DISTRIBUTION PATTERNS OF AN INVASIVE SNAIL (*BITHYNIA TENTACULATA*)
IN NAVIGATION POOLS 7 and 8 OF THE UPPER MISSISSIPPI RIVER

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DISTRIBUTION PATTERNS OF AN INVASIVE SNAIL (*BITHYNIA TENTACULATA*)

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By William P. Gray

We recommend acceptance of this thesis in partial fulfillment of the candidate's requirements for the degree of Master of Science in Biology

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ABSTRACT

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Since the early 2000’s, *Bithynia tentaculata* (Caenogastropoda:Bithyniidae) has invaded the upper Mississippi River drainage system, harboring several species of parasitic trematodes that are killing large numbers of migratory waterfowl. As previous attempts to remove the snails have been unsuccessful, my study focused on habitat preferences of *B. tentaculata* in order to determine which new habitats were vulnerable to invasion. Snail samples were collected at 8 different islands in Navigation Pools 7 and 8 in the upper Mississippi River (UMR), and I determined the abundance and distribution of different snail species around these islands. There were larger densities of *B. tentaculata* found in Navigation Pool 7, which was colonized prior to Navigation Pool 8. In both Navigation pools, *B. tentaculata* were found primarily on the bottom side of large substrates. *Bithynia tentaculata* densities were positively correlated with soluble reactive phosphorus (SRP) concentrations in Pool 8, but not in Pool 7 where SRP concentrations were higher. There were no detectable effects of increased *B. tentaculata* densities on native snail species. Further research is necessary to determine how *B. tentaculata* is being limited by inter and intra-specific competition in Navigation pools 7 and 8 of the UMR.
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Introduction

When non-indigenous organisms are introduced into novel habitats, they have the potential to become invasive. Invasive organisms are distinguished from other non-indigenous organisms by the negative economic and/or environmental impacts caused by their spread (Pimental et al., 2000). Interactions among invasive and native species (e.g., predation, competition and parasitism) can affect ecosystems in many ways (Pimentel et al., 2000). Examples of invasive predators (e.g., *Boiga irregularis*) and invasive competitors (e.g., *Harmonia axyridis*) are well known, however less research exists on interactions between invasive hosts and parasites. Disease outbreaks can occur as a result of the introduction of new species. These introduced species can act as new hosts for parasites, or may affect the susceptibility of native species to infection through competition (Poulin et al., 2011).

*Bithynia tentaculata* is a small freshwater aquatic snail native to Europe, which grazes on benthic algae, as well as aquatic vegetation in shallow, near-shore habitats. The species was introduced to North America in the 1870s, spread throughout the Great Lakes (Sauer et al. 2007) and was recently discovered in the upper Mississippi River (UMR) (Sauer et al. 2007). *Bithynia tentaculata* serves as an intermediate host for several parasitic flatworms (digenean trematodes): *Cyathocotyle bushiensis*, *Sphaeridiotrema globulus*, *Sphaeridiotrema pseudoglobulus*, and *Leyogonimus polyoon* (Sauer et al. 2007). These parasites spend their metacercarial stage within the snails. The
parasites are then transmitted to native snail populations and other organisms (e.g., migrating waterfowl species), which serve as hosts for later stages of the parasites’ life cycles (Sandland et al., 2013). Parasite transmission to native waterfowl is of great concern to wildlife managers along the UMR. These parasites damage the intestinal tract of infected birds, ultimately resulting in the birds’ death. There have been several large waterfowl die-offs in recent years as a result of the birds feeding on trematode-infected snails (Sauer et al. 2007).

Previous research primarily was focused on locating areas in the UMR where trematode infection rates in *B. tentaculata* were high (Sauer et al. 2007, Herrmann and Sorenson, 2011). However, additional information is needed for better predicting the establishment and movement of this host species. The effects of environmental conditions on habitat occupancy by *B. tentaculata* could be useful in understanding the distribution of the snail and its parasites.

Along with species invasions, physical changes in the UMR have also had a great impact on the relationship between the organisms living in the benthos and migratory bird species. Over the course of the 20th century, channel dredging and flood management have caused large-scale changes in the UMR, reducing the abundance and quality of near-shore benthic habitats (Theiling et al. 1996). Prior to installation of the lock and dam system in the UMR, the river was shallow and contained many side channels and backwater lakes. These low-flow habitats provided a crucial habitat for waterfowl that use the river as a resting area during their yearly migrations (Sauer et al., 2007). After the lock and dam system was installed, many of these areas were inundated, reducing the diversity of habitat available to wildlife (Moore et al. 2010).
To mitigate this loss of habitat, the U.S. Army Corps of Engineers started the Habitat Rehabilitation and Enhancement Program (HREP) in 1986 in order to provide shallow water habitat rich in aquatic vegetation for waterfowl and game fish to feed within the UMR. These projects included dredging of secondary channels, shoreline stabilization, water level management, and island creation (U.S. Army Corps of Engineers, 2006). In Navigation Pool 7, near Onalaska, WI, several artificial islands were created in the early 2000’s, and the shoreline of a naturally occurring ridge (Red Oak Island) was stabilized. In Navigation Pool 8, near Stoddard, WI, the artificial islands were built starting in the early 2000’s and finishing in 2008. While these islands do provide habitat for waterfowl, they also provide habitats for colonization of *B. tentaculata*, thus increasing the potential of parasite transmission to migrating birds.

While the habitat preferences of *B. tentaculata* are unknown, scientists believe they are related to both substrate type and water velocity. Gabel et al. (2008), investigated the ability of *B. tentaculata* to remain anchored to the substrate when exposed to ship induced wave action. They found that: (1) snails placed on more complex substrates were able to resist drifting better than those placed on simpler substrates; (2) there was a negative relationship between *B. tentaculata* abundance and water velocity; and (3) *Bithynia tentaculata* could possibly be restricted from near-surface waters due to wave action (Gabel et al., 2008). In addition a previous study on the UMR found that snail populations were denser in areas with submerged aquatic vegetation (Benjamin Walker, 2012). *Bithynia tentaculata* abundance was also shown to be greatest on more complex substrates in the UMR, where snails were observed to mostly occur on the underside of large substrate particles (cobbles and boulders) (Herrmann and Sorenson, 2009).
The abundance of *B. tentaculata* may also be influenced by total hardness levels in the surrounding environment. Snails can be limited in growth by low total hardness, as the shell of most snail species consists mostly of CaCO$_3$. Snails living in areas of low total hardness show reduced growth, and less resistance to crushing by predators (Brodersen and Madsen, 2003). Dissolved Ca$^{2+}$ is derived from areas draining limestone/dolomite bedrock. Tributaries differing in hardness converge into the main channel of the UMR, (such as the joining of the Black River and the UMR in Navigation Pool 7) which may possibly affect *B. tentaculata* distribution. A field study of the abundance of *B. tentaculata* abundance in 72 lakes in Finland found that *B. tentaculata* were excluded from lakes where total hardness was less than approximately 7.1mg Ca/L (Aho et al. 1981). While total hardness includes not only Ca$^{2+}$, but all dissolved bivalent cations, this does show that low total hardness levels can affect *B. tentaculata* populations.

In contrast with total hardness, little is known about the relationship between *B. tentaculata* abundance and the dissolved nutrient content (e.g., NO$_3^-$, NH$_4^+$, PO$_4^{3-}$) of the surrounding water in the UMR. For example, Dussart (1979) found that increasing NO$_3^-$ concentration associated with decreasing *B. tentaculata* abundance in rivers in the U.K. Insufficient quantities of these nutrients also can affect the growth of the primary food source (periphytic algae) of *B. tentaculata*. There are differences in nutrient concentrations in different areas of the UMR, with phosphorus levels higher in the less oxygenated backwaters than in the highly oxygenated main channel (Houser and Richardson, 2010). These differences could also affect the ability of the digenean trematodes to be transmitted as reductions in nutrient availability can direct and indirectly
alter trematode transmission in other systems (Jokela et al., 1999; Sandland and Minchella, 2003; Seppala et al., 2008).

In addition to abiotic factors, biotic interactions such as predation, parasitism, and competition may also affect the distribution and abundance of *B. tentaculata*. Of these, competition between *B. tentaculata* and native gastropods has been the most thoroughly studied. In one habitat where *B. tentaculata* was been previously introduced, they have excluded certain species of native gastropods, not only affecting the snail assemblage, but the structure of the larger benthic community (Harman and Forney, 1970).

The best example of the effects of competition by *B. tentaculata* on native gastropods is from Lake Oneida in New York, where it was introduced prior to 1910. In the fifty-year span following an initial survey by Baker (1916, 1918), native snail populations (*Physa* and *Pleurocera*) declined from being the dominant species to being only a minor component of the benthic gastropod assemblage. During this time, densities of *B. tentaculata* increased to 15-41 snails/m² within Lake Oneida in 1964-65 (Mattice, 1972). This has corresponded with the extirpation of *Pleurocera* from the lake (Harman and Forney, 1970). In the UMR, there is currently little information on the effects of *B. tentaculata* on the native gastropod assemblage or on the larger benthic community.

To predict where *B. tentaculata* densities are greatest in shallow benthic habitats, more information is needed on the biotic or abiotic conditions where *B. tentaculata* is present or absent. This information will be critical in determining which areas are most vulnerable to invasion by *B. tentaculata* and its parasitic hitchhikers. In order to address this information need, I examined: (1) the effect of several abiotic factors (substrate size, depth, flow rate, and total hardness) on *B. tentaculata* biomass and abundance in shallow
benthic habitats of the UMR; and (2) the effect of *B. tentaculata*’s presence on the indigenous gastropod and the broader invertebrate community.
Methods

In 2008, the density of *Bithynia tentaculata*, native snails, and the incidence of trematode infection in the snails were measured at 16 sites located across 8 artificial islands (Habitat Restoration and Enhancement Projects) in the UMR. These islands are located in Navigation Pools 7 and 8, with Arrowhead (AH), Broken Gun (BG), Cormorant (CO), and Red Oak (RO) islands in Pool 7 (Figure 1); and East (E1), Candy Bar (CBI), North (N1), and Trapping (T1) islands in Pool 8.

![Map showing island locations](image)

**Fig. 1** Island sites located in Navigation Pool 7 of the UMR. AH = Arrowhead Island, BG = Broken Gun Island, CO = Cormorant Island, RO = Red Oak Island
Fig. 2 Island sites located in Navigation Pool 8 of the UMR. CBI = Candy Bar Island, E1 = East Island, N1 = North Island, TI = Trapping Island

Island selection was based on 3 main criteria: substrate composition, island location, and island age. Islands in the 2 pools were chosen to include a range of densities of *B. tentaculata* presence (0 to more than 100 *B. tentaculata*/m²). Sampling across a range of snail densities was necessary in order to quantify and compare the effects of habitat and competition on patterns of snail distribution. Sites also include a variety of substrate particle sizes as substrate composition in the benthic zone (sand, cobble, boulders, etc.) can be correlated with water velocity in habitats where snails can persist (Gabel *et al.* 2008). Finally, islands were also selected based on age. Including variability in island age allowed me to investigate how snail numbers vary based on the length of time habitats have been available for colonization by the snails. All islands in Pool 7 were 10 years or older and have established benthic communities surrounding
them. Islands in Pool 8 range from 10 years old (Trapping Island) to islands less than one year in age (North Island).

At each island, two sites were established on opposite sides of each island. Two transects were established at each site, with one transect parallel to water flow and facing downstream from the island and the other exposed to the current at a 90 degree angle from the first transect. Two random samples were taken at two depths along each transect (0.3 m and 0.6 m). Using a 33 gallon cylindrical trash can to limit the collection area, a 1mm² mesh net was used to screen the water column. In addition, particles were collected and surveyed for invertebrates. All collected invertebrates and macrophytes transported in water to the laboratory. Invertebrates were sorted in the laboratory within a three day period and stored in 70% ethanol for later identification to genus. Taxonomic identification was determined using published keys (Pennak, 1989; Hilsenhoff et al., 1995).

To compare B. tentaculata abundance among sites, snail abundance was recorded for randomly selected substrate particles at each site. Particle length along the principal axis, total number of snails, and snail length on each side of the particle were measured. The snails were classified as being small (1-3 mm), medium (3-6 mm), or large (9+ mm). Water velocity was recorded for each sampling point at the substrate level and at 60% of the depth using a Marsh-McBirney Flow Mate 2000 flow meter. A 500 mL water sample was collected from each site, filtered through 0.45 μm (Whatman – 25mm diameter) glass fiber filters, and separated into bottles for analysis (2 drops of sulfuric acid were added to samples used for DIN analysis) by the Upper Midwest Environmental Sciences Center for SRP, DIN using HPLC (High Performance Liquid Chromatography). Total
hardness was analyzed in the lab using EDTA titration analysis (APHA, 2005). In addition, water quality parameters including salinity, dissolved oxygen content, and water temperature were also measured using a Hydrolab DataSonde 4A multi-probe.

Statistical analyses

Differences in *B. tentaculata* densities between different sites and navigation pools were analyzed using one-way ANOVA. Differences in mean *B. tentaculata* densities at each sample depth (0.3 and 0.6 m) were tested using an independent samples t-test. The relationship between water quality parameters (current velocity, DIN concentration, SRP concentration, total hardness, salinity, and water temperature) and snail density were analyzed using simple linear regression. In order to estimate what effect, if any, substrate size had on *B. tentaculata* density, there has to be some measurement of substrate particle surface area. Because only particle length was collected during the field season, abundance was used instead of density as a measure of *B. tentaculata* presence. The relationship between substrate particle size and *B. tentaculata* abundance was also tested using simple linear regression. In addition, the densities of other snail species were also measured to determine what effect increased *B. tentaculata* densities have on native snail populations. Lastly, snail sex and length were compared to determine if (1) there was a difference in snail size between the two navigation pools, and (2) what the ratio of males to female snails was in areas of high *B. tentaculata* abundance.
Results

Bithynia density

There was no difference in densities of *B. tentaculata* between the two sample depths ($F_{1,31} = 0.49, p=0.49$). As a result, for all subsequent analysis data were pooled across depths. *Bithynia tentaculata* densities in Navigation Pool 7 were 4 times greater than those measured in Navigation Pool 8 ($F_{1,15} = 9.91, p = 0.01$) (Fig. 3).

![Graph showing mean ± se B. tentaculata densities (Bithynia/m²) at island sites in Navigation Pools 7 and 8 of the UMR in 2008.](image)

*Fig. 3* Mean ± se *B. tentaculata* densities (Bithynia/m²) at island sites in Navigation Pools 7 and 8 of the UMR in 2008

Snail densities varied greatly across the eight sites in Navigation Pool 7 ($F_{7,15} = 4.59, p = 0.02$). *Bithynia tentaculata* densities were greater at Arrowhead East,
Arrowhead West, Broken Gun East, and Cormorant West (CO-W) than at the other 4 sites. (Fig. 4). The high mean *B. tentaculata* density observed at CO-W was due to an extremely large number of *B. tentaculata* collected at this site during the spring.

Furthermore, sites with high *B. tentaculata* densities were often part of the same island as sites with low measured densities. For example, Cormorant East (CO-E) had one of the lowest mean *B. tentaculata* densities observed in Navigation Pool 7, while CO-W possessed the highest. Both sites at Red Oak Island (RO-N & RO-S) had low measured *B. tentaculata* densities throughout the season.

![Graph showing mean (± 1 se) *B. tentaculata* densities (Bithynia/m²) among collection sites in Navigation Pool 7 of the UMR in 2008 (AH-E = Arrowhead Island East, AH-W = Arrowhead Island West, BG-E = Broken Gun Island East, BG-W = Broken Gun Island West, CO-E = Cormorant Island East, CO-W = Cormorant Island West, RO-N = Red Oak Island North, RO-S = Red Oak Island South).](image)

**Fig. 4** Mean (± 1 se) *B. tentaculata* densities (*Bithynia/m²*) among collection sites in Navigation Pool 7 of the UMR in 2008 (AH-E = Arrowhead Island East, AH-W = Arrowhead Island West, BG-E = Broken Gun Island East, BG-W = Broken Gun Island West, CO-E = Cormorant Island East, CO-W = Cormorant Island West, RO-N = Red Oak Island North, RO-S = Red Oak Island South)
*Bithynia tentaculata* densities also varied greatly across the eight sites in Navigation Pool 8 ($F_{7,13} = 3.67, p = 0.04$). Snail densities were highest at Candy Bar Island South and East Island West sites (Fig. 5). At these two sites, snail densities approached those seen at the more populated sites in Navigation Pool 7 (Fig. 4). In addition, as observed in Navigation Pool 7, sites with greater observed *B. tentaculata* densities were found on the same island as sites with low *B. tentaculata* densities. In Navigation Pool 8, both East Island (E1-E and E1-W) and Candy Bar Island (CBI-N and CBI-S) had sites that differed substantially in overall *B. tentaculata* densities. *Bithynia tentaculata* densities were lower at both Trapping (TI-N and TI-S) and North Islands, which contributed to the low overall density numbers for the season from Navigation Pool 8. North Island was one of the most recently available sites for *B. tentaculata* to colonize, as construction was still in progress at the time of sampling.
Fig. 5 Mean (± 1 se) *B. tentaculata* densities (*Bithynia/m²*) among collection sites in Navigation Pool 8 of the UMR in 2008 (CBI-N = Candy Bar Island North, CBI-S = Candy Bar Island South, E1-E = East Island East, E1-W = East Island West, N1-N = North Island North, N1-S = North Island South, TI-N = Trapping Island North, TI-S = Trapping Island South)

*Bithynia tentaculata* densities were compared to several water quality parameters that were measured in each Navigation Pool at the time of *Bithynia* collection. These parameters included water flow at the substrate level and at 60% of total depth, water temperature, dissolved oxygen levels (DO), pH, salinity, total hardness, dissolved inorganic nitrogen (DIN), and soluble reactive phosphorus (SRP) (Tables 1 and 2). In Navigation Pool 8, there was a positive relationship between *B. tentaculata* density and SRP concentration ($R^2 = 0.55$, $p = 0.04$) (Fig. 6), however this pattern was not observed in Navigation Pool 7. In addition, SRP concentrations were on average higher in Navigation Pool 7 than in Pool 8 ($F_{1,14} = 11.76$, $p < 0.01$) (Fig. 7 and 8). No other
significant relationships were found among the other various water quality parameters and *B. tentaculata* density (all $p > 0.05$).

Fig. 6 Mean (± 1 se) *B. tentaculata* densities (*Bithynia/m²*) compared to soluble reactive phosphorus concentration at each site in Navigation Pool 8 of the UMR in 2008.
Fig. 7 Mean (± 1 se) soluble reactive phosphorus concentrations (mg/L) at the eight sampling sites within Navigation Pool 7 of the UMR for the year 2008. (AH-E = Arrowhead Island East, AH-W = Arrowhead Island West, BG-E = Broken Gun Island East, BG-W = Broken Gun Island West, CO-E = Cormorant Island East, CO-W = Cormorant Island West, RO-N = Red Oak Island North, RO-S = Red Oak Island South)
Bithynia density and the surrounding benthic snail community in the UMR

Density of *B. tentaculata* was compared to density of *P. gyrina* and all other snail species within the UMR (*Amnicola* sp. not included). Increases in *B. tentaculata* density appeared to have no effect on *P. gyrina* or other snail species densities within the UMR during 2008 ($t_{14} = -0.323, p > 0.05$) ($t_{14} = -0.466 p > 0.05$).
Bithynia abundance on individual substrate particles

Particles sampled at the substrate level were collected only measuring particle length, so calculations of *B. tentaculata* density were not used. Particles colonized by *B. tentaculata* were on average larger than those left uncolonized (*t*₁₄ = -4.53, *p* < 0.01) (Fig. 9).

Fig. 9 Mean (± 1 se) *B. tentaculata* presence on the top of sampled particles compared to particle size at island sites in Navigation Pools 7 and 8 of the UMR. Inset: Average particle diameter for rocks colonized or un-colonized by *B. tentaculata* in Navigation Pools 7 and 8 of the Upper Mississippi River.
Fig. 10 Mean (± 1 se) *B. tentaculata* presence on the bottom of sampled particles compared to particle size at island sites in Navigation Pools 7 and 8 of the UMR.

There was no difference in substrate particle size between the island sites within the two Navigation pools ($t_{15} = 0.82$, $p > 0.05$). *Bithynia tentaculata* abundances were higher on the bottom than on the top surface of particles ($t_{15} = -2.35$, $p = 0.02$) (Fig. 9 and 10). Although the size of particles colonized by *B. tentaculata* were larger than uncolonized particles, there was no relationship between *B. tentaculata* abundance on the top of particles ($F_{1,15} = 1.02$, $p > 0.05$) (Fig. 9); however, *B. tentaculata* abundance on the bottom side of particles ($F_{1,15} = 5.29$, $p = 0.02$) (Fig. 10).

Snails collected were also measured (total length, mm) and sexed. No difference in mean size was found between sexes ($p = 0.66$). In addition, there was no significant difference in snail length between the 8 different islands in the two navigation pools ($p = 0.58$).
Discussion

Dussart (1979) examined the effect of water quality and habitat availability on the distribution of *B. tentaculata* in streams in the southern region of the United Kingdom. *Bithynia tentaculata* density was inversely affected by nitrate concentration, K⁺ concentration, and substrate type. At least half of the streams studied by Dussart (1979) were more eutrophic than those measured in the UMR. *Bithynia tentaculata* present in those habitats could be less prone to phosphorus deficiencies as a result (Leiss and Hillebrand, 2006). Nutritionally deficient food has been found to limit snail growth in other studies as well. For example, * Elimia spp. (Pleuroceridae)* fed small portions of food grew faster when given foods rich in phosphorus (Stelzer and Lamberti, 2002). However, this limitation disappeared as food abundance was increased. Based on this work, it is important to understand the relationship between nutrient concentrations and *B. tentaculata* in the UMR as low levels of these nutrients could limit the spread of the snail in the region.

Soluble Reactive Phosphorus concentration

Soluble reactive phosphorus (SRP) is typically the most limiting nutrient for organisms in freshwater habitats (Kalff, 2003). There was a positive relationship between SRP concentration and *B. tentaculata* abundance in Navigation Pool 8, however there was no correlation between *B. tentaculata* and SRP concentration in Navigation Pool 7. This difference could exist for several reasons. One possibility is the increased *B.
*tentaculata* densities seen in Navigation Pool 7 resulted in increased competition, reducing the ability of individual snails to gather food resources. Habitats in Navigation Pool 7 may have enough food resources to provide *B. tentaculata* sufficient resources to make up for nutrient deficiencies in their diet (Stelzer and Lamberti, 2002). In either case, P is a possible limiting nutrient for *B. tentaculata* population growth in some areas of the UMR. This may not be the case in all instances, as Leiss and Hillebrand (2006) found that N:P ratios of 32:1 or higher indicate phosphorus limitation for grazing snails; this was not the case in my study. In addition, my study was not conducted in the main channel of the UMR. Soluble-reactive phosphorus levels are typically lowest in the more oxygen-rich main channel, when compared to the backwaters where P is released from anoxic sediments (Houser and Richardson, 2010).

Dissolved Inorganic Nitrogen concentration

In aquatic systems where SRP is not limiting, the next most limiting nutrient is typically dissolved inorganic nitrogen (DIN) (Kalff, 2003). Dussart found that there was a negative correlation between NO$_3^-$ concentration and *B. tentaculata* population density. Conversely, I found no relationship between DIN concentration and *B. tentaculata* density, suggesting that DIN was not affecting *B. tentaculata* population density in either pool. In previous studies, DIN was not found to be limiting, as there was a much stronger positive correlation between *B. tentaculata* population densities and K$^+$ concentration (Dussart, 1979). In addition, DIN concentrations were similar in both the UK streams and in the UMR, suggesting that DIN concentration in the UMR is not limiting (Dussart, 1979). In addition to SRP and DIN, other nutrients (Ca$^{2+}$), can affect population density of organisms, especially in snails.
Total Hardness

Calcium concentrations of 7.1 mg/L or less limit the distribution of *B. tentaculata* and other snail species (Aho et al., 1981). In UK streams there was no positive correlation between Ca$^{2+}$ concentration and *B. tentaculata* population density (Dussart, 1979); Ca$^{2+}$ concentrations were well above the 7.1 mg/L reported in most of the streams in Dussart's study. Similarly, I found no correlation between Ca$^{2+}$ concentrations and *B. tentaculata* density in either pool of the UMR, as the Ca$^{2+}$ concentration was high during our sampling season (>58 mg/L). In addition to nutrient levels being important in the spread of *B. tentaculata* populations in the UMR, the availability of suitable physical substrates for colonization also affects *B. tentaculata* population size.

Substrate size and water velocity

In previous studies in both the United Kingdom and the UMR, *B. tentaculata* was found primarily on large substrates, primarily on the bottom side (Dussart, 1979; Herrmann and Sorenson, 2009). Gabel et al. (2008) suggested that snails inhabit the bottom side of substrates in order to find refuge from high water velocities that would otherwise dislodge them. In a laboratory study, *Physa* and *Stagnicola* were found to be vulnerable to dislodgement from most substrates at high water velocities (Moore, 1964). In addition, water velocities necessary to achieve this were found to be higher on larger substrates vs. when snails were placed on clay or sand. While my results suggest no relationship between *B. tentaculata* and water velocity in the UMR, more detailed point measurements along particle surfaces are required to thoroughly determine if a such a relationship exists. The Marsh-McBirney Flow Mate 2000 used in my study was designed to measure water velocity in the open water column, not near the substrate.
where *B. tentaculata* resides. Our findings resulted in a limited view of the effects of water flow on *B. tentaculata* abundance. Previous studies using acoustic Doppler velocimeters have found that the distribution of larval blackflies (Diptera: Simuliidae), an organism which also lives in the boundary layer out of the main flow, can be dependent on water velocity at 2 mm, but not at 10 mm (Finelli et al., 1999). As *B. tentaculata* lives in this narrow zone around substrate particles, the measurements taken in my study may not be relevant in determining the influence of water velocity on *B. tentaculata* distribution in the UMR. Future studies are needed to determine whether large substrates provide refugia not only for *B. tentaculata*, but for other invasive species within the UMR. Additional information may allow recommendations about adding smaller substrates like gravels or sands to increase substrate disturbance in high flow periods could discourage *B. tentaculata* colonization on future and existing HREP islands can be designed and/or modified, respectively.

**Biotic factors**

While abiotic parameters limit the spread of a species geographic range, biotic interactions such as competition could limit the abundance of an invasive species in a new habitat. The introduction of *B. tentaculata* may affect the distribution and abundance of native species in shallow benthic habitats (Baker, 1916; Harvey and Forney, 1970). Between the initial surveys conducted by Baker in Lake Oneida (1916) and the later studies by Harvey and Forney (1970), *B. tentaculata* replaced *Physa* and *Pleurocera* as the dominant snail species (density 15-44 snails/m²) (Harvey and Forney, 1970). One other possible reason for this change in snail populations is that many lakes in New York, including Lake Oneida, have become increasingly eutrophic over the last century. As *B.
*Bithynia tentaculata* also has the ability to filter feed from the surrounding waters using its ctenidium, it may be outcompeting snails which feed exclusively on periphyton in deeper lakes. *Bithynia tentaculata* can supplement its diet with particles collected from the surrounding water column (Stelzer and Lamberti, 2002). Because of the difference in depth between the two systems, it is difficult to make direct comparisons between this study and many of the previous studies on *B. tentaculata* populations. However, *B. tentaculata* could also be supplementing its diet by filter-feeding during the spring and fall flood seasons in the UMR, when high turbidity reduces light penetration even in shallow waters. Short-lived disturbance events like this are common in lotic systems, as a result of high flow. In addition, in large lotic and lentic systems with a large surface area, wind-induced waves can also dislodge organisms from the benthos. These events can limit species from areas they might otherwise inhabit.

Studies on colonization dynamics in large river systems show that species diversity temporally decreases as a small number of dominant species out-compete early colonizers (Oemke and Burton, 1986). While measured densities of *B. tentaculata* in Navigation Pool 7 were higher than those found in Lake Oneida, a negative correlation was not found between *B. tentaculata* and *Physa gyrina* densities or with other native snail species. *Bithynia tentaculata* were first detected in the UMR in 2002 (Sauer et al., 2007), so it may also be possible that *B. tentaculata* will become a more dominant species in the shallow benthic habitats of the UMR.
Limitations of this study

Budget and time concerns introduced a number of limitations into this study. Sampling large areas was restricted by the time required to process samples. This limitation prevented sampling of a wider selection of sampling sites from Navigation Pools 7 and 8, and other navigation pools. In addition, I was not able to sample during the winter months, as safety was a concern due to river ice.

When measuring flow, measurements were taken from the top-sides of particles. Measurements from beneath substrate particles where most *B. tentaculata* would be a more adequate assessment, but these measurements are not currently feasible in a natural setting. Future laboratory research could provide much needed data from these crucial microhabitats, which may elucidate if water velocity affects snail substrate choice in the UMR.
Future directions for research

Continued monitoring of *B. tentaculata* in Navigation Pools 7 and 8 is recommended to better understand its colonization dynamics and the spread of the species. Because the parasites carried by *B. tentaculata* are ingested by waterfowl and can lead to avian mortality during critical migration periods, *B. tentaculata* density can potentially be an indicator of river ecosystem health. Therefore, studying and potentially controlling the spread of *B. tentaculata* will be an important step in preventing the spread of the parasites that kill large quantities of waterfowl.

Future monitoring should consist of expanding the current research at the eight islands in Navigation Pools 7 and 8 into four studies. The first study would explore the ecological stoichiometry of the snails and their food sources, allowing for a more detailed examination of limiting nutrients at each site and how *B. tentaculata* densities are affected as a result. Both snail and algal samples would be taken from the field and analyzed for nutrient content to determine what effect, if any, that nutritionally deficient food sources have on *B. tentaculata* population size. In addition, *B. tentaculata* could be raised in the laboratory and fed diets with different nutritional content to determine the effect being fed nutritionally deficient food has on *B. tentaculata* growth and reproduction. A second study would take a closer look at the effects of competition on *B. tentaculata* population growth. Field studies would be very similar to the current monitoring program, where the number of snails of each species are counted from
samples taken at each site. Laboratory studies would consist of both B. tentaculata and native snail species being placed in both single species and mixed species enclosures with a fixed food supply to determine the effects of both intraspecific and interspecific competition on snail growth. The third study would be a continuation of the existing parasite study, which in addition will use snails and data from the stoichiometry study to determine the effect of snail nutritional content on parasite infection rate. Finally, the fourth study would determine B. tentaculata’s ability to live in habitats apart from the main channel, as it is currently unknown if B. tentaculata can exist in habitats with lower N:P ratios (backwaters) mentioned in Hauser and Richardson (2010), or with higher water velocities (smaller tributaries).
References


Table 1 Water chemistry results from the island sites located in Navigation Pool 7 of the UMR. DO = Dissolved oxygen, DIN = Dissolved inorganic nitrogen, SRP = Soluble reactive phosphorus (AH-E = Arrowhead Island East, AH-W = Arrowhead Island West, BG-E = Broken Gun Island East, BG-W = Broken Gun Island West, CO-E = Cormorant Island East, CO-W = Cormorant Island West, RO-N = Red Oak Island North, RO-S = Red Oak Island South)

<table>
<thead>
<tr>
<th>Water Temp. (°C)</th>
<th>DO (mg/L)</th>
<th>pH</th>
<th>Salinity (ppt)</th>
<th>Total Hardness (mg/L)</th>
<th>DIN (mg/L)</th>
<th>SRP (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AH-E</td>
<td>22.7 ± 2.4</td>
<td>9.00 ± 2.18</td>
<td>7.9 ± 0.5</td>
<td>204.1 ± 14.9</td>
<td>1.66 ± 1.14</td>
<td>0.076 ± 0.049</td>
</tr>
<tr>
<td>AH-W</td>
<td>23.0 ± 2.8</td>
<td>8.51 ± 3.00</td>
<td>8.0 ± 0.6</td>
<td>197.3 ± 23.8</td>
<td>1.59 ± 1.28</td>
<td>0.054 ± 0.033</td>
</tr>
<tr>
<td>BG-E</td>
<td>22.8 ± 1.8</td>
<td>7.28 ± 1.48</td>
<td>7.7 ± 0.5</td>
<td>112.4 ± 38.5</td>
<td>0.46 ± 0.47</td>
<td>0.066 ± 0.028</td>
</tr>
<tr>
<td>BG-W</td>
<td>22.6 ± 2.3</td>
<td>7.62 ± 1.22</td>
<td>7.6 ± 0.5</td>
<td>107.6 ± 40.6</td>
<td>0.57 ± 0.47</td>
<td>0.064 ± 0.020</td>
</tr>
<tr>
<td>CO-E</td>
<td>21.4 ± 6.5</td>
<td>8.86 ± 1.27</td>
<td>8.1 ± 0.6</td>
<td>204.5 ± 23.9</td>
<td>1.62 ± 1.21</td>
<td>0.073 ± 0.047</td>
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<tr>
<td>CO-W</td>
<td>23.0 ± 2.8</td>
<td>8.00 ± 1.46</td>
<td>7.9 ± 0.5</td>
<td>205.3 ± 18.4</td>
<td>1.76 ± 1.16</td>
<td>0.055 ± 0.030</td>
</tr>
<tr>
<td>RO-N</td>
<td>18.8 ± 2.9</td>
<td>7.23 ± 1.80</td>
<td>6.6 ± 0.5</td>
<td>209.6 ± 19.4</td>
<td>1.65 ± 1.16</td>
<td>0.050 ± 0.027</td>
</tr>
<tr>
<td>RO-S</td>
<td>18.7 ± 2.5</td>
<td>7.41 ± 1.69</td>
<td>6.6 ± 0.5</td>
<td>211.3 ± 21.4</td>
<td>1.60 ± 1.17</td>
<td>0.058 ± 0.039</td>
</tr>
</tbody>
</table>

Table 2 Water chemistry results from the island sites located in Navigation Pool 8 of the UMR. DO = Dissolved oxygen, DIN = Dissolved inorganic nitrogen, SRP = Soluble reactive phosphorus (CBI-N = Candy Bar Island North, CBI-S = Candy Bar Island South, E1-E = East Island East, E1-W = East Island West, N1-N = North Island North, N1-S = North Island South, TI-N = Trapping Island North, TI-S = Trapping Island South)

<table>
<thead>
<tr>
<th>Water Temp. (°C)</th>
<th>DO (mg/L)</th>
<th>pH</th>
<th>Salinity (ppt)</th>
<th>Total Hardness (mg/L)</th>
<th>DIN (mg/L)</th>
<th>SRP (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBI-N</td>
<td>23.0 ± 2.9</td>
<td>6.48 ± 2.28</td>
<td>7.7 ± 0.3</td>
<td>210.3 ± 21.7</td>
<td>1.52 ± 0.98</td>
<td>0.047 ± 0.029</td>
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<tr>
<td>CBI-S</td>
<td>23.0 ± 2.9</td>
<td>8.08 ± 2.14</td>
<td>7.8 ± 0.3</td>
<td>208.1 ± 19.4</td>
<td>1.50 ± 0.93</td>
<td>0.064 ± 0.038</td>
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<tr>
<td>E1-E</td>
<td>22.7 ± 2.9</td>
<td>6.62 ± 2.38</td>
<td>7.9 ± 0.4</td>
<td>192.7 ± 21.1</td>
<td>1.02 ± 0.82</td>
<td>0.030 ± 0.022</td>
</tr>
<tr>
<td>E1-W</td>
<td>21.9 ± 2.8</td>
<td>8.44 ± 1.71</td>
<td>7.8 ± 0.4</td>
<td>199.8 ± 19.2</td>
<td>1.11 ± 0.89</td>
<td>0.052 ± 0.032</td>
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<tr>
<td>N1-N</td>
<td>22.8 ± 2.5</td>
<td>9.25 ± 2.55</td>
<td>7.9 ± 0.4</td>
<td>232.0 ± 13.6</td>
<td>2.37 ± 1.21</td>
<td>0.043 ± 0.023</td>
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<tr>
<td>N1-S</td>
<td>22.8 ± 2.5</td>
<td>10.07 ± 2.73</td>
<td>8.0 ± 0.3</td>
<td>226.5 ± 14.5</td>
<td>2.01 ± 1.30</td>
<td>0.039 ± 0.024</td>
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<tr>
<td>TI-N</td>
<td>22.9 ± 2.8</td>
<td>8.90 ± 1.78</td>
<td>8.0 ± 0.5</td>
<td>223.3 ± 15.7</td>
<td>2.05 ± 1.64</td>
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</tr>
<tr>
<td>TI-S</td>
<td>23.2 ± 2.8</td>
<td>9.12 ± 1.81</td>
<td>8.0 ± 0.3</td>
<td>222.7 ± 13.7</td>
<td>2.01 ± 1.01</td>
<td>0.043 ± 0.024</td>
</tr>
</tbody>
</table>