

Chronic Nutrient Enrichment Increases the Density and Biomass of the Mudsnail, *Nassarius obsoletus*

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Abstract In summer 2009, the effects of 6 years of landscape-level experimental nutrient enrichment on the eastern mudsnail, *Nassarius obsoletus* (formerly *Ilyanassa obsoleta*), were examined. The experiment was conducted in five tidal creeks (two nutrient-enriched, three reference creeks) in the Plum Island Estuary, Massachusetts, USA. (42°44' N, 70°52' W). After 6 years of enrichment, *N. obsoletus* size structure differed between treatment creeks with adult snails on average 14 % larger in enriched creeks. *N. obsoletus* densities (in individuals per square meter) and biomass (in grams dry weight per square meter) were four times higher in nutrient-enriched versus reference creeks. Nutrient enrichment did not significantly affect the biomass of benthic microalgae (a *N. obsoletus* food resource), but snail density was significantly correlated with benthic microalgal biomass, suggesting bottom-up control of snails. *N. obsoletus* is abundant on the east and west coast of North America; thus, *N. obsoletus* density and biomass may be useful variables for monitoring eutrophication effects on North American estuaries.

Keywords Biomonitoring · Bioindicator · Eutrophication · *Ilyanassa obsoleta* · Estuarine management · Bottom-up

Introduction

Human activity in watersheds increases riverine flux of nitrogen to coastal waters (Green et al. 2004), which can ultimately impair coastal water quality and ecosystem health (Nixon 1995, Diaz and Rosenberg 2008, Deegan et al. 2012). Understanding the impact of nutrient enrichment on key organisms in estuaries such as primary producers (Levine et al. 1998; Wigand et al. 2003; Fox et al. 2009) and invertebrate consumers (Bertness et al. 2008; Fleeger et al. 2008) is crucial to understanding how ecosystem function is altered under enriched conditions (Deegan et al. 2007; Fox et al. 2009). Mollusks are ecologically (and often commercially) important benthic species in estuaries and are thus excellent organisms to study nutrient-enrichment effects.

From the Bay of Fundy to northern Florida, legions of the mudsnail, *Nassarius obsoletus* (formerly *Ilyanassa obsoleta*¹), stipple the tidal-flat landscape at low tide. Despite the common name of “eastern mudsnail”, *N. obsoletus* is now also found in great abundance on the west coast of North America where it is non-native (Carlton 1992). Little is known, however, about the effects of nutrient enrichment on this abundant and widespread snail.

Nutrient enrichment may affect mudsnails via changes in algal food resources (e.g., increased benthic microalgal

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¹ *N. obsoletus* (Say 1822) has gone through many name changes since it was first described; most recently from *Ilyanassa obsoleta* to *N. obsoletus* (Turgeon et al. 1998). At this writing, the Integrated Taxonomic Information System (www.its.gov) lists this snail as *N. obsoletus* based on Turgeon et al. (1998). The World Registry of Marine Species (www.marinespecies.org) lists this snail as *I. obsoleta* based on Malacolog (www.malacolog.org). Both names have been used over the past 14 years but we follow Turgeon et al. (1998) and use *N. obsoletus*.

biomass). Adult *N. obsoletus* are omnivorous, feeding both on plant and animal tissue (Scheltema 1964), and require a mixed diet to sustain growth and survival (Curtis and Hurd 1979). While not a strict herbivore, *N. obsoletus* does feed heavily on benthic microalgae, particularly diatoms (Bianchi and Levinton 1981; Connor and Edgar 1982; Novak et al. 2001). Juveniles are thought to be obligate herbivores (Brenchley 1987) with the presence of diatoms being an important environmental cue for metamorphosis of planktonic larvae (Leise et al. 2009).

Given that nutrient enrichment can affect local food availability, changes in *N. obsoletus* density and biomass are likely the most obvious responses to enrichment. Observing these responses, however, may require sampling at large temporal and spatial scales. *N. obsoletus* are highly aggregated in their distributions (Levinton et al. 1995; Hamilton et al. 2006). Fertilization studies at small spatial (e.g., 1 m²) and temporal (<1 year) scales have demonstrated an aggregative response of *N. obsoletus* to an increase in localized food (algal) patches (e.g., Hamilton et al. 2006). These responses, however, are simply a post-settlement redistribution of individuals as snails move from a food-poor to a food-rich patch at small scales (Kelaher et al. 2003; Hamilton et al. 2006). Anthropogenic nutrient enrichment affects entire ecosystems, and, thus, at the landscape scale (hectares), changes in snail density can indicate a population-level response to enrichment. Further, *N. obsoletus* have slow growth rates (~6 mm year⁻¹ in their first 3 years; then 0.2–1.5 mm year⁻¹ to a maximum of 35-mm shell height; Curtis and Hurd 1983; Curtis et al. 2000), and observable changes in size structure and population dynamics likely require >1 year to manifest (i.e., first-year snails, at 6-mm shell height, are difficult to detect).

In this study, we examined the response of *N. obsoletus* populations to large-scale (4–5 ha), long-term (6-year) nutrient enrichment. We hypothesized that nutrient enrichment would lead to increased snail density and individual size, and, as a result, increased biomass, with these changes being driven by benthic microalgal availability.

Methods

Site Description

This study was conducted in five first-order (primary) tidal creeks in the Plum Island Estuary, Massachusetts. These creeks are all located within or near the broader salt marsh that lines the 14.5-km Rowley River estuary (42°44' N, 70°52' W, site map in Johnson 2011). Tidal creeks are similar in length (300–500 m) and volume (4.1–7.5 × 10⁶ L) (Johnson et al. 2007). The vegetated marsh platform is bordered at the creek edge by a 2–

3-m band of tall-form *Spartina alterniflora* (~1.5-m shoot height in August). The high-marsh platform (above mean high water) is dominated by *Spartina patens* mixed with *Distichlis spicata*. Creeks have steep-sided walls (~1.5–2-m depth). The term “mudflat” is used here to describe patches of mud that form part of the creek bottom and are exposed at low tides. Tidal creek bottoms are 1–4.5-m wide with 60–70 % of the creek bottom exposed at low tide. Mudflats (0.5–1 m wide) are on either side of the deepest part of the creek channel (i.e., the thalweg), which bisects the creek bottoms and has shallow water flows (5–20 cm) at low tide. Thus, the mudflats in this system are not the mudflats typically described in more open water bays and sounds, which can be hundreds of meters to kilometers wide. Within the mudflats, benthic microalgae (predominately diatoms) are the dominant primary producers, with macroalgae such as *Ulva lactuca* being uncommon in these habitats (Galván et al. 2008; DSJ personal observation).

Nutrient Additions

Two creeks were selected to receive nutrient enrichment and three creeks remained as references. Reference creeks were relatively pristine with regard to water column nutrient concentrations (background concentrations of <5 μM NO₃⁻, ~1 μM PO₄³⁻; Deegan et al. 2007). To mimic anthropogenic nutrient enrichment, nutrients were added in solution to the water column of each creek with a targeted concentration of 50–70 μM NO₃⁻ and 6 μM PO₄³⁻ with each flooding tide. This was achieved by pumping a concentrated nutrient solution into the twice-daily flooding waters with the pump rate adjusted every 10 min throughout the flooding tide to maintain targeted concentrations. Nutrients were added on at least 120 days during the plant growing season (mid-May to mid-September) of each year from 2004 to 2009. Nutrient enrichment concentrations were typical of those found in estuarine systems designated as moderately to severely eutrophic by the Environmental Protection Agency (2002).

Shell Height–Biomass Regression of *N. obsoletus*

To generate a shell height (SH)–mass relationship for *N. obsoletus*, 100 snails (13.30–24.40-mm SH) were collected in June 2009. Snails were allowed to evacuate their guts for 24 h before measurements were taken. Snail SH was measured in millimeters with Vernier calipers from the apex of the spire to the tip of the siphonal notch, and the snails (without shells) were dried in pre-weighed tins in a 70 °C oven to a constant mass (typically 24 h). Based on those measurements, the following equation was used to estimate

the shell-free dry weight (in grams) of snails for biomass estimates:

$$\text{Shell-free dry weight (g)} = 0.01(\text{SH in mm}) - 0.0904$$

$R^2=0.50$, $p=3.7 \times 10^{-16}$, intercept standard error (SE)=0.018, slope SE=0.010.

The spires of some shells were eroded, which, despite a significant relationship, may have decreased the explanatory power (as indicated by an R^2 of 0.50) of SH for biomass.

N. obsoletus Density, Size Structure, and Biomass

Snail densities were estimated by counting all individuals hand-collected within a haphazardly thrown quadrat (0.0625 m²) on the mudflat at low tide in August 2009. Ten quadrats were tossed within a 200-m section of each creek (total of 50). Prior to nutrient enrichment (1999–2003), snail densities were higher in reference creeks (13–94 individuals per square meter) versus creeks to be enriched (0–2 individuals per square meter; Fig. 1).

To estimate snail body size, 10 snails from each quadrat were randomly selected and measured for SH (on average, 10 individuals comprised 40 % of the snails in each quadrat). *N. obsoletus* are considered sexually mature adults at SHs ≥ 14 mm (Curtis and Hurd 1983). We categorized snails as sexually mature adults (≥ 14 -mm SH) or juveniles (< 14 -mm SH), which provided an estimate of size-class proportions per quadrat (% juvenile, % adult). We estimated *N. obsoletus* biomass (grams dry weight per square meter) as the snail density per quadrat multiplied by average individual biomass (grams dry weight per individual, based on SH-biomass regression) for that quadrat.

Benthic Microalgal Biomass

Because benthic microalgae—represented in the mudflats of the current study system primarily as vertically

migrating diatoms (Galván et al. 2008)—is an important food source to *N. obsoletus* and could influence snail growth and density; we examined the effect of nutrient enrichment on benthic algal biomass (measured as benthic chlorophyll *a* (chl *a*)). Ten benthic cores (push corer, 2.7-cm diameter, 2-cm depth) were taken in exposed mudflats along a 200-m stretch of each creek in August 2009. Cores were frozen and total chl *a* (milligram chlorophyll *a* per square meter) was determined (Lorenzen 1967; acetone extraction and spectrophotometric analysis). Prior to nutrient enrichment (1998–2003), the average chl *a* concentration in creeks to be enriched was 63 mg chl *a* m⁻² and 94 mg chl *a* m⁻² in reference creeks (Deegan et al. 2007).

Statistical Analyses

Given that our sampling was hierarchical (occurring at different scales; e.g., quadrats within creeks within nutrient level) for many variables, we used linear mixed-effects models to detect effects of nutrient enrichment and to determine the spatial scale with the highest variability. In these models, nutrient level was the fixed effect and random effects were the nested components (creek, quadrat, and individual) for a particular response variable. Variance component analysis was used to determine the level of variability associated with each scale (creek, quadrat, or individuals). These analyses were performed in JMP (v. 7, SAS Institute Inc., Cary, North Carolina, 1989–2007).

To detect differences in the size distribution of snails, Kolmogorov–Smirnov (K-S) tests were conducted on SH. K-S tests were first conducted on creek pairs within treatments (one pair for nutrient creeks, three pairwise combinations for reference creeks) to determine if pooling creeks within treatments was justified (i.e., are size distributions between creeks within a treatment similar?). The nutrient creek pairs were similar ($p=0.22$); however, only one creek pair within reference creeks was similar ($p=0.67$; other creek pairings $p \leq 0.04$). To avoid spurious results, we pooled the similar creek pair for reference creeks and compared it to the pooled nutrient creeks using a K-S test (enrichment $n=200$, reference $n=200$).

To examine potential bottom-up effects of benthic algal biomass on *N. obsoletus* density, the average snail density for each creek was regressed against the average benthic microalgal biomass (as chl *a*). Because snail density and benthic microalgal biomass was estimated with sampling error, a model-2 (major axis) regression was used (Legendre 1998). Model-2 regression and K-S tests were performed in R (R Development Core Team 2009).

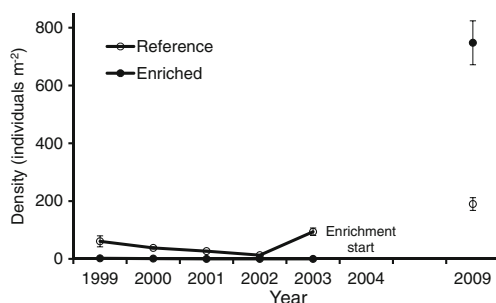


Fig. 1 Mean (± 1 SE) density of *N. obsoletus* in the tidal creeks of the Plum Island Estuary (PIE, Massachusetts, USA). Nutrient enrichment began in 2004. Pre-treatment data (1999–2003, $n=20$ –200) were collected by the PIE-Long Term Ecological Research program and is available at <http://ecosystems.mbl.edu/pie/>. Post-treatment data (2009, enriched $n=20$ and reference $n=30$ quadrats) were collected in present study

Results

N. obsoletus Density, Size Structure, and Biomass

N. obsoletus SHs ranged from 1.65 to 24.65 mm, though 99 % had a SH ≥ 8.00 mm. The size distributions between treatments differed significantly (K-S: $D=0.34$, $p<0.001$; Fig. 2), with a higher mean juvenile proportion (< 14 -mm SH) in nutrient-enriched creeks (32 %) than in reference creeks (17 %), though not so significantly ($F_{1,3}=0.35$, $p=0.596$). Despite the differences in size structure, mean SHs of individuals were not significantly different between treatments (nutrient = 15.60 mm vs. reference = 15.09 mm; $F_{1,3}=0.94$, $p=0.399$). Examining only adults (≥ 14 -mm SH), snails in enriched creeks were significantly larger by 14 % (mean SH: 17.97 mm) than in reference creeks (mean SH: 15.86 mm) ($F_{1,3}=39.31$, $p=0.008$).

Mean *N. obsoletus* densities were 3.9 times higher in enriched creeks (748 snails m^{-2}) than in reference creeks (190 snails m^{-2}) ($F_{1,3}=61.75$, $p=0.004$; Fig. 1). The mean shell-free biomass of *N. obsoletus* was significantly higher by 4.0 times in enriched creeks (1090 g DW m^{-2}) than in reference creeks (273 g DW m^{-2}) ($F_{1,3}=32.35$, $p=0.011$, Fig. 3).

Benthic Microalgae Biomass

Mean benthic microalgal biomass was higher, though not so significantly, in nutrient-enriched creeks (82 $mg\ m^{-2}$) than in

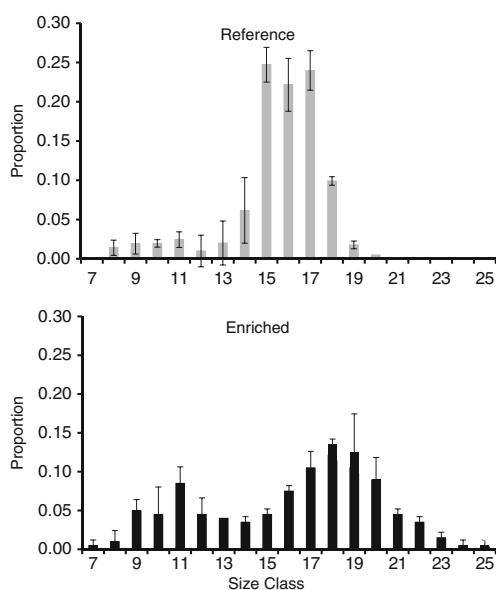


Fig. 2 Size distributions of *N. obsoletus* based on shell heights expressed as mean proportions (± 1 SE, enriched $n=2$, reference $n=3$). *X*-axes represent size class bins in 1-mm increments where the number represents largest size in that size class (e.g., 7=snails ≤ 7.00 but >6.00 -mm shell height). In enriched creeks, two snails were found in size class 2, representing a proportion of 0.005. Size class 2 was not included for figure clarity

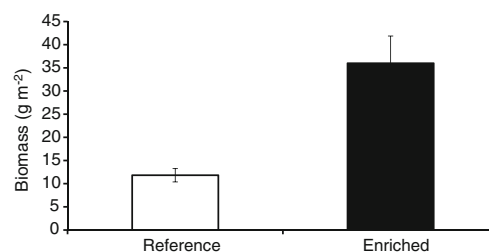


Fig. 3 Mean (± 1 SE, enriched $n=20$ and reference $n=30$ quadrats) *N. obsoletus* biomass in reference and nutrient-enriched creeks

reference creeks (47 $mg\ m^{-2}$; $F_{1,3}=5.35$, $p=0.104$; Fig. 4). The high small-scale variability (almost 100 % of the variation occurred among cores within a branch) may have affected our ability to detect nutrient effects (Tables 1 and 2). Despite this, a p value of 0.104 in a large-scale study such as this may be considered ecologically, if not statistically, significant (Carpenter et al. 1995, Schindler 1998). Snail density was significantly and positively related to chl *a* concentration (major-axis regression model; slope = 15.3 (95 % CI 7.7–612) intercept = -518 (95 % CI $-36,814$ to -57), one-tailed $p=0.02$; Fig. 5).

Variance Component Analysis

Most of the variation in this system for each response variable of *N. obsoletus* occurred at the scale of the sampling unit (Table 2). A similar trend was observed by Johnson et al. (2007) in this system for annelids. The high small-scale variability in this system may have resulted in low statistical power to detect significant nutrient effects. The response variables that were significant were often those with large effect sizes (e.g., snail density and biomass) and were robust in spite of the high patchiness of the system.

Discussion

N. obsoletus responded to 6 years of nutrient enrichment with a four-time increase in density relative to reference creeks. This result is compelling, considering that prior to

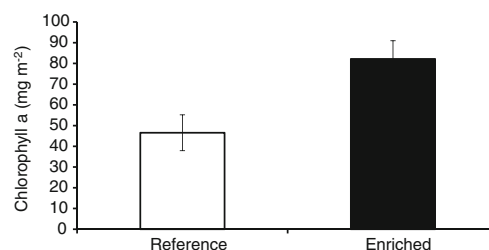


Fig. 4 Mean (± 1 SE, enriched $n=20$ and reference $n=30$ cores) chl *a* concentration as a measure of benthic microalgal biomass in reference and nutrient-enriched creeks

Table 1 Summary of fixed effects (nutrient vs. reference) for chl *a* and *N. obsoletus* response variables from linear mixed-effects models

Variable	<i>F</i> value	<i>P</i> value
Snail density (ind. m ⁻²)	61.75	<i>0.004</i>
Snail biomass (gm ⁻²)	32.35	<i>0.011</i>
Proportion juvenile	0.35	0.596
Shell height (mm); all snails	0.94	0.399
Shell height (mm); adults only	39.31	<i>0.008</i>
Chl <i>a</i> (mgm ⁻²)	5.35	0.104

Degrees of freedom for all *F* statistics are 1, 3. Values set in italics indicate significance at an $\alpha \leq 0.05$. Corresponding results for random effects are presented in Table 2

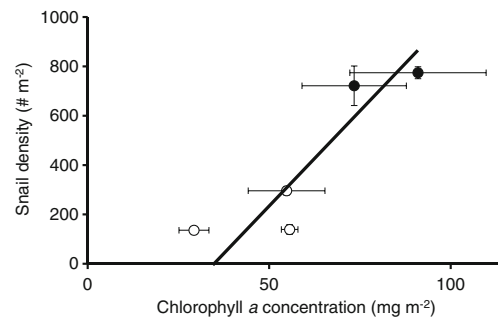
enrichment, reference creeks had higher snail densities than creeks to be enriched (often with no snails found in creeks to be enriched, Fig. 1). Thus, nutrient enrichment may strongly influence *N. obsoletus* densities. Similarly, Fox et al. (2009) observed that *N. obsoletus* densities were 67 times higher in a highly eutrophic estuary (600 ind. m⁻²) than in an oligotrophic estuary (9 ind. m⁻²) in Waquoit Bay (Cape Cod, Massachusetts, USA).

Although there was no statistically significant difference in mudflat benthic microalgal biomass between enriched and reference creeks, there was a strong positive relationship between snail density and benthic microalgal biomass among creeks. This relationship suggests bottom-up control of *N. obsoletus* populations. Further, mean SH of individual adult *N. obsoletus* (>14-mm SH) was 14 % greater in nutrient-enriched creeks. This per-capita-size increase, coupled with the large density increase, resulted in a four-time

Table 2 Variance component analysis of random effects for chl *a* and *N. obsoletus* response variables from linear mixed-effects models

Variable	Random effect	Variance	% of total variance
Density (ind. m ⁻²)	Creek(Trt)	619	1
	Quadrat(Creek,Trt)	54,228	99
Biomass (gm ⁻²)	Creek(Trt)	26	10
	Quadrat(Creek,Trt)	233	90
Proportion juvenile	Creek(Trt)	0.008	6
	Quadrat(Creek,Trt)	0.119	84
SH (mm); all snails	Creek(Trt)	0	0
	Quadrat(Creek,Trt)	2.3	23
	Snail(Quad,Creek,Trt)	7.68	77
SH (mm); adults only	Creek(Trt)	0.10	4
	Quadrat(Creek,Trt)	0.02	1
	Snail(Quad,Creek,Trt)	2.49	95
Chl <i>a</i> (mgm ⁻²)	Creek(Trt)	4.43	0
	Cores(Creek,Trt)	1524	100

SH shell height, Trt treatment

**Fig. 5** Mean *N. obsoletus* density (± 1 SE, $n=10$ quadrats) and chl *a* concentration (± 1 SE, $n=10$ benthic cores). Open circles represent reference creeks and filled circles nutrient-enriched creeks. Model-2 regression line overlays data

increase in the average biomass (grams shell-free dry weight per square meter) of snails in enriched creeks versus reference creeks. Nutrient enrichment has led to increased animal biomass in this system for other taxa (e.g., killifish, Deegan et al. 2007; annelids, Johnson and Fleeger 2009; snails and small crustaceans, Johnson 2011), suggesting that nutrient stimulation at the base of the food web can support higher consumer biomass.

Concurrent with the bottom-up effects of benthic algal biomass (as stimulated by nutrients) on *N. obsoletus* were the reciprocal top-down effects of grazing of *N. obsoletus* on benthic microalgae. In enriched creeks, benthic algal primary production (as opposed to biomass) was 40 % higher than in reference creeks (S. Sheldon, unpublished data) but did not result in significantly higher standing stocks of benthic microalgae after 6 years of enrichment. Pascal et al. (2012) found that a subset of grazers, including *N. obsoletus*, consumed 2.5 times more benthic microalgal production in nutrient-enriched creeks than in reference creeks, suggesting that grazing is masking bottom-up effects of nutrients on algal biomass. Thus, grazing and nutrient enrichment likely have simultaneous yet opposite effects on benthic microalgae.

A question arises as to how nutrients ultimately lead to increased *N. obsoletus* densities. New individuals in a local population may be the consequence of post-settlement movement (an aggregative response; Hamilton et al. 2006) or the metamorphosis and settlement of planktonic larvae. It is likely that both mechanisms resulted in increased densities. While settled snails will aggregate around locally-rich food inputs at small scales (Kelaher et al. 2003; Hamilton et al. 2006), there is no evidence that snails detect increased biomass of benthic microalgae in enriched creeks and migrate towards them. Thus, it is unlikely that snails migrated from the broader estuary (creek entrances are at least 500 m away) into the nutrient-enriched creeks by detecting higher chl *a* concentrations. If we assume, however, a random walk model of foraging by snails, those individuals that find enriched food patches (i.e., nutrient-enriched creeks) may

remain as part of the resident population in these creeks. Thus, over the years, the population grows.

Moreover, our finding of proportionally more juveniles in the populations in enriched creeks suggests that the recruitment of new snails to the population may have also contributed to population changes with nutrient enrichment. Nutrient enrichment stimulates benthic microalgae production, which may favor the settlement of snail larvae from the water column. The planktonic larvae of *N. obsoletus*, which are widely dispersed (particularly in macrotidal systems) can be induced to metamorphose by the presence of particular diatoms (Leise et al. 2009). A density increase may thus be explained, in part, if nutrient enrichment stimulates the abundance of diatoms that stimulate settlement and metamorphosis of planktonic snail larvae.

The timing of our sampling should be noted regarding our findings. Curtis and Hurd (1983) found first-year snails in August–October with a maximum SH of 6 mm in a Delaware, USA, estuary. In our study system, *N. obsoletus* produces eggs in mid- to late June (DSJ personal observation over 3 years). Snail larvae can remain in the water column ~30 days in the laboratory (Scheltema 1961) after emergence from eggs. After hatching, assuming the same developmental time in the field, the larvae would settle and metamorphose in late July to mid-August as first-year snails. Newly settled snails are ~1-mm SH (Scheltema 1964) and grow ~6 mm year⁻¹ (Curtis and Hurd 1983). While we sampled during the snail growing season (growth occurs from late spring to early fall; Curtis and Hurd 1983), we did not adequately sample first-year snails (≤6-mm SH) because 99 % of the snails detected were >8-mm SH. We did detect some second-year snails (6–12 mm SH; Curtis and Hurd 1983).

Other factors such as predation and parasitism may impact snail densities. It is unlikely that predation is responsible for the density changes observed between enriched and reference creeks. Two common predators of *N. obsoletus*—diamondback terrapins, *Malaclemys terrapin*, and blue crabs, *Callinectes sapidus*—are not found in Plum Island marshes. The invasive green crab, *Carcinus maenas*, is found in Plum Island marshes and was abundant prior to nutrient enrichment (Young et al. 1999) but has declined dramatically across the estuary and was rarely encountered during the enrichment years of this study (Deegan et al. 2007, DSJ personal observation). This decrease in green crab abundances may explain the estuary-wide increase in *N. obsoletus* during enrichment years (snail densities in all creeks were higher post-enrichment versus pre-enrichment). Black-bellied plovers (*Pluvialis squatarola*), least sandpipers (*Calidris minutilla*), and willets (*Tringa semipalmata*) also prey upon *N. obsoletus* (Recher 1966), but no changes in these bird abundances were detected among

creeks (S. Wilkins, D.S. Johnson, unpublished data). Sandpipers forage more frequently on intertidal mudflats in nutrient-enriched than reference creeks (Johnson et al. 2009); snail abundances, however, increased in nutrient creeks, rather than decreasing as would be expected if there were strong top-down control by birds. The mummichog, *Fundulus heteroclitus*, is an abundant predator in these marshes (Deegan et al. 2007, Lockfield 2011), but *N. obsoletus* is not a common prey for these fish (Kneib 1986, Allen et al. 1994). We made no measurements of parasitism but recognize that parasitism by trematodes can be prevalent (Curtis and Hurd 1983) and can affect snail size by retarding growth rates and increasing snail longevity (Curtis et al. 2000). The effect of nutrient enrichment on the incidence of *N. obsoletus* parasitism is unknown.

Changes in *N. obsoletus* densities may impact other consumers. *N. obsoletus* has a key role in shaping soft-sediment community structure in intertidal sand and mudflats via direct and indirect competition and/or disturbance (Kelaher et al. 2003). High-density aggregations of mudsnails can limit the abundance of infauna such as annelids (Kelaher et al. 2003), tubiculous amphipods (Dewitt and Levinton 1985; Drolet et al. 2009), and bivalves (Dunn et al. 1999). Through their plowing and burrowing activities, snails can alter microtopographic features of the benthos, which has implications for the recruitment and distribution of infauna such as copepods (Sun and Fleeger 1994; Kelaher et al. 2003). Additionally, foraging activities by *N. obsoletus* at high densities have been shown to limit polychaete abundances (Hunt et al. 1987; Kelaher et al. 2003), which may explain, in part, the weak response of annelids to nutrient enrichment as observed by Johnson and Fleeger (2009) in the mudflats of these tidal creeks.

Our results may have implications for the monitoring of polluted estuaries. *N. obsoletus* has been used as a sentinel species in marine ecotoxicological studies (Bryan et al. 1989) and has been suggested as a bioindicator of coastal pollution (Curtis 1994). In those studies, pollution had negative effects on *N. obsoletus*, while in the current study, nutrient effects may be considered positive on *N. obsoletus* populations. Brown and Luoma (1995) suggest that for a species to be a reasonable candidate for use in monitoring, it should be abundant, widely distributed, and amenable to low-cost and easy-to-monitor programs. We suggest that *N. obsoletus* population and size-structure variables fit these criteria, and, so, it may be suitable for monitoring estuarine nutrient pollution. Although animal tissue concentration of a pollutant of interest is the typical variable used with marine bioindicators (e.g., the Mussel Watch Project, <http://ccma.nos.noaa.gov/about/coast/nsandt/musselwatch.aspx>), populations of organisms may be useful for monitoring coastal nutrient pollution. Just as EPT indices in freshwater streams rely on the presence/absence of pollution-intolerant insect

taxa (orders Ephemeroptera, Plecoptera, and Trichoptera), changes in *N. obsoletus* population size and structure—coupled with other diagnostics (e.g., inorganic nutrients, changes in plant/alga species distributions)—may indicate eutrophication when integrated over years of chronic nutrient enrichment. Based on the current study, *N. obsoletus* may be an indicator of moderate nutrient enrichment (70 μM ; EPA 2002), though it is possible that lower concentrations may also lead to increased snail abundance (see below).

The presence of non-native species is another important concern for managing estuaries. Nutrient enrichment may facilitate the invasion of *N. obsoletus* by allowing it to proliferate in non-native estuaries once established (e.g., North American west coast). Carlton (1992) reported that *N. obsoletus* was “astronomically abundant” in San Francisco Bay (California, USA), where it is non-native. San Francisco Bay has been experiencing nutrient enrichment for decades (~30 μM dissolved inorganic N; Cloern 2001, <http://sfbay.wr.usgs.gov/access/wqdata>), which may have facilitated the “astronomical” abundances of *N. obsoletus* observed in this estuary.

Our results demonstrate that nutrient enrichment can have strong impacts on *N. obsoletus* populations by increasing densities and biomass and altering size structure. Increased densities in eutrophic estuaries have been noted elsewhere (Fox et al. 2009), and we suggest that this may be a symptom of eutrophication in highly enriched estuaries. Thus, *N. obsoletus* population dynamics may be integrated into monitoring programs to examine the effect of nutrient pollution in coastal areas of North America.

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