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Predation of zebra mussels by round gobies, *Neogobius melanostomus*

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Synopsis

Preliminary gut analysis of a recent Great Lakes invader, the round goby, *Neogobius melanostomus* (7.0–8.4 cm), collected from the Detroit River, showed that they ate zebra mussels (58%), snails (6%), and other invertebrates (36%), including aquatic insects (*Hexagenia*), softshelled crayfish, and zooplankton. Because zebra mussels, *Dreissena polymorpha*, predominated as prey, we investigated the ability of round gobies to consume different size classes of zebra mussels. In laboratory experiments, we examined feeding preferences of three size classes of round gobies (5.5–6.9 cm; 7.0–8.4 cm; 8.5–10.3 cm standard length) on four different size classes of zebra mussels (6.0–9.9 mm, 10.0–12.9 mm, 13.0–15.9 mm, 16.0–18.9 mm). All sizes of round gobies ate zebra mussels < 10.0 mm. Only the largest size class of round gobies ate larger zebra mussels (10.0–12.9 mm) when all prey sizes were presented. The association between the total mass of zebra mussels available and the amount consumed by round gobies increased positively up to about 6.5 g of available mussels and then levelled off. Round gobies consumed an average of 1.0 g of mussels in 24 h. There was a significant positive relationship between gape size and standard length of round gobies. Although larger round gobies (over the size range of fish in our study) are able to consume larger zebra mussels, small mussels were preferred. Our findings suggest that the preference of small zebra mussels by round gobies has the potential to alter the size structure of zebra mussel populations.

Introduction

The round goby, *Neogobius melanostomus*, and tubenose goby, *Proterorhinus marmoratus*, are two exotic species of fishes that were first observed in the St. Clair River of the Laurentian Great Lakes in 1990 (Crossman et al. 1992, Jude et al. 1992). These gobies, probably arrived in ballast water discharged from ships from the Black-Caspian Sea area (Crossman 1991, Mills et al. 1993). Round gobies now inhabit all of the Laurential Great Lakes in localized areas (D.J. Jude personal communication). These isolated populations among lakes are likely the result of interbasin transfer by ship ballast water. However, spread of a population within a bay or basin of a lake is likely the result of dispersal.

Round gobies are voracious consumers of benthic organisms, feeding primarily on bivalve molluscs in their native range (Ghedotti et al. 1995). Like other mollusc-feeding fishes, round gobies possess upper and lower pharyngeal teeth (French 1993, Ghedotti et al. 1995). In aquaria, round gobies eat benthic tubenose gobies and darters, *Etheostoma* spp., and they may eat other benthic fishes including sculpins *Cottus* spp., darters and logperch, *Percina caprodes* (D.J. Jude personal communication). In our laboratory aquaria, round gobies fed aggressively on all items presented including *Hexagenia* mayflies, dragonflies, crayfish, *Orconectes propinquus*, and zebra mussels, *Dreissena polymor-*

pha. Given the high densities of zebra mussels (up to 3.4×10^5 mussels per m^2 in the western basin of Lake Erie, Leach 1993) and their continental distribution in North America (Strayer 1991), there are abundant food resources available for the round goby.

In this study, preliminary findings from gut analysis of round gobies collected from the Detroit River suggested that the dominant prey items were zebra mussels. Laboratory experiments were designed to examine predation of zebra mussels by round gobies by manipulating sizes of round gobies and sizes and numbers of mussels. Size classes of organisms used in experiments were based on size frequency distributions of round gobies and zebra mussels collected in June 1994 from the upper Detroit River, Ontario. Thus, round gobies (depending on their gape size) may select a particular size of zebra mussel in areas where mussel abundance is high. Our null hypothesis was that prey consumption by round gobies did not differ among different size classes of zebra mussels. We also investigated the functional feeding response of zebra mussels by round gobies to determine the maximum amount of zebra mussels consumed when prey were unlimited.

Methods

Preliminary gut analysis of round gobies

Twelve medium sized (7.0–8.4 cm standard length, SL) round gobies were caught (10 June 1994) from the upper Detroit River on the Canadian side of Peche Island Provincial Park. Fish were placed in 70% ethanol for digestive tract analysis. Volume of food removed from guts was analysed by removing the digestive tract and measuring the difference between a digestive tract with and without food. Contents (and volume) were determined.

Collection and maintenance of organisms

Round gobies were collected from three sites (Goose Bay Park, Coventry Gardens, and Peche Island Provincial Park) along a 10 km shoreline on the Canadian side of the upper Detroit River in June 1994. Substrate was characterized by limestone cobbles and boulders from reclaimed break walls overlying soft clay in water that was < 1.5 m deep. A 1.8 m long nylon seine net (6.3 mm mesh) and hook and line (with earthworms as bait) were used to collect round gobies in shoreline areas. Fish were returned to the laboratory in a cooler with continuously aerated river water. Fish were held (1–2 days) in plastic wading pools (surface area 0.55 m^2) filled with aerated, dechlorinated water. Pools also contained cobble stones with benthic invertebrates and plastic tubes (10 cm lengths, 4 cm inner diameter), which provided refuges for fish.

We collected zebra mussels by hand in nearshore areas at two sites, Peche Island (42° 40′ N, 82° 55′ W) and Tremblay Beach (42° 18′ N, 82° 30′ W). All sizes of zebra mussels were collected from cobble stones at Peche Island in the upper Detroit River. Because so few small zebra mussels were found in the Detroit River, smaller mussels (< 10 mm from anterior end to posterior end) were collected at Tremblay Beach, Lake St. Clair, Ontario. Zebra mussels and associated rocks were placed in coolers containing lake or river water and transported to the laboratory. Rocks containing zebra mussels were placed in aerated dechlorinated water in glass aquaria. Zebra mussels were held for about 2–3 weeks prior to experiments. Mussels were fed *Chlorella* (Acta Pharmacal Co., Sunnyvale, California) ad libitum.

The size of mussel consumed is ultimately determined by mouth size of the predator. On 10 July 1996, we collected 50 round gobies from the Detroit River using a trawl net (1.0 cm stretch mesh). We measured the width and height of the gape (using digital calipers) and standard length of live fish to determine the relationship between the two variables.

Laboratory experiments

Size classes of organisms used in the experiment were based on preliminary measurements of 30 gobies and 894 zebra mussels that were collected in June 1994. Although round gobies range in standard length from 2 to 25 cm in the St. Clair River (D.J. Jude personal communication), the largest round goby that we have collected in the Detroit River was 14 cm. The standard length of fish used in the laboratory experiment (5.5–10.3 cm) reflected the length frequency distribution of round gobies in the Detroit River in 1994. We divided the size range of fish into three arbitrarily delineated length categories (5.5–6.9 cm, 7.0–8.4 cm, 8.5–10.3 cm).

A pilot study was conducted to determine the maximum size of zebra mussel that a round goby would consume. Each of five round gobies (8.5–10.3 cm SL) was placed in dechlorinated, aerated water in glass aquaria; they had been deprived of food for 24 h. Ten mussels up to 16 mm in length were measured and placed in each aquarium. After 24 h, any uneaten mussels were collected and counted.

Experiment 1: effect of predator and prey size on mussel consumption

Twelve large (8.5–10.3 cm SL), 14 medium (7.0–8.4 cm SL), and 11 small (5.5–6.9 cm SL) round gobies (age 1–2 years) were used in the experiment. We selected a size range of mussels that included the largest mussels consumed (16 mm) in the pilot experiment. Four size classes of zebra mussels (6.0–9.9, 10.0–12.9, 13.0–15.9, and 16.0–18.9 mm total length, TL) were used. The total number of mussels used in the experiment was 1480 (10 mussels/size class × 4 size classes of mussels × 37 fish).

Round gobies were removed from holding tanks and a single round goby was placed in a 40 l glass aquarium containing aerated, dechlorinated water and a plastic refuge. The sides of each aquarium were covered with cardboard. Each fish was used only once and was deprived of food for 24 h before each trial. Zebra mussels from each of four sizes (n = 10 per class) were then scattered on the bottom of each aquarium. After 24 h, the round goby and remaining zebra mussels were removed from each aquarium. A two-way analysis of variance (ANOVA) was performed to test for effects of predator and prey size on the number of mussels consumed.

Experiment 2: relationship between mussel biomass and predation

Many small zebra mussels (< 10 mm) and round gobies were collected for an experiment to examine mussel consumption by round gobies over a range of mussel masses. Each goby was placed in an aquarium that contained a predetermined mass of small (6.0–9.9 mm) zebra mussels, collected from Tremblay Beach. Biomass of mussels (weighed to the nearest 0.1 g) ranged from 0.5–20 g. We examined 15 different amounts of mussels (3 replicates per quantity).

Each fish (deprived of food for 24 h) was transferred from its holding tank to a glass aquarium containing one refuge and aerated, dechlorinated water. Round gobies were allowed 24 h to feed. After 24 h, zebra mussels were removed and weighed to determine wet mass of zebra mussels remaining. The difference between zebra mussel mass before and after the experiment represented the amount consumed by each round goby. Nonlinear regression analysis (Statistical Graphics Corporation[1]) was used to determine the relationship, if any, between mussel biomass and the amount consumed by round gobies.

[1] Statistical Graphics Corporation. 1991. Statgraphics, version 5. Reference Manual, STSC Inc., Rockville.

Table 1. Significance of regression between gape measures (height, mm; width, mm and area, mm^2) and standard length. Mean (± SE) values are presented for each gape measure (n = 50). Equation format: Y = A + BX.

Factors	Mean (± SE)	A	B	SE	R^2	p
Gape height	8.6 (0.44)	– 1.3	0.16	0.001	0.94	< 0.001
Gape width	6.2 (0.34)	– 1.4	0.13	0.001	0.91	< 0.001
Gape area	60.1 (6.29)	– 79.7	2.32	0.015	0.91	< 0.001

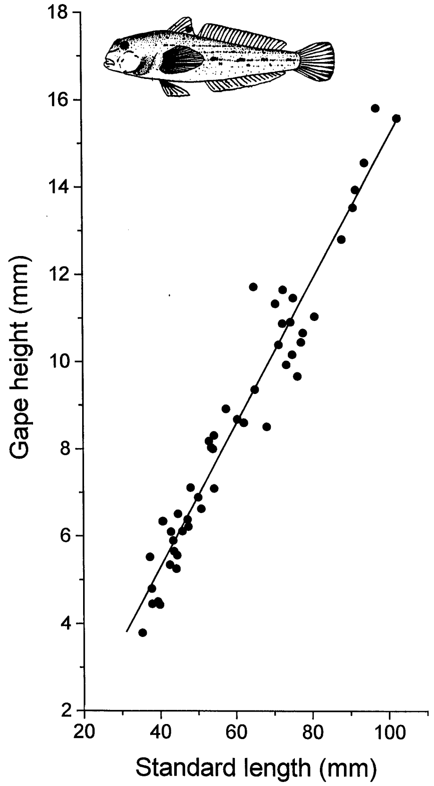

Figure 1. The relationship, Y = – 1.30 + 0.164 X, between gape height and standard length of round gobies.

Results

Analysis of digestive tracts from medium sized (7.0–8.4 cm) round gobies collected from the Detroit River showed that a mean of 58% (range: 10–90%) of all gut contents were zebra mussels. The 'other' prey items that comprised 36% of the diet included aquatic insects (the burrowing mayfly, *Hexagenia*), whole softshelled crayfish, ostracods, and benthic zooplankton. *Gastropoda* (snails) made up about 6% of the gut contents.

Fifty round gobies collected near Peche Island on the Detroit River were measured for gape height (range: 3.8 to 15.8 mm), gape width (range: 2.5 to 11.7 mm) and standard length (range: 3.5 to 10.3 cm). Gape height, gape width and gape area were all significantly ($p < 0.001$) related to standard length (Table 1, Figure 1). The largest round goby (10.3 cm) had a gape height of 16 mm, a width of 11 mm and a gape area of 176 mm^2.

Results of the two-way ANOVA (experiment 1) indicated that sizes of round gobies and zebra mussels and the interaction between the variables significantly influenced the number of mussels consumed (Table 2). Although all three sources of variation were significant, the largest F-value was obtained for mussel size, indicating the importance of this variable. Small (5.5–6.9 cm SL) and medium (7.0–8.4 cm SL) sized round gobies ate only the smallest size class (6.0–9.9 mm TL) of zebra mussels (Table 3). The largest round gobies (8.5–10.3 cm SL) ate the smallest size class of zebra mussels and mussels, 10.0–12.9 mm. The large, medium, and small classes of round gobies ate an average of 69%, 64% and 14%, respectively, of the mussels offered, suggesting that the smallest gobies may depend on other food items in its diet.

There was a significant ($p < 0.001$) non-linear relationship, $Y = 1.023\,(1\text{-}e^{-0.345X})$, between the mass of zebra mussels consumed by individual round gobies and the total mass of mussels available (Figure 2). The association between the total mass of mussels available and the amount consumed by round gobies increased up to 1.023 (± 0.052) g of available mussels, beyond which the amount of mussels con-

Table 2. Summary of two-way ANOVA with replication on the effect of round goby size (SL, standard length), zebra mussel size (length) and their interaction on the amount of zebra mussels consumed by the gobies.

Source	df	Mean square	F	p
Goby SL	2	27.375	21.454	< 0.001
Mussel length	3	217.210	170.227	< 0.001
Goby × mussel	6	26.754	20.967	< 0.001
Error	136	1.276		

Table 3. The number of zebra mussels (mean ± S.E.) of each size class consumed by different size classes (standard length) of round gobies.

Goby length (cm)	Zebra mussel length (mm)			
	6.0–9.9	10.0–12.9	13.0–15.9	16.0–18.9
5.5– 6.9	1.4 (0.28)	0	0	0
7.0– 8.4	6.4 (0.72)	0	0	0
8.5–10.3	6.9 (0.72)	0.1 (0.01)	0	0

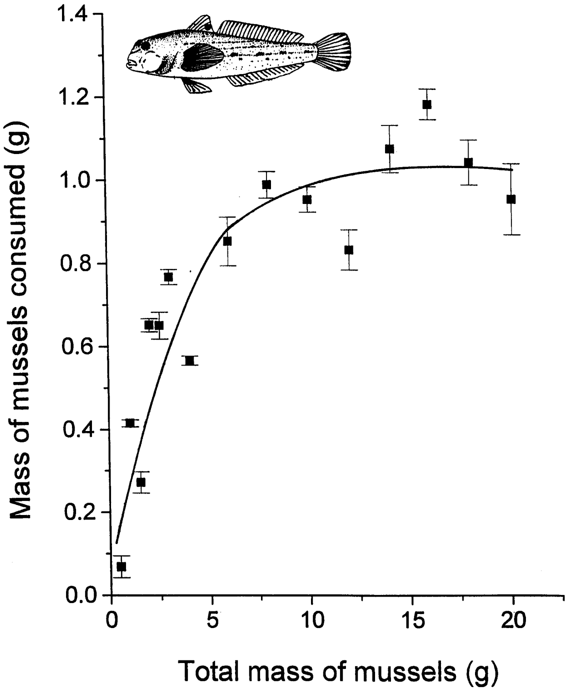

Figure 2. The relationship, Y = 1.023(1-$e^{-0.345X}$), between the mass of mussels consumed by individual round gobies and the total mass of mussels available (15 mussel densities × 3 replicates per density).

sumed levelled off. Round gobies ate about 6–7 zebra mussels (6.0–9.9 mm), the equivalent of 1 g wet weight of mussels, in 24 h.

Discussion

Results of gut analysis from round gobies collected from the Detroit River showed that mid-sized gobies (7.0–8.4 cm) ate mostly zebra mussels. In our laboratory study, the smallest gobies (5.5–6.9 cm) ate the fewest zebra mussels; larger gobies (8.5–10.3 cm) ate more zebra mussels (Table 3). Gut length and capacity of round gobies also will affect the number of mussels consumed. Since all guts were not 100% full, it is possible that the smallest gobies could hold more zebra mussels.

When presented with zebra mussels of a range of sizes (6.0–9.9, 10.0–12.9, 13.0–15.9, and 16.0–18.9 cm TL), round gobies (up to 10.3 cm) ate mussels < 10 mm in length almost exclusively. Jude et al. (1995) showed that the diet of small round gobies (4.7–6.5 cm) consisted of benthic zooplankton, aquatic insects, and mussels. Evidently, soft-bodied, mobile organisms are consumed more frequently by small rather than large gobies. The diet of large gobies shifts to include mainly zebra mussels (Jude et al. 1995, this study).

Differences in size classes of prey consumed by round gobies reflect ease of handling and gape or mouth size, relating to vulnerability of prey size (Gelwick & Matthews 1996). We showed that there was a significant postive relationship between gape size and standard length of round gobies. Round gobies with a standard length of 10.3 cm had a gape height and width of 16 × 11 mm. Ghedotti et al. (1995) reported that zebra mussels larger than 6 × 12 mm could not be eaten by a round goby (7.2 cm SL) with a gape of about 6 × 8 mm. Although larger round gobies can eat larger zebra mussels, we showed that small mussels were preferred. However, further studies are needed to determine if the mussel length or thickness is the limiting factor for mussel consumption by the round goby.

Small zebra mussels predominate in some locations. For example, small mussels (< 10 mm) were abundant at Tremblay Beach, Lake St. Clair (this study). Also, zebra mussels (2.0–11.0 mm) comprised up to 90% of the individuals inhabiting the reefs in western Lake Erie (Bunt et al. 1993). Recently (July 1996), round gobies were reported and confirmed from the western basin of Lake Erie (southwest tip of Pt. Pelee – R. Wickett personal communication; Colchester Harbour – A. Dextrase personal communication). Since predators typically have a greater impact on preferred prey when food is abundant than when it is scarce (Brewer 1988), round gobies have a potential to alter the size structure of mussel populations in specific locales.

The time that round gobies spent searching for food in our laboratory study was minimal, owing to the size of the tank. In nature, spatial distribution of small zebra mussels would be expected to affect feeding habits of round gobies by adding a cost of search time and predator avoidance (Stein & Magnuson 1976). Zebra mussels, however, are so prevalent in the Great Lakes (Leach 1993) that additional search costs would be low.

Individual round gobies showed a type II functional response (Holling 1959) when presented with a range of mussel densities (Figure 2). The saturation level for individual round gobies eating zebra mussels (< 10 mm) was about 1 g in 24 h. Other organisms, such as crayfish, *Orconectes propinquus*, also consume small zebra mussels (MacIsaac 1994, Martin & Corkum 1994). Diving ducks, specifically greater scaup, *Aythya marila*, and lesser scaup, *A. affinis*, reduce mussel biomass substantially in the western basin of Lake Erie (Hamilton et al. 1994). However, Wormington & Leach (1992) anticipated that the effect of diving ducks on zebra mussels would be minimal and restricted to local areas. Scaup eat zebra mussels 11.0–21.0 mm long (Hamilton et al. 1994). Thus, several predators use the entire size spectrum of zebra mussels.

French (1993) determined the potential for different fish species to control zebra mussels in eastern North America. Potential predators including freshwater drum, *Aplodinotus grunniens*, two species of centrarchids, redear sunfish, *Lepomis microlophus*, and pumpkinseed, *Lepomis gibbosus*, have both upper and lower pharyngeal teeth, enabling these fishes to crush molluscs. The large molariform, conical teeth of round gobies also are well suited to crush shells. We observed entire zebra mussels that escaped crushing, open shells that were still intact and ground pieces of shells in the gut of round gobies. We also observed round gobies ejecting empty whole shells and pieces of shells by spitting shells out through their mouths and passing them out through their anus.

Despite the energy transferred from mussels to both vertebrates and invertebrates, biotic control of zebra mussels is unlikely. Typically, high densities of zebra mussels are controlled by population crashes or physical disturbances rather than by predators (Stanczykowska 1977). Moreover, it is dangerous biologically to introduce an exotic fish in an attempt to control zebra mussels because of potential negative effects that round gobies have on native fish such as mottled sculpin, *Cottus bairdi* (Jude et al. 1995, Dubs & Corkum 1996). Other characteristics of round gobies (multiple spawners, nest guarding and nocturnal feeding) suggest that this species will continue to become well established in the Great Lakes (Leach 1995). Clearly, detailed field studies are warranted to evaluate interactions between round gobies and potential competitors, predators and prey. The round goby has the potential to compete with other native fish species including darters and sculpins for habitat availability. With the continued expansion and increase in numbers of round gobies throughout the Great Lakes, we anticipate that this exotic will affect other trophic levels. Since zebra mussels are the dominant prey of mid to large-size round gobies, we predict that this exotic fish will disperse beyond its current distribution in the Great Lakes and enter adjoining waters where zebra mussels are abundant.

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References cited

Brewer, R. 1988. The science of ecology. Saunders College Publ., Philadelphia. 922 pp.

Bunt, C.M., H.J. MacIsaac & W.G. Sprules. 1993. Pumping rates and projected filtering impacts of juvenile zebra mussels (*Dreissena polymorpha*) in western Lake Erie. Can. J. Fish. Aquat. Sci. 50: 1017–1022.

Crossman, E.J. 1991. Introduced freshwater fishes: a review of the North American perspective with emphasis on Canada. Can. J. Fish. Aquat. Sci. 48 (Suppl. 1): 46–57.

Crossman, E.J., E. Holm & R. Cholmondeley. 1992. First record for Canada of the rudd, *Scardinius erythrophthalmus*, and notes on the introduced round goby, *Neogobius melanostomus*. Can. Field-Nat. 106: 206–209.

Dubs, D.O.L. & L.D. Corkum. 1996. Behavioural interactions between round gobies (*Neogobius melanostomus*) and mottled sculpins (*Cottus bairdi*). J. Great Lakes Res. 22: 838–844.

French III, J.R.P. 1993. How well can fishes prey on zebra mussels in Eastern North America? Fisheries 18: 13–19.

Gelwick, F.P. & M.J. Matthews. 1996. Trophic relations of stream fishes. pp. 475–492. *In:* F.R. Hauer & G.A. Lamberti (ed.) Methods in Stream Ecology, Academic Press, San Diego.

Ghedotti, M.J., J.C. Smihula & G.R. Smith. 1995. Zebra mussel predation by round gobies in the laboratory. J. Great Lakes Res. 21: 665–669.

Hamilton, D.J., C.D. Ankney & R.C. Bailey. 1994. Predation by diving ducks on zebra mussels: an exclosure experiment. Ecology 75: 521–531.

Holling, C.S. 1959. The components of predation as revealed by a study of small-mammal predation of European sawfly. Can. Entomol. 91: 293–320.

Jude, D.J., R.H. Reider & G.R. Smith. 1992. Establishment of Gobiidae in the Great Lakes basin. Can. J. Fish. Aquat. Sci. 49: 416–421.

Jude, D.J., J. Janssen & G. Crawford. 1995. Ecology, distribution, and impact of the newly introduced round and tubenose gobies on the biota of the St. Clair and Detroit Rivers. pp. 447–460. *In:* M. Munawar, T. Edsall & J. Leach (ed.) The Lake Huron Ecosystem: Ecology, Fisheries, and Management, Ecovision World Monograph Series, S.P.B. Academic Publishing, Amsterdam.

Leach, J.H. 1993. Impact of the zebra mussel (*Dreissena polymorpha*) on water quality and fish spawning reefs in western Lake Erie. pp. 381–397. *In:* T.F. Nalepa & D.S. Schloesser (ed.) Zebra Mussels: Biology, Impacts, and Control, Lewis Publishers, Boca Raton.

Leach, J.H. 1995. Non-indigenous species in the Great Lakes: were colonization and damage to ecosystem health predictable? J. Aquat. Ecosystem Health 4: 117–128.

MacIsaac, H.J. 1994. Size selective predation on zebra mussels (*Dreissena polymorpha*) by crayfish (*Orconectes propinquus*). J.N. Amer. Benthol. Soc. 13: 206–216.

Martin, G.W. & L.D. Corkum. 1994. Predation of zebra mussels by crayfish. Can. J. Zool. 72: 1867–1871.

Mills, E.L., J.H. Leach, J.T. Carlton & C.L. Secor. 1993. Exotic species in the Great Lakes: a history of biotic crises and anthropogenic introductions. J. Great Lakes Res. 9: 1–54.

Stańczykowska, A. 1977. Ecology of *Dreissena polymorpha* (Pall.) (Bivalvia) in lakes. Pol. Arch. Hydrobiol. 24: 461–530.

Stein, R.A. & J.J. Magnuson. 1976. Behavioural response of a crayfish to a fish predator. Ecology 57: 751–761.

Strayer, D.L. 1991. Projected distribution of the zebra mussel, *Dreissena polymorpha*, in North America. Can. J. Fish. Aquat. Sci. 48: 1389–1395.

Wormington, A. & J.H. Leach. 1992. Concentrations of migrant diving ducks at Point Pelee National Park, Ontario, in response to invasion of zebra mussels, *Dreissena polymorpha*. Can. Field-Nat. 106: 376–380.