significantly differ among four locations of Lake Huron, the slope terms were dropped from the ANCOVA model to test on the equality of intercepts among four locations. For both sexes, intercepts varied significantly among the four locations (ANCOVA, all $P < 0.001$). Thus, an ANCOVA model with location as the treatment effect and $\log_{10}(OR)$ as the covariate was used to estimate the value of the slope, a , for each sex.

For females:

Saginaw Bay: $\log_{10}(TL) = 0.807 \times \log_{10}(OR) + 1.911$ (N=100, $R^2=0.497$)

Rockport: $\log_{10}(TL) = 0.807 \times \log_{10}(OR) + 1.894$ (N=37, $R^2=0.808$)

Hammond Bay: $\log_{10}(TL) = 0.807 \times \log_{10}(OR) + 1.906$ (N=74, $R^2=0.688$)

Thunder Bay: $\log_{10}(TL) = 0.807 \times \log_{10}(OR) + 1.941$ (N=100, $R^2=0.583$)

For males:

Saginaw Bay: $\log_{10}(TL) = 0.966 \times \log_{10}(OR) + 1.945$ (N=101, $R^2=0.722$)

Rockport: $\log_{10}(TL) = 0.966 \times \log_{10}(OR) + 1.947$ (N=115, $R^2=0.690$)

Hammond Bay: $\log_{10}(TL) = 0.966 \times \log_{10}(OR) + 1.973$ (N=126, $R^2=0.601$)

Thunder Bay: $\log_{10}(TL) = 0.966 \times \log_{10}(OR) + 1.980$ (N=97, $R^2=0.681$)

Growth

For both sexes, round goby growth showed significant spatial variation within Lake Huron (Fig. 5; Table 3). Round gobies at Thunder Bay grew significantly faster than round gobies at Hammond Bay, Rockport, and Saginaw Bay (Fig. 5). Males grew significantly faster than females (Table 4), and attained larger asymptotic length than

females at all four locations of Lake Huron (Table 5). Round gobies can reach 7 years of age for both sexes in Lake Huron, where some of the oldest round gobies noted in the literature have been found (Table 6).

Mortality

Round gobies were fully recruited to the gear by age 3 at Saginaw Bay, while they did not fully recruit until age 4 at Rockport, Hammond Bay, and Thunder Bay. Instantaneous mortality rate, estimated by catch-curve analysis, was 1.085/year ($SE=0.226/\text{year}$) for the round goby population at Hammond Bay (Fig. 6), giving an annual mortality rate of 66%. Annual mortality rates at Rockport, Thunder Bay, and Saginaw Bay were estimated to be 68%, 62%, and 85%, respectively. Variances could not be estimated for Saginaw Bay, Rockport, and Thunder Bay because only two points were available on the descending limb of the catch curve.

Discussion

Round gobies at Thunder Bay grew significantly faster than round gobies at Hammond Bay, Rockport and Saginaw Bay. This spatial variation may be due to spatial differences in the quality and quantity of food, as well as spatial differences in other environmental factors. Similarly, Huo et al. (2014) and French and Black (2009) explained spatial variation in round goby growth in Lake Michigan and Lake Huron by invoking spatial variation in food quality and quantity and in other environmental factors. In a feeding experiment conducted by Coulter et al. (2011), round gobies fed dreissenid mussels had significantly lower growth than individuals fed juvenile fish and chironomids and displayed the same weight loss as round gobies fed only

zooplankton. Thus, round goby growth likely depends on the availability of zooplankton, dreissenid mussels, juvenile fish, and chironomids, as well as the pursuit times and search costs for each of these diet items. Environmental factors, such as water temperature, photoperiod, and water depth experienced by round gobies may have also contributed to observed growth differences among locations. In addition, round goby population density may have affected round goby growth.

Predation is likely an important factor controlling round goby survival in Lake Huron. Over the past 20 years, the invasive round goby has become established in the Laurentian Great Lakes (Kornis et al., 2012) and has been incorporated into the diet of a broad array of piscivorous fishes (Dietrich et al., 2006; Madenjian et al., 2011; Pothoven and Madenjian, 2013; Truemper and Lauer, 2005). Coupling our findings with those of He et al. (2015), round gobies in Lake Huron appear to be under predatory control by piscivores, including lake trout (*Salvelinus namaycush*), walleye (*Sander vitreus*), and lake whitefish (*Coregonus clupeaformis*). We estimated that round goby annual mortality was relatively high (> 60%) at all four locations in Lake Huron. He et al. (2015) reported annual consumption estimates of round gobies by piscivore populations that were as high as, or exceeded, annual consumption estimates of either alewives (*Alosa pseudoharengus*) or rainbow smelt (*Osmerus mordax*) during 2003-2010, and abundances of both were thought to be strongly influenced by piscivore populations in Lake Huron. Results from our study indicated that round gobies in Saginaw Bay experienced higher mortality than those in other locations in Lake Huron, as annual mortality rate in Saginaw Bay was estimated to be 85%.

Undoubtedly, predation by walleyes contributed to this relatively high mortality rate, as round gobies predominate the present-day diet of walleyes caught in Saginaw Bay (Jovanovic, 2013). In addition, freshwater drum (*Aplodinotus grunniens*), channel catfish (*Ictalurus punctatus*), and yellow perch (*Perca flavescens*) feed on round gobies in Saginaw Bay (Fielder and Thomas, 2006; Fielder et al., 2007). Annual mortality rates were also relatively high at Hammond Bay, Rockport and Thunder Bay, where predation by lake whitefish, lake trout, and walleye may be important (He et al. 2015; Pothoven and Madenjian 2013).

This study demonstrated for the first time that life span of the round goby can reach 7 years for both sexes in Lake Huron, and that these fish are among the oldest round gobies noted in the literature. Age estimation for round gobies appears to depend on aging technique. A great deal of research has documented that sectioned otoliths provide the most precise and accurate age estimates (Gunn et al., 2008; Phelps et al., 2007), partly because otoliths are metabolically inert and not subject to resorption and partly because thin sectioning affords better resolution of the annuli (Phelps et al., 2007; Sponaugle, 2009). In addition, observed round goby growth in Lake Huron was slow compared with literature from their native range in the Ponto-Caspian region (Nikolske, 1956; Gümüs and Kurt, 2009). Perhaps this relatively slow growth also contributes to the apparent greater longevity in Lake Huron than in the native range.

Although two different gears were deployed to catch the round gobies used in our study, and each gear has its own sampling bias, ranges in total lengths of round gobies

used for aging were very similar between different gears. Further, the round goby length-frequency distributions were also similar. Thus, sampling bias with regard to round goby size did not appear to drastically differ between gears. Nonetheless, the sampling bias for either gear has not been quantified.

Not only does our study represent an important step in the understanding of round goby biological characteristics, but results provide further evidence for predatory control of round gobies in Lake Huron, given relatively high mortality rates in three of four locations. Thus, our study findings supported those of He et al. (2015), who proposed that piscivores were exerting top-down control on round goby abundance in Lake Huron based on relatively high estimates of annual consumption of round gobies by piscivore populations. Likewise, round goby populations appeared to be under predatory control in Lake Michigan (Huo et al., 2014) as well as in eastern Lake Erie (Madenjian et al., 2011). Further assessment of the trophic linkages between predators and round gobies in the Great Lakes is needed to completely understand the role of round gobies in the Laurentian Great Lakes.

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Table 1

Analysis of covariance for the body-otolith relationships for round goby (*Neogobius melanostomus*) among four locations in Lake Huron for each sex during 2014. LOC is location, OR denotes otolith radius and LOC : OR is the interaction term. *: significant level at $\alpha = 0.05$; **: significant level at $\alpha = 0.01$; ***: significant level at $\alpha = 0.001$.

Model Term	Female				Male			
	LOC	OR	LOC:OR	Residuals	LOC	OR	LOC:OR	Residuals
Degree of freedom	3	1	3	303	3	1	3	431
Sum of squares	0.028	0.725	0.001	0.429	0.03	2.074	0.006	1.038
Mean squares	0.009	0.725	<0.001	0.001	0.01	2.074	0.002	0.002
<i>F</i> -value	6.473	512.232	0.239		4.118	861.818	0.886	
<i>P</i> -value	<0.001***	<0.001***	0.869		0.007**	<0.001***	0.459	

Table 2

Analysis of covariance for the body-otolith relationships for round goby (*Neogobius melanostomus*) between sexes for each location in Lake Huron during 2014. OR denotes otolith radius and SEX : OR is the interaction term. *: significant level at $\alpha = 0.05$; **: significant level at $\alpha = 0.01$; ***: significant level at $\alpha = 0.001$.

Model Term	Saginaw Bay				Rockport				Hammond Bay				Thunder Bay			
	Sex	OR	Sex:OR	Residuals	Sex	OR	Sex:OR	Residuals	Sex	OR	Sex:OR	Residuals	Sex	OR	Sex:OR	Residuals
Degree of freedom	1	1	1	197	1	1	1	148	1	1	1	196	1	1	1	193
Sum of squares	0.018.	0.474	0.013	0.301	0.026	0.761	0.367	0.367	0.040	0.525	0.005	0.389	0.023	0.687	0.004	0.409
Mean squares	0.018	0.474	0.013	0.002	0.026	0.761	0.020	0.002	0.040	0.525	0.005	0.002	0.023	0.687	0.004	0.002
F-value	11.397	310.050	8.669		10.483	306.360	0.880		19.998	264.023	2.278		10.929	324.685	1.816	
P-value	0.001***	<0.001***	0.004**		0.001***	<0.001***	0.350		<0.001***	<0.001***	0.133		0.001***	<0.001***	0.179	

Table 3

Growth variation tests of round goby (*Neogobius melanostomus*) among four locations for each sex in Lake Huron during 2014. *: significant level at $\alpha = 0.0083$; **: significant level at $\alpha = 0.0017$; ***: significant level at $\alpha = 0.00017$; L_F : maximum likelihood for full model; L_R : maximum likelihood for reduced model; SB: Saginaw Bay; RP: Rockport; HB: Hammond Bay; TB: Thunder Bay.

Model Term	SB-RP	SB-HB	SB-TB	RP-HB	RP-TB	HB-TB
Male						
$\ln(L_F)$	248.3127	269.4531	218.3871	308.0587	255.4007	277.0790
$\ln(L_R)$	247.8882	260.9980	202.4745	297.4738	243.1866	261.1774
χ^2	0.8489	16.9102	31.8553	21.1698	24.4283	31.8032
Degree of freedom	3	3	3	3	3	3
<i>P</i> -value	0.8377	0.0007**	<0.0001***	<0.0001***	<0.0001***	<0.0001***
Female						
$\ln(L_F)$	187.3203	270.2618	291.6182	188.6645	207.8377	295.0115
$\ln(L_R)$	181.4395	261.7718	272.2761	185.2627	185.6493	246.4532
χ^2	11.7616	16.9800	38.6843	6.8037	44.3767	97.1165
Degree of freedom	3	3	3	3	3	3
<i>P</i> -value	0.0082*	0.0007**	<0.0001***	0.0784	<0.0001***	<0.0001***

Table 4

Growth variation tests of round goby (*Neogobius melanostomus*) between sexes for each location in Lake Huron during 2014. *: significant level at $\alpha = 0.05$; **: significant level at $\alpha = 0.01$; ***: significant level at $\alpha = 0.001$; L_F : maximum likelihood for full model; L_R : maximum likelihood for reduced model

Statistic	Saginaw Bay	Rockport	Hammond Bay	Thunder Bay
	Male-Female	Male-Female	Male-Female	Male-Female
$\text{Ln}(L_F)$	239.8442	194.0844	297.9598	265.3361
$\text{Ln}(L_R)$	218.1185	182.9260	277.3678	253.2455
χ^2	43.4513	22.3168	41.1839	24.1813
Degree of freedom	3	3	3	3
P -value	<0.001***	<0.001***	<0.001***	<0.001***

Table5

Growth model parameters ($\pm$ SE) for round gobies (*Neogobius melanostomus*) caught at four locations in Lake Huron during 2014. L_{∞} : asymptotic length; k : von Bertalanffy growth constant; t_0 : theoretical age at zero length; N: number of back-calculated total lengths at age.

Parameter	Saginaw Bay		Rockport		Hammond Bay		Thunder Bay	
	Male	Female	Male	Female	Male	Female	Male	Female
L_{∞} (mm)	147.41 $\pm$ 47.45	75.32 $\pm$ 7.43	155.20 $\pm$ 30.56	152.12 $\pm$ 68.93	138.73 $\pm$ 22.40	91.61 $\pm$ 9.343	126.49 $\pm$ 15.54	108.23 $\pm$ 11.79
k (year ⁻¹)	0.203 $\pm$ 0.098	0.589 $\pm$ 0.167	0.185 $\pm$ 0.057	0.144 $\pm$ 0.099	0.181 $\pm$ 0.052	0.315 $\pm$ 0.072	0.255 $\pm$ 0.061	0.267 $\pm$ 0.068
t_0	-0.160 $\pm$ 0.152	-0.008 $\pm$ 0.168	-0.240 $\pm$ 0.129	-0.735 $\pm$ 0.343	-0.625 $\pm$ 0.202	-0.482 $\pm$ 0.169	-0.315 $\pm$ 0.151	-0.730 $\pm$ 0.252
R^2	0.817	0.764	0.854	0.841	0.808	0.870	0.831	0.750
N	202	200	230	73	251	147	192	199

Table6

Maximum total length and totallengthatage of round goby (*Neogobius melanostomus*) from different locations. Data for males and females are separated (/). Lengths reported in the literature as standard length were converted to total length using the following equation: $TL = 1.1977 \times SL + 0.4586$ ($R^2 = 0.9932$, $n = 193$) (Kornis et al., 2012). n/a denotes no data were available. *: observed total length; †: denotes that standard length reported from source and converted to total length using equation in table heading; —: no data; *MTL*: maximum total length; *TL*: total length; *SL*: standard length.

		Age (years)									
		0	1	2	3	4	5	6	7		
Region	<i>MTL</i> (mm)	<i>TL</i> (mm)								Max	Source
Harbor Beach, Lake Huron*	97/—	n/a	40/—	61/—	77/—	89/—	97/—	n/a	n/a	5/—	French and Black (2009)
Hammond Bay, Lake Huron*	105/—	n/a	45/—	72/—	87/—	98/—	105/—	n/a	n/a	5/—	French and Black (2009)
Hammond Bay, Lake Huron*	119/75	n/a	n/a	65/55	67/59	77/67	87/75	100/—	119/—	7/5	Present Study
Rockport, Lake Huron*	104/115	n/a	n/a	57/52	65/59	81/72	93/78	104/115	n/a	6/6	Present Study
Saginaw Bay, Lake Huron*	101/74	n/a	n/a	56/62	67/62	83/74	101/—	n/a	n/a	5/4	Present Study
Thunder Bay, Lake Huron*	112/100	n/a	n/a	63/60	71/68	83/79	100/80	112/98	109/100	7/7	Present Study
Sleeping Bear Dunes, Lake Michigan*	129/112	n/a	n/a	71/79	90/80	102/94	119/105	—/111	n/a	5/6	Huo et al. (2014)
Sturgeon Bay, Lake Michigan*	131/119	n/a	n/a	55/73	75/74	89/90	103/96	n/a	131/—	7/5	Huo et al. (2014)
Waukegan, Lake Michigan*	125/107	n/a	n/a	70/68	83/83	96/95	113/—	n/a	n/a	5/4	Huo et al. (2014)
Upper Detroit River*	124/112	n/a	76/70	91/78	—/100	n/a	n/a	n/a	n/a	2/3	MacInnis and Corkum (2000a)
Pennsylvania Tributary Streams, Lake Erie*	112/—	44/—	68/—	80/—	94/—	n/a	n/a	n/a	n/a	4/—	Phillips et al. (2003)
Central Basin Lake Erie*	190/144	55/49	75/70	104/90	148/130	177/—	n/a	n/a	n/a	4/3	Johnson et al. (2005)
Southern Black Sea†	250/197	n/a	107/103	140/129	162/147	183/168	190/182	n/a	n/a	5	Gümüş and Kurt (2009)
Gulf of Gdańsk*	235/187	n/a	n/a	119/94	136/125	146/133	155/144	209/175	n/a	6	Sokołowska and Fey (2011)
Caspian Sea*	190/160	n/a	69/63	88/67	111/81	138/85	n/a	n/a	n/a	4	Nikolski (1956)

Figure captions

Fig. 1. Map of sampling locations at Saginaw Bay, Rockport, Hammond Bay, and Thunder Bay in Lake Huron for round gobies (*Neogobius melanostomus*) during 2014.

Fig. 2. Total length composition by sex of round gobies (*Neogobius melanostomus*) from four locations in Lake Huron during 2014.

Fig. 3. Age composition by sex of round gobies (*Neogobius melanostomus*) caught at four locations in Lake Huron during 2014.

Fig. 4. Body-otolith relationships, by location and sex, of round gobies (*Neogobius melanostomus*) in Lake Huron during 2014. Lines represent fitted regression lines. Symbols represent observed values.

Fig. 5. Fitted von Bertalanffy growth curves, by sex, for round gobies from four locations in Lake Huron. Symbols represent back-calculated total lengths.

Fig. 6. Catch curve for round gobies (*Neogobius melanostomus*) from Hammond Bay in Lake Huron during 2014. The fit of natural logarithm of number of fish as a function of age, for ages 4-6, by simple linear regression analysis yielded an estimate of the instantaneous mortality rate Z .

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6