*Persistence of an invasive fish (*Neogobius melanostomus*) in a contaminated ecosystem*

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Persistence of an invasive fish (*Neogobius melanostomus*) in a contaminated ecosystem

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Abstract Post-establishment dynamics of invasive species have been under-studied. However, understanding these dynamics is particularly important for the management of invasive species known to impact native communities. Following the invasion of a highly invasive species, the round goby (*Neogobius melanostomus*), we document long-term population changes after establishment and address how population dynamics of a successful invader change through persistence and integration. Round goby present a threat to the areas they invade by out-competing native species for resources. Furthermore, as a pollution tolerant species, round goby present a second threat by acting as a possible vector for contaminant transfer to higher trophic levels in invaded ecosystems with areas of contamination. We sampled round goby for 11 years (2002–2012) at four low contamination sites and two high contamination sites within Hamilton Harbour ON, Canada, an International Joint Commission Area of Concern. Across sampling years, we show that round goby abundance has declined at low contamination sites, while remaining stable at high contamination sites. Moreover, we show that average body size decreased and reproductive investment increased both across sampling years and between sites of low and high contamination. Our results document population demographic shifts in a persisting invasive species, and underscore the importance of management practices for this species in contaminated environments.

Keywords Population dynamics · Round goby · Hamilton harbour · Contamination · International area of concern

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Introduction

Most research on the introduction and establishment of an invasive species in a new environment has focused on documenting the early stages of species invasions (i.e. the spread and establishment phases), while potential for eradication is still viable.

Understanding the persistence and integration of invasive species into an invaded area over a longer time-scale has received less attention (Puth and Post 2005). Although eradication becomes less feasible, documenting how an invasive species integrates into a new environment can help to inform management of the species, and aid in controlling damage to the invaded environment (Andersen et al. 2004). This is especially important when a well-established invasive species is known to have an extensive and profound impact on native species, potentially leading to long-term and significant declines in the ecological and economic productivity of an invaded ecosystem (Davis 2009; Lockwood et al. 2009).

The round goby (*Neogobius melanostomus*) invasion of the Laurentian Great Lakes is one example of a well-established invasive species with widespread impacts on the environments it has invaded. This small, benthic fish—native to the Black and Caspian Seas of Europe—was introduced to the Great Lakes via ship ballast water discharge in the early 1990s (Jude et al. 1992). As a multiple spawner with a long breeding season ($\sim$3–4 months), invading round goby spread quickly (Corkum et al. 1998). Since 1990, they have spread more rapidly throughout all five Great Lakes than any previous aquatic invader (Corkum et al. 2004; Kornis et al. 2012). In addition to their reproductive habits, a number of behavioural and physiological characteristics have contributed to the success of their invasion, and the resultant concern for the invaded environments. Round goby are opportunistic foragers, and are known to consume the eggs of larger fish species important for local fisheries (Fitzsimons et al. 2006; Roseman et al. 2006; Steinhart et al. 2004). Round goby are highly aggressive in interspecific interactions, and are associated with the decline of native species using the same habitat (Bergstrom and Mensigner 2009; Balshine et al. 2005; Janssen and Jude 2001; Dubs and Corkum 1996). Taken together, these characteristics suggest that round goby will pose a threat to the balance and health of the ecosystems they invade, and the productivity of fisheries in these areas.

In addition to their interactions with and impacts on native species, round goby present another pressing concern for invaded areas, they are a potential vector for contaminant transfer to higher trophic levels (Poste and Ozersky 2013; Kwon et al. 2006; Hanari et al. 2004). As a mussel specialist, round goby readily ingest contaminants sequestered in tissue of filter-feeding mollusks (Lederer et al. 2006; Gossiaux et al. 1998). Moreover, as a benthic species, with a small home-range (Marentette et al. 2011; Ray and Corkum 2001) round goby have the potential to accumulate contaminants directly from sediment and the water column in highly impacted areas (Bowley et al. 2010; Marentette et al. 2010). These contaminants can then be passed to higher trophic levels via multiple predator pathways, as round goby are a known prey species for water birds (Jakubas 2004; Somers et al. 2003), water snakes (King et al. 2006), and larger fish species (Reyjol et al. 2010; Taraborelli et al. 2010; Dietrich et al. 2006; Truemper and Lauer 2005). Round goby are often reported to exist in polluted, as well as pristine, aquatic environments, and are thought to be a pollution tolerant species (Pinchuk et al. 2003). Consequently, it is feasible for round goby to act as a sentinel species to ascertain how invasive species demographics may be affected in contaminated habitats, and assess the potential for contaminant transfer in the ecosystem.

We have monitored round goby in Hamilton Harbour, ON, Canada for 11 years (2002–2012) to address two inter-related questions about species invasions. First, by monitoring round goby population demographics after their establishment in Hamilton Harbour (Vélez-Espino et al. 2010), we addressed how the population demographics of a successful invader are altered as they integrate and persist in a non-native ecosystem. Second, as Hamilton Harbour is an area with long-term heterogeneous contamination from industrial steel production, urban run-off and combined sewer overflows (RAP 1992, 2002), we can use round goby as a sentinel species to assess how a stressor, contamination from multiple sources, affects the population demographics of an established invasive species. Moreover, we assess the potential for this invasive species to be an ecosystem stressor by acting as a vector for mobilizing contaminants up trophic levels. To answer these questions we assessed a suite of demographic parameters, including: fish abundance, body size, body condition, proportion of the population in reproductive condition, gonadosomatic index (GSI), and the relative frequency of male alternative reproductive tactics (round goby males come as one of two morphs, guarding males and sneaker males; Marentette et al. 2009).

A previous study tracked the round goby population in Hamilton Harbour over a shorter period (Young et al. 2010), and found a decline in round goby abundance across time. We therefore predicted that round goby abundance in the Harbour would continue to decline and possibly stabilize as this species integrate into the ecosystem through predator–prey interactions. As mentioned previously, diet shifts to include more round goby have been documented in a number of predator species (Reyjol et al. 2010; Taraborelli et al. 2010; Dietrich et al. 2006; Truemper and Lauer 2005; Jakubas 2004; King et al. 2006; Somers et al. 2003), but a complete population crash of round goby would be highly unlikely without an extreme weather or disease event because this species is such a well-established invader with a high and rapid reproductive capacity (Davis 2009; Bomford and O'Brien 1995). As a predation response strategy, we predicted that on average body size and size-at-first-reproduction would decrease over time in the round goby population. This decrease in body size in response to predators is predicted to occur based on classic life-history theory models (Stearns 1976), and such shifts have been abundantly documented in aquatic invertebrates, (Ball and Baker 1996; reviewed in Riessen 1999), and in aquatic vertebrate species (Hernaman and Munday 2005; Johnson 2001; Reznick et al. 2001; Chivers et al. 1999). Again, we expected these patterns to stabilize over time as predator–prey interactions equilibrated. In addition, we assessed the relative frequency of round goby male alternative tactics over time, as it was previously predicted the guarding male morph would be more abundant earlier in the invasion process (Marentette et al. 2009). Finally, as a result of physiological contaminant burdens and endocrine disruption observed in fish from contaminated sampling areas (Marentette et al. 2010; Bowley et al. 2010), we predicted that round goby from sites with higher contamination would be less abundant, smaller, and have altered reproductive investment patterns compared to the fish from sites with lower contamination. Such trends have been observed in round goby and other fish species from contaminant burdened environments (Marentette et al. 2010; Kruitwagen et al. 2006; Canli and Atli 2003; Rowe 2003).

Methods

Sampling sites and collection methods

The data for this study extends the collections described in Young et al. (2010). Between 2002 and 2012, we sampled round goby in Hamilton Harbor, ON, Canada (43°N, 70°W), twice per month, from May through October of each sampling year. We collected round goby from the following sites: La Salle Park, Grindstone Creek, Desjardins Canal, Fisherman's Pier, Pier 27, and Sherman Inlet (43°N, 79°W; Fig. 1). The first four sites represent sites of lower contamination in Hamilton Harbour, while the latter two sites represent sampling sites with higher contamination (Zeman 2009). Sampling was conducted at low contamination sites from 2002 to 2012, while the high contamination sites were sampled only from 2006 to 2012. Choice and categorization of these sites was based on their proximity to contaminant sources (Marentette and Balshine 2012; Marentette et al. 2010). Hamilton Harbour is an International Joint Commission Area of Concern (International Joint Commission 1999), but contamination within the Harbour is heterogeneously distributed, and areas of highest contamination are associated with Randal Reef and the Windermere Arm (Zeman 2009; Pozza et al. 2004; RAP 2002, 1992; Fig. 1). These areas contain pollutants from historical industrial steel processing, extensive urban run-off, as well as combined sewer overflows and wastewater effluent discharge. The most prominent and concerning contaminants in these areas are polycyclic aromatic hydrocarbons, polychlorinated biphenyl, and metals such as lead, zinc, and cadmium (Zeman 2009; RAP 1992).

At each site, we sampled round goby using minnow traps baited with approximately 25 g of frozen corn kernels. Two traps were set at each site from the years 2002–2004, and four traps were set at each site from the years 2005–2012. Traps were set at least 10 m apart, each at a depth of 1 m, and approximately 5 m from the shoreline. Traps were recovered 24 h after being set, any traps that had washed up on shore, been accidentally opened, or intentionally tampered with were excluded. All fish were counted per trap and sexed by examining the urogenital papilla (Miller 1984). Any fish that were unable to be sexed were recorded as juveniles. Water

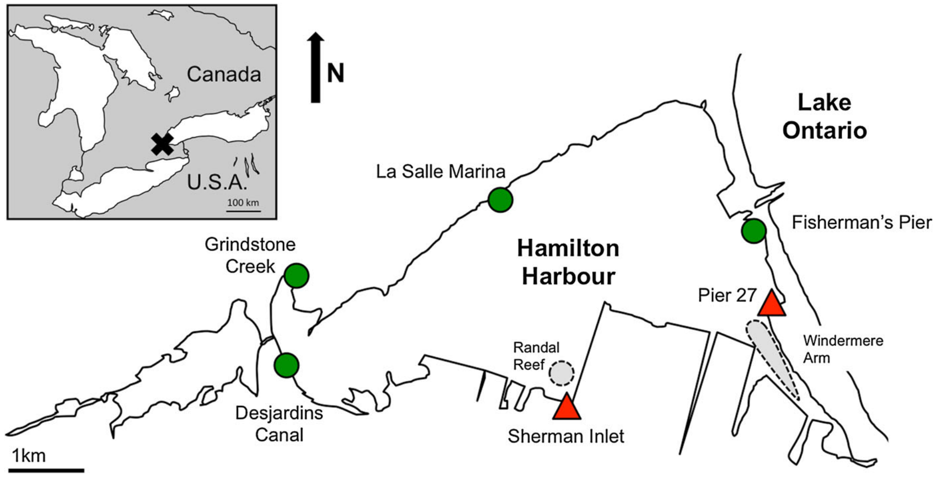

Fig. 1 A map of Hamilton Harbour, ON, Canada (43°N, 79°W), the western-most embayment of Lake Ontario, with sampling sites and areas of high contamination undergoing remediation plotted. *Circle* site markers show low contamination sampling sites, and *triangle* site markers show high contamination sampling sites. *Gray with black-hatched borders* show two highly contaminated areas of Hamilton Harbour undergoing remediation (RAP 1992, 2002). A *scale bar* depicts distance in kilometers

quality was assessed on each sampling date, and at each sampling site, by measuring water temperature, dissolved oxygen (Lamonte tracer probe), pH (YSI 550A and a multi-parameter 35 probe), and water clarity (Secchi disk). Fish were then euthanized and brought to the laboratory on ice for further analysis.

Morphological measurements

In the laboratory, round goby morphological parameters were measured. Standard length (snout to caudal peduncle), head width, and papilla length were taken using calipers measuring to the nearest 0.1 cm. Body mass, liver mass, and gonad mass were measured to the nearest 0.001 g using a digital balance (Acculab Vicon Digital Scale). Body condition was then determined using Fulton's body condition index ($10^5 \times$ [body mass (g)/standard length (mm)^3]) (Ricker 1975). Gonad mass was taken from 2004 onwards, allowing the GSI to be calculated for each fish as 100 × [gonad mass (g)]/[body mass (g) − gonad mass (g)] (Schreck and Moyle 1990). Round goby were classified as reproductive if their GSI exceeded 1 % for males and 8 % for females (Marentette and Corkum 2008; MacInnis 1997).

Statistical analyses

Statistical tests were performed using R version 2.15.2 (R Core Team 2012). Quantile–quantile plots were used to visually check normality. Population abundance, standard length, body mass, body condition, GSI, proportion reproductive, and the proportion of male reproductive tactics were analyzed by fitting data to linear mixed effects models using the "nlme" package (Pinheiroet al. 2013). We controlled for unknown among-site differences by allowing for sampling site to act as a random effect in our models. We included a linear effect of time, and the categorical effects of sex (male and female) and site type (low or high contamination) in our models. The model for population abundance also included a quadratic effect of time in order to test whether the rate of decrease of round goby population abundance was changing over time. Generally, year was centered at 2006, the first year of data collection at contaminated sites. However, the population abundance model was centered at 2002 when it was run for low contamination sites only. Any non-significant interactions were subsequently removed from further analyses. For each model, sample size for number of individuals (n) and either number of sites by year combinations (n_{s*y}), or number of sites by year by sex combinations (n_{s*y*s}) is given. With the exception of the analysis of population abundance, juveniles were not included in any of our models because sex cannot be assigned to juvenile fish.

We used number of fish per trap as a measure of population abundance, as this helped account for

Table 1 Total number of round goby collected, partitioned by sex, site, and year

	DC		GC		LS		FP		P27		SI	
	M	F	M	F	M	F	M	F	M	F	M	F
2002	226	128	90	64	185	88	287	118	–	–	–	–
2003	52	13	17	16	61	27	76	14	–	–	–	–
2004	77	72	46	58	51	26	90	57	–	–	–	–
2005	157	66	77	30	226	73	131	72	–	–	–	–
2006	180	56	59	24	193	98	116	64	9	6	83	45
2007	116	57	20	19	142	47	97	47	156	99	80	89
2008	78	35	16	4	71	29	42	21	65	16	62	51
2009	42	31	13	10	68	40	32	19	–	–	–	–
2010	41	14	30	6	180	69	125	41	192	68	69	58
2011	93	65	18	8	191	73	137	80	150	101	218	166
2012	88	64	32	10	136	48	161	78	202	109	108	64

sampling irregularities such as trap theft or breakage. Occasionally, extra traps were set at the four sites (away from the population sampling study traps) to collect fish for other experiments. These fish were excluded from the population abundance counts, but were measured and included in analysis of morphological characters. Hence, the sample sizes for population abundance analyses and morphological characteristic analyses are not identical. Male reproductive morph (guarding male or sneaker male) was assigned based on a linear discriminant analysis that included the following variables: seminal vesicle mass, seminal vesicle mass to testes mass ratio, and head width to standard length ratio. Guarding males typically have larger seminal vesicles and head widths (Marentette et al. 2009). Male round goby with reproductive tactics that could not be predicted with 80 % confidence were labeled as 'unknown'.

Ethical note

All methods for handling round goby were approved by McMaster University's Animal Research Ethics Board and adhere to the standards of the Canadian Council on Animal Care.

Results

Over the 11-year study, 9,052 round goby were collected from Hamilton Harbour. Of the fish caught, 8,666 could be sexed, and 363 fish were classified as sexually immature juveniles. An additional 23 fish were not recorded as males, females or juveniles, and were excluded from subsequent analyses. Overall, many more males ($n_{male} = 5{,}715$) were caught than females ($n_{female} = 2{,}951$), and when we examined the sex ratio on a trap basis, more traps were male-biased than female-biased [effect size (mean $\pm$ standard error) = 1.30 ± 0.20, $n = 8{,}666$, $n_{s*y} = 112$, $p \leq 0.001$: see Table 1 for abundance summary].

When we fitted a quadratic trend model to the population abundance data (from lower contamination sites only, allowing for among-site variation both in population abundance and in the quadratic trend), this model revealed a decrease in population abundance across time. The initial slope of the decline was 1.20 ± 0.40 fish/trap/year, but the magnitude of the decline decreased over time by 0.08 ± 0.03 fish/trap/year/year (i.e. a positive quadratic term). However, due to the small number of sites (only four) and the large variation among sites, these trends were not significant ($p_{linear} = 0.08$, $p_{quadratic} = 0.12$). We then fitted a model to the combined abundance data from low contamination and high contamination sites (Fig. 2) and incorporated differences in the time trends between low contamination and high contamination sites, removing these when non-significant. This created a model with linear and quadratic fixed effects of time and random among-site variation in these terms, with an additional term quantifying the

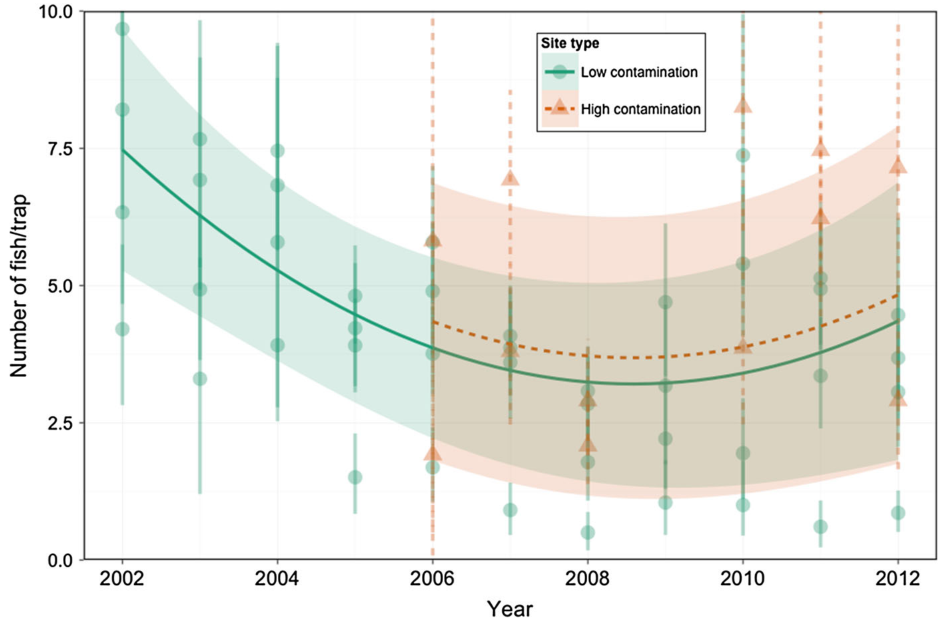

Fig. 2 Population abundance with *smooth lines* showing the predictions of a linear mixed effects model separated by site type (i.e. high or low contamination) with a quadratic trend in time. *Ribbons* indicate 95 % confidence intervals of the model predictions. *Background points* show mean number of fish per trap for each individual sampling site (*triangles* denote high contamination sites, *circles* denote low contamination sites), while *bars* around these *points* show 95 % confidence intervals for the mean value at each site

difference between low contamination and high contamination site types. With the augmented data sets, both the linear and quadratic terms were significant, and we found an estimated decrease of 0.51 ± 0.12 fish/trap/year in 2006 ($p = 0.01$), with the magnitude of this decline decreasing by 0.10 ± 0.03 fish/trap/year ($p = 0.03$). The estimated difference in population abundance between low and high contamination sites was small, and not statistically significant (0.48 ± 1.50 fish/trap, $p = 0.80$).

Next, we fitted linear trend models to data for body condition (Fig. 3a), body length (Fig. 3b) and body mass. Average body length was 7.00 ± 0.02 cm (range 3.40–13.20 cm), and average body mass was 10.10 ± 0.08 g (range 0.90–64.80 g), where males were longer and heavier than females (length: effect size = 1.10 ± 0.08 cm, $n = 9{,}438$, $n_{s*y*s} = 112$, $p \leq 0.001$; mass: effect size = 5.10 ± 0.30 g, $n = 9{,}439$, $n_{s*y*s} = 112$, $p \leq 0.001$). Males were also in better body condition than females (effect size = 0.05 ± 0.02 g/mm^3, $n = 9{,}434$, $n_{s*y*s} = 112$, $p = 0.02$). Across years, body length and body mass decreased (length: effect size = −0.10 ± 0.02 cm, $n = 9{,}438$, $n_{s*y*s} = 112$, $p = 0.004$; mass: effect size = −0.40 ± 0.10 g, $n = 9{,}439$, $n_{s*y*s} = 112$, $p = 0.01$), while in contrast, body condition increased over time (effect size = 0.015 ± 0.004 g/mm^3, $n = 9{,}434$, $n_{s*y*s} = 112$, $p = 0.03$). Fish from areas of low contamination were longer and heavier than the fish in high contamination areas (length: effect size = 0.80 ± 0.20 cm, $n = 9{,}438$, $n_{s*y*s} = 112$, $p = 0.008$; mass: effect size = 2.70 ± 0.50 g, $n = 9{,}439$, $n_{s*y*s} = 112$, $p = 0.008$), but body condition did not differ statistically between fish from low and high contamination sites (effect size = 0.09 ± 0.04 g/mm^3, $n = 9{,}434$, $n_{s*y*s} = 112$, $p = 0.10$).

A linear trend model was fit to GSI data and reproductive data. Investment in reproduction as measured by GSI did not change over time (effect size: 0.13 ± 0.10, $n = 7{,}808$, $n_{s*y*s} = 96$, $p = 0.26$), but fish from more contaminated sites had higher GSI than those from lower contamination sites (effect size: 1.43 ± 0.34, $n = 7{,}808$, $n_{s*y*s} = 96$, $p = 0.01$). However, when this model was run with only reproductive round goby (i.e. males with a GSI >1 %, and females with a GSI >8 %, see Methods section), the GSI difference between low and high contamination sites was no longer present (effect size: 0.63 ± 0.45, $n = 2{,}225$, $n_{s*y*s} = 94$, $p = 0.24$). Overall, 32 % of the males caught, and 24 % of the females caught were in reproductive condition. The proportion of reproductive fish did not change over time (effect size = 0.01 ± 0.01, $n = 8{,}118$, $n_{s*y*s} = 96$, $p = 0.22$; Fig. 4), but there was a larger proportion of reproductive males at high contamination sites, compared to males at the low contamination sites, and females at both site types (effect size = 0.10 ± 0.02, $n = 8{,}118$, $n_{s*y*s} = 96$, $p = 0.02$).

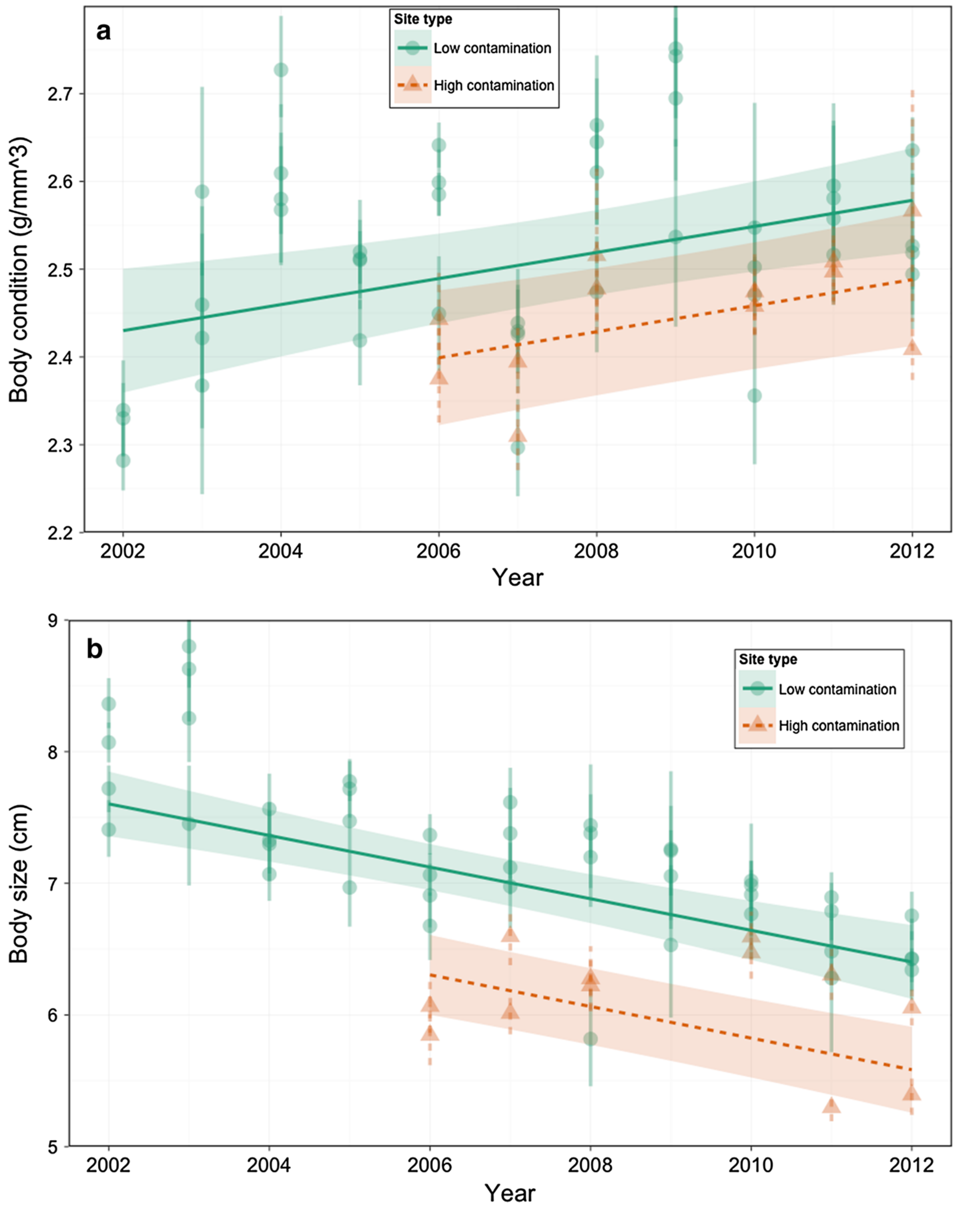

Fig. 3 **a** Body size with *smooth lines* showing the predictions of a linear mixed effects model separated by site type (i.e. high or low contamination). **b** Body condition with *smooth lines* showing the predictions of a linear mixed effects model separated by site type. For both panels, *ribbons* indicate 95 % confidence intervals of the model predictions. *Background points* show mean values for individual sites (*triangles* denote high contamination sites, *circles* denote low contamination sites), while *bars* around these *points* show 95 % confidence intervals for each mean value

Lastly, we fit a linear trend model to the male reproductive tactic data, and found that the proportion of guarding males did not change over time (effect size $= 0.001 \pm 0.01$, $n = 1{,}172$, $n_{s*y} = 42$, $p = 0.93$), nor did it vary between low and high contamination sites (effect size $= -0.1 \pm 0.09$, $n = 1{,}172$, $n_{s*y} = 42$, $p = 0.25$; Fig. 5).

Discussion

Summary

In support of our predictions, round goby abundance and body size declined across time. However, we found that round goby were equally abundant at low

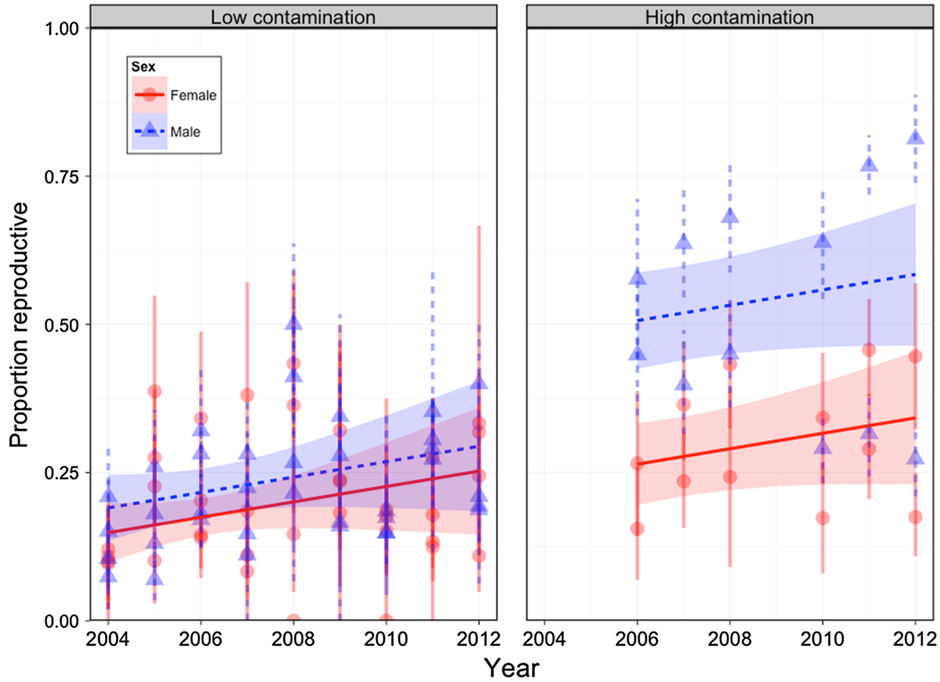

Fig. 4 Proportion of reproductive round goby across sampling years faceted by site type (i.e. high or low contamination). *Smooth lines* show the predictions of a linear mixed effects model separated by sex. *Ribbons* indicate 95 % confidence intervals of the model predictions *Background points* show the mean proportion of reproductive round goby at individual sites (*triangles* denote males, *circles* denote females), while *bars* show 95 % confidence intervals for each mean value

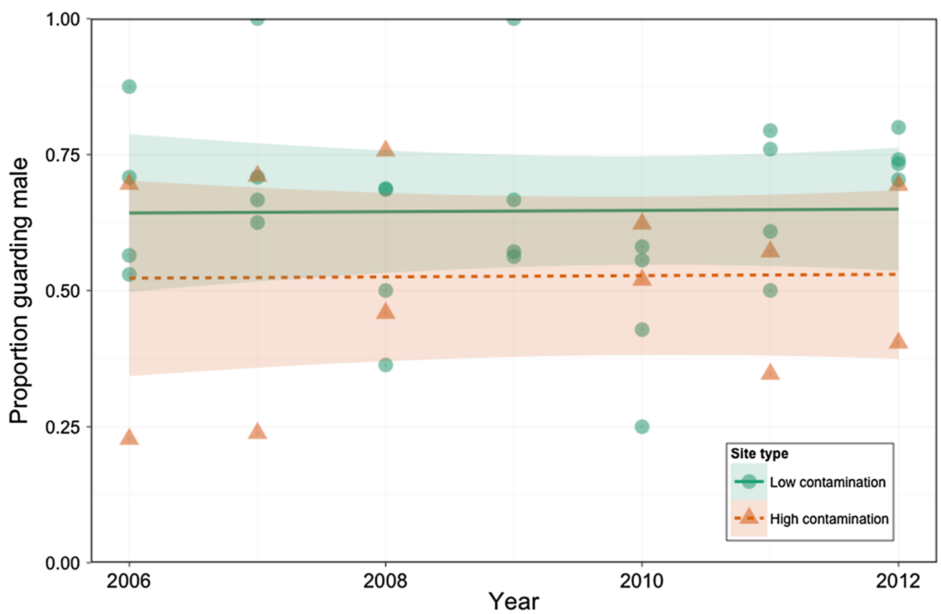

Fig. 5 Proportion of guarding males across sampling years with *smooth lines* showing the predictions of a linear mixed effects model separated by site type (i.e. high or low contamination). *Ribbons* indicate 95 % confidence intervals of the model predictions, while *background points* show mean proportion of parental males at individual sites (*triangles* denote high contamination sites, *circles* denote low contamination sites)

and high contamination sites within the Harbour. Again, in support of our predictions, round goby were smaller at contaminated sites, but surprisingly fish at these sites had higher investment in reproduction, and a greater proportion of reproductive males were observed. In contrast to our original predictions, we found no difference in the relative abundance of male alternative reproductive morphs across sampling years, or between sites of varying contaminant load. The implications of these findings will be discussed in detail below.

Trends across sampling years (2002–2012)

While round goby abundance declined across the years we sampled, the rate of decline stabilized in recent years. Additionally, we observed a similar decline in body size (both length and mass) across years. Taken together, these findings strongly indicate that round goby in Hamilton Harbour may have initially increased beyond their carrying capacity and density saturation threshold (Vélez-Espino et al. 2010), but once high intra- and interspecific competition for food and shelter ensued this may have selected for slower growth, smaller overall body size, and even an eventual reduction in overall abundance (Blanckenhorn 2000; Peters 1983). The declines in body size and abundance may have also been the result of predators such as double-crested cormorants (Somers et al. 2003), and larger fish species such as yellow perch, largemouth and smallmouth bass, northern pike, and walleye (Reyjol et al. 2010; Taraborelli et al. 2010; Dietrich et al. 2006; Truemper and Lauer 2005) recognizing and consuming the round goby as a prey source as the goby became established in the Harbour. Indeed, these predator species have been surveyed in close proximity to our sampling sites (Bowlby et al. 2010; Brousseau and Randall 2008; Somers et al. 2003), and round goby are known to be a substantial prey source for these species (Hossain et al. 2012). In support of this idea, Brownscombe and Fox (2013) showed that round goby tethered in established locations receive more predation events than round goby tethered in newly invaded areas with naïve predators. Conversely, body condition increased across sampling years, and this may be associated with the declines in abundance. Increased predation may lead to lower intraspecific competition for food and shelter resources, facilitating improved body condition. Though our sampling and subsequent removal of round goby from Hamilton Harbour occurred frequently (twice per month), it did not affected population abundance trends; had this had occurred we would have observed a continuous decline across years and within each sampling season, and this pattern was not observed. These findings highlight the equilibration process that occurs between native species and an invading species when they persist beyond establishment and integrate into the ecosystem of an invaded area. This phenomena of population decline after initial population expansion has been documented in other invaders, including the zebra mussel invasion of the Great Lakes (Petrie and Knapton 1999; Schloesser and Nalepa 1994), and in pike, killifish and black acara invasions of the wetlands of Florida, United States (Trexler et al. 2000). It has been theorized that population saturation and increased predation pressure interact to cause the observed cases of invasive species boom-and-bust dynamics (Davis 2009; Simberloff and Gibbons 2004).

The relative abundance of male reproductive morphs remained constant across sampling years. Marentette et al. (2009) had predicted, based on theory of alternative reproductive tactics (Gross 1996), that the guarding male reproductive morph would be more abundant during the earlier stages of an invasion when there would have been less male–male competition for defendable nests and mating opportunities, followed by a subsequent rise in the relative abundance of the sneaker male reproductive morph as the population density and competition for nests increased. In our population monitoring of round goby in Hamilton Harbour, we may not have captured the earliest stages of the round goby invasion, and it is possible that the proportion of each male reproductive tactic had already settled into an equilibrium state, as the population was established by the start of our sampling regime.

Trends between sites of low and high contamination

Round goby were equally abundant at both low and high contamination sites suggesting that highly contaminated areas are not barriers to round goby establishment. The presence of round goby at these contaminated sites over a long time-span, and at similar densities to low contamination sites, supports previous claims that the round goby is a pollution tolerant species (Pinchuk et al. 2003). These results underscore the management concerns for this invasive fish species which provides a potential pathway for the transport of contaminants up trophic levels in invaded ecosystems. Indeed, contaminant transfer from zebra mussel, to round goby, to smallmouth bass has already been documented in Lake Erie (Hogan et al. 2007; Kwon et al. 2006), making this issue a present and serious concern for Lake Ontario.

Though contaminant load did not prevent round goby from residing in areas of high contamination, fish collected from these sites were smaller overall. Smaller body size has been documented in marine and freshwater fish when collected from areas of prolonged contamination (Kruitwagen et al. 2006; Canli and Atli

2003), and reduced growth has been observed when fish were raised on contaminated sediments (Rowe 2003). Previous work has shown that round goby collected from our high contamination sampling sites in Hamilton Harbour were younger when aged using otolith analyses (JR Marentette, unpublished data), perhaps indicating earlier mortality in high contamination sites, reduced recruitment at low contamination sites, or a habitat-use shift with increasing age. The round goby collected from contaminated sites had a higher proportion of males in reproductive condition (~50 %, compared to ~25 % at low contamination sites), and had a larger relative investment in reproductive tissue across both sexes (as measured by gonadosomatic index). Evidence of endocrine disruption and intersex have been reported in other aquatic species from contaminated sites Hamilton Harbour (Kavanagh et al. 2004; Arcand-Hoy and Metcalfe 1999; de Solla et al. 1998), and in round goby (Bowley et al. 2010; Marentette et al. 2010). It is possible that these differences in reproductive characteristics are linked to the presence/absence of contaminants at our high contamination versus low contamination sampling sites (Marentette et al. 2011; Zeman 2009; RAP 2002), however, controlled exposure experiments would be necessary to elucidate whether the compounds causing these reproductive irregularities. The above findings emphasize how the population dynamics of an invasive species can be altered in response to an environmental stressor, and show that these demographics can vary even within a small geographical range and while the invasive species is equilibrating with the ecosystem.

Caveats

This study updates our understanding of round goby population dynamics initially presented in Young et al. (2010). Our study further expanded the previous work by adding additional sampling years, sampling at highly contaminated sites, as well as new variables of interest. These results provide a more thorough analysis of the demographics of the round goby population in Hamilton Harbour, and to also address how aspects of the environment (i.e. contaminant load) may affect the demographics of invasive species. We sampled fish using minnow traps that have previously been thought to under-represent round goby population abundance, especially for young-of-the-year fish (compared to seine net or trawling; Johnson et al. 2005). Indeed, we caught few juveniles over the 11-year study. However, given the Harbour's varied substrates with large rocks and boulders, the long-term nature of the study, and the extensive sampling area covered, trapping was the most feasible, consistent and viable method to record changes in adult abundance. Furthermore, we must acknowledge two issues of long-term monitoring that the current work does not address. First, we cannot guarantee that our sampling sites represent separate distinct populations. Due to the pelagic phase of round goby larvae (Hensler and Jude 2007), it is likely that they are not distinct, but genetic relatedness assays would be required to confirm this statement. However, adult round goby are known to be highly philopatric (Marentette et al. 2011; Ray and Corkum 2001), indicating that our results are most attributable to environmental differences between sampling sites of varying contaminant load. Second, we treated our high contamination sampling sites as a uniform stressor on round goby, but we recognize that contaminants are likely to be present at different concentrations and forms at each site. We have attempted to account for this variability in our statistical modeling by allowing individual sites to act as a random effect.

General conclusions

We have characterized the persistence and integration stages of an invasion a highly successful invasive species in the Laurentian Great Lakes, the round goby. Our work has documented how the population characteristics of a well-established invasive species can shift across time as they equilibrate with the non-native ecosystem, and also how an environmental stressor can impact these characteristics, even within a small geographic range. Our results have important implications for understanding the maintenance of round goby population abundance through potential predator–prey interactions. While round goby may have a positive impact on some native species by providing a food source, negative impacts from the mobilization of contaminants to higher trophic levels in the invaded ecosystems underscores the importance for close monitoring and management of round goby in areas of contamination. We will continue to monitor the round goby population in Hamilton Harbour, with specific focus on the declining body size and abundance of round goby in the Harbour, as this will have direct consequences for their interactions with native species. Future work will focus on elucidating the mechanisms behind the increased proportion of males in reproductive condition, higher reproductive tissue investment, and smaller body size at contaminated sites using controlled contaminant exposure studies. Combining this experimental work with our long-term population monitoring data, will allow us to thoroughly understand the mechanisms causing the patterns observed at the population level, both across time and spatial scales.

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