SPATIAL AND SEASONAL DISTRIBUTION OF THE INVASIVE ROUND GOBY (*NEOGOBIUS MELANOSTOMUS*) AND RUSTY CRAYFISH (*ORCONECTES RUSTICUS*) ON CRITICAL NEARSHORE SPAWNING REEFS IN NORTHERN LAKE MICHIGAN

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This is dedicated to my family
for all of their support
throughout this project.

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ABSTRACT

SPATIAL AND SEASONAL DISTRIBUTION OF THE INVASIVE ROUND GOBY (*NEOGOBIUS MELANOSTOMUS*) AND RUSTY CRAYFISH (*ORCONECTES RUSTICUS*) ON CRITICAL NEARSHORE SPAWNING REEFS IN NORTHERN LAKE MICHIGAN

by Krista Marie Robinson

Round Goby (*Neogobius melanostomus*) and Rusty Crayfish (*Orconectes rusticus*) are invasive species that are substantially changing the energy flow and ecology of Lake Michigan. There are limited data regarding Round Goby and Rusty Crayfish distribution and movement, with few studies examining seasonal movement and use of interstitial habitats over time. The goals of Chapter 1 and Chapter 2 were to determine the changes in the spatiotemporal distributions of Round Goby and Rusty Crayfish, respectively, on spawning reefs in Grand Traverse and Little Traverse Bays, Lake Michigan. Specifically, the objectives were to (1) determine if and how Round Goby and Rusty Crayfish abundance varies temporally and by depth, and (2) quantify changes of interstitial habitat use. The purpose of Chapter 3 was to determine the effectiveness of baited photoquadrats and minnow traps to sample Round Goby in complex benthic habitats.

Standard minnow traps, buried egg bags, and underwater videos were used in 2012 and 2013 to monitor seasonal changes of Round Goby and Rusty Crayfish. For both species, relative abundances peaked at all depths in mid-October, with the highest densities at shallow depths. Although densities decreased in December as temperatures declined, a portion of the Round Goby population moved deeper into the reef substrate. Rusty Crayfish, however, were not present on reefs in December, which may indicate an overall decrease in activity level for this species during this time of year. These findings will help define seasonal abundance shifts in

order to better develop effective management strategies incorporating an understanding of Round Goby and Rusty Crayfish in the Great Lakes.

Underwater video and photoquadrats have become standard non-destructive monitoring methods in marine ecosystems, and yet they are still not commonly used in freshwater systems. This technique could be extremely useful in interpreting dynamics in the Laurentian Great Lakes, where high water visibility and low habitat and community diversity would appear to be ideally suited for these methods. For Chapter 3, we determined the effectiveness of baited photoquadrats in addition to minnow traps for monitoring benthic fish communities in shallow, littoral habitats of northern Lake Michigan.

Photoquadrats baited with Lake Trout (*Salvelinus namaycush*) eggs, determined to be the most effective attractant, proved to be an efficient tool for quantitatively sampling Round Goby. Baited photoquadrats allowed sites to be surveyed rapidly (requiring < 1 hour per site), and replicate samples produced data with low variability. In contrast, baited minnow traps produced highly variable catch-per-unit-effort (CPUE) irrespective of set time or trap entrance width. Additionally, we found that minnow traps positioned < 10 m apart may not provide an independent measure of relative abundance. Short minnow trap set times produced highly variable counts and often resulted in empty traps. The high water clarity found in most of the Laurentian Great Lakes make them ideally suited for underwater video monitoring and photoquadrat sampling. Researchers and managers should consider augmenting traditional nearshore sampling methods by incorporating this monitoring approach.

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CHAPTER I

SPATIAL AND SEASONAL DISTRIBUTION OF THE INVASIVE ROUND GOBY (*NEOGOBIUS MELANOSTOMUS*) ON CRITICAL NEARSHORE SPAWNING REEFS IN NORTHERN LAKE MICHIGAN

Introduction

An understanding of the spatial and temporal ecology is fundamental to understand population dynamics and community processes (Lucas and Baras 2000; Landsman et al. 2011). Spatial distributions of fishes can be influenced by both biotic (e.g., competition, predation) and abiotic constraints (Gibson 1967; Eklöv 1997; Jackson et al. 2001). Physical factors (Gibson 1967; Jackson et al. 2001; Nyboer and Chapman 2013), habitat complexity (Eklöv 1997), and behavioral interactions (Gibson 1967) can impact the spatial distributions of fish. By determining the relative importance of factors influencing spatiotemporal dynamics, researchers can ultimately gain a comprehensive understanding of the components that impact the basic survival and growth of an individual (Huse and Giske 1998). Although the spatial ecology of native fishes is critical, understanding the movement and distribution of non-native species remain top priorities for fisheries managers and researchers alike, especially in freshwater systems (Charlebois et al. 2001; Landsman et al. 2011).

Identifying the seasonal distributions improves our understanding of life history characteristics and the potential impact on an ecosystem. Successful invasive species are generally characterized by short generation times, high growth rates, small body sizes, generalist diets, and tolerance of a range of salinities and temperatures (Kolar and Lodge 2002; García-Berthou 2007). The specific factors contributing to dispersal rates, population expansions, and persistence of invasive fishes are influenced by their life history traits and spatial ecology (Lodge et al. 1998; Mack et al. 2000; Sakai et al. 2001; Allendorf and Lundquist 2003). An improved understanding seasonal changes in non-native species distributions across habitats is important because it can inform how the species may impact community structure and ecosystem functioning (Lodge et al. 1998; Sakai et al. 2001).

The Round Goby (*Neogobius melanostomus*) is a non-native fish initially discovered in the St. Clair River in 1990 (Jude et al. 1992). Native to Eurasia, this highly successful benthic invader quickly colonized all five of the Great Lakes by 1995 through natural dispersal and human transport (Charlebois et al. 1997; Clapp et al. 2001). The widespread colonization of the Round Goby is due in part to their aggressive behavior, multiple spawning events, rapid growth, and tolerance for various environmental conditions (Charlebois et al. 1997; Corkum et al. 1998; MacInnis and Corkum 2000). Round Goby often outcompete native benthic fishes in nearshore habitats for shelter and food by dominating resources (Dubs and Corkum 1996; Balshine et al. 2005; Bergstrom and Mensinger 2009). Competitive interactions with Round Goby have even led to the extirpation of Mottled Sculpins (*Cottus bairdi*) and Slimy Sculpin (*C. cognatus*) in many nearshore areas of Lake Michigan (Janssen and Jude 2001). Round Goby here had strong effects on Great Lakes ecosystems by through changing energy pathways (Djuricich and Janssen 2001; Johnson et al. 2005) and altering aquatic benthic community dynamics (Kuhs and Berg 1999; Dopazo et al. 2008; Ruetz et al. 2012).

As a bottom-dwelling fish, Round Goby use the interstitial spaces of complex rocky habitats for refuge and food sources (Jude and DeBoe 1996; Chotkowski and Marsden 1999; Ray and Corkum 2001). Predation by the Round Goby on fish eggs deposited on rocky spawning reefs is listed as one of many factors affecting the reproductive success of several native fish species in the Great Lakes including Lake Trout, Lake Whitefish (*Coregonus clupeaformis),* Cisco (*C. artedii*), and Smallmouth Bass (*Micropterus dolomieu*) (Jones et al. 1995; Chotkowski and Marsden 1999; Bronte et al. 2003; Steinhart et al. 2004). Interstitial predators like Round Goby have the potential to higher Lake Trout egg mortality on rocky substrates than epibenthic predators alone (Jones et al. 1995; Savino et al. 1999; Claramunt et al. 2005). Egg mortality is critically influenced by the spatiotemporal overlap of eggs and their predators (Savino et al. 1999). To further understand the role of Round Goby in the Great Lakes nearshore community, it is important to quantify their abundance in relation to their spatial and temporal distribution.

In their native region, Round Goby are generally found in rivers and coastal waters from spring through fall but move offshore to deeper waters (≥ 60 m) in the winter (Charlebois et al. 1997; Lynch and Mensinger 2012). In Lake Erie, Round Goby are distributed in nearshore waters to depths up to 20 m in the spring and fall but are thought to migrate deeper in the late fall (Weimer and Keppner 2000). Round Goby have high site affinity (Ray and Corkum 2001; Lynch and Mensinger 2012), and their home ranges have been estimated to be as small as 5 m^2 ± 1.2 (Ray and Corkum 2001) with potential to be over 400 m^2 (Cookingham and Ruetz 2008). Although Round Goby are usually found in habitats with hard surfaces (e.g., gravel, cobble, boulders) or macrophytes (Jude and DeBoe 1996; Ray and Corkum 2001), they can also occupy areas with soft substrates including sand and mud and differences may occur seasonally (Charlebois et al. 1997; Johnson et al. 2005). Many methods have been proposed for sampling and tracking Round Goby over a variety of these habitats (Diana et al. 2006; Bergstrom et al. 2008; Cookingham and Ruetz 2008; Gutowsky and Fox 2011); however, data are limited on their seasonal habitat use patterns in North America (Charlebois et al. 2001), especially seasonal abundance over a range of depths.

The objective of this study was to quantify the spatial and temporal distribution of Round Goby in northern Lake Michigan. Specifically, the objectives were to (1) determine if and how Round Goby distribution changed over time and water depth, and (2) quantify Round Goby interstitial habitat use over time on nearshore spawning reefs. During the periods associated with native fish spawning, we expect to see a seasonal increase in Round Goby abundance on the spawning reefs as well as an increase in interstitial habitat use. We postulate that as water temperatures decline, Round Goby will exhibit an offshore movement, with the most pronounced effects seen at the shallowest depths. The findings from this study will help managers better understand seasonal abundance shifts in order to develop effective management strategies. The present study will also have critical implications for fisheries management, especially for the restoration initiatives aiming to increase recruitment and survival of reef spawning native fish populations.

Methods

Study Sites

Sampling was conducted in Grand Traverse and Little Traverse Bays, Lake Michigan, from 9 July 2012 to 30 November 2012 and 9 September 2013 to 2 December 2013. Both bays are located in northeastern Lake Michigan, with Grand Traverse Bay separated into eastern and western arms by Old Mission Peninsula (Figure 1.1). Six study sites were evaluated for changes in Round Goby abundance over time and depth. Three study sites (North, Central, and South) were located on a spawning reef complex (44°54’N, 85°25’W) in the eastern arm of Grand

Traverse Bay near Elk Rapids, Michigan, and one study site (Ingalls Point) was located in the western arm of Grand Traverse Bay near Ingalls Bay (45°04'N, 85°34'W) (Figure 1.1). Of the two study sites located in Little Traverse Bay, one site (Bay Harbor) was located in southern Little Traverse Bay near Bay Harbor, Michigan (45°22'N, 84°59'W), and the other site (LTB Crib) was located in northern Little Traverse Bay near Harbor Springs, Michigan (45°25'N, 84°56'W). The South site in Grand Traverse Bay was not sampled in 2013.

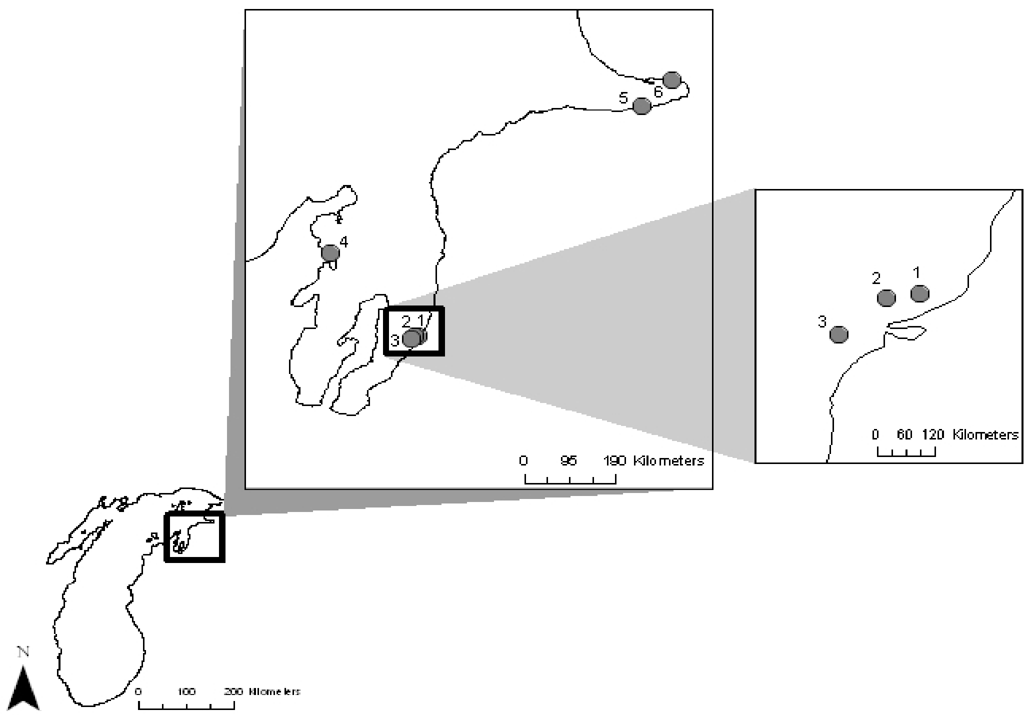

Figure 1.1. Location of the six spawning reefs (2 m depth) in Grand Traverse and Little Traverse Bays, Lake Michigan where Round Goby spatial and temporal distribution was evaluated. Site key: 1 = North, 2 = Central, 3 = South, 4 = Ingalls Point, 5 = Bay Harbor, and 6 = LTB Crib.

All sites are active spawning reefs (Michigan Department of Natural Resources, unpublished data) that are similar in depth (1.85 ± 0.04 m, mean ± SE) and distance from shore (Barton et al. 2011). Interstitial depth varied by site (0.5-1.5 m), and the primary habitat type on the reefs consisted of a cobble-rubble rock mixture comprised of substrate approximately 10-20 cm in diameter (Barton et al. 2011). To determine changes in Round Goby abundance over depth in 2012, each site consisted of one spawning reef depth (2 m) and two deeper depths (6 m and 9 m). The 6 m and 9 m depths for each site were determined by moving offshore from the spawning reef until the appropriate depth was located. All depths remained fixed for the entire sampling period and were chosen regardless of substrate type. In 2013, a 15 m depth was added to every site except the Grand Traverse Bay North site.

Field Sampling 2012

Round Goby were sampled using standard Gee minnow traps (23 cm x 45 cm with 0.64 cm steel wire mesh) with either 3 cm ("small" hereafter) or 6 cm ("large" hereafter) entrance openings. Ten traps, alternating small and large entrance openings, were placed 1 m apart on a trap line. Each trap was tagged and baited with previously collected, frozen, and thawed Lake Trout eggs. Lake Trout eggs (~30 g) were placed in 8 cm x 13 cm mesh bags and suspended in the middle of each trap. One trap line was set at each depth. Traps fished for 24 hours biweekly throughout the sampling period. All Round Goby collected were immediately measured for total length (mm) and euthanized. Any other fish species captured were identified, measured, and released. Rusty Crayfish (*Orconectes rusticus*), another invasive egg predator on the spawning reefs, were measured for carapace length (mm), sexed, and euthanized if caught in the minnow traps. Water temperature (°C) was taken at each depth by lowering a temperature probe to the bottom substrate after all minnow traps were lifted.

Egg bags (similar to Barton et al. 2011 and Claramunt et al. 2005) were used to quantify interstitial habitat use. Each egg bag was approximately 50 cm deep with a mesh size of 0.16

cm. Scuba divers buried 10 egg bags 1 m apart along a single transect at the 2 m depths of each site. Egg bags were retrieved every two weeks by removing any substrate from inside the egg bag and cinching the tops closed with cable ties to decrease the chance of any Round Goby escaping (Fitzsimons et al. 2007; Barton et al. 2011). Any losses, which were minimal, from the egg bags were noted by divers and included in the abundance estimates. New egg bags were buried into the same locations as the ones previously removed. All samples were processed within 24 hours, and any Round Goby collected were measured and euthanized. Any non-target species that were captured were handled similarly to the minnow traps catches.

Round Goby abundance over time was measured with a SeaViewer® Sea-Drop 950 underwater video camera (www.seaviewer.com). The unbaited video camera was attached to the top of a steel rod frame (height = 1.26 m; base = 0.25 m^2) facing downward so that the image encompassed the entire base. The video camera was suspended approximately 16 cm from the top of the frame. Due to strong currents, a buoy was tied to the rope directly above the frame to prevent it from tipping. At each depth, the video camera was lowered to the bottom and continuous video was recorded for one minute. Ten one-minute videos were recorded for each depth; each video camera drop was 1 m apart. Scuba divers occasionally used a handheld Canon PowerShot D20 underwater camera at some of the 2 m depths that were too shallow for the camera frame. Ten pictures were taken with the handheld camera over each egg bag.

All videos were processed by counting the number Round Goby present in four time intervals (0-15, 15-30, 30-45 and 45-60 sec) as well as the total throughout the video. If at least 50% of a Round Goby was visible in the viewing area, the Round Goby was included in the count. If a Round Goby left the field of view but returned, that individual was assumed to be a new fish. For the images taken with the handheld camera, the total number of Round Goby was counted in each photograph using Windows Photo Viewer. If more than ten Round Goby were seen in the image or if it was difficult to identify an individual, the photograph was opened in Windows Paint at 150% zoom. Each fish was then marked with a black line on their dorsal side, and all black lines were totaled for the image. Two people independently analyzed images in the laboratory, and any discrepancies were settled by a third person.

Field Sampling 2013

In 2013, we changed our methods to reflect the recommendations offered by Chapter 3 regarding minnow trap set times and minnow trap independence. Standard Gee minnow traps with small and large entrance holes were again used to sample Round Goby abundance at different depths. Ten traps were deployed at each depth (2 m, 6m, 9m, and 15 m), and each trap was baited with Lake Trout eggs (~ 30 g). Traps were individually buoyed and set 10 m apart (Chapter 3). All traps fished for 1.5 hours approximately every three weeks throughout the sampling period. Similar to 2012, all Round Goby collected were measured for total length (mm) and euthanized. Any other fish species captured were identified, measured, and released. Rusty Crayfish captured were measured for total carapace length (mm), sexed, and euthanized. Water temperature (°C) was taken at each depth by lowering a temperature probe to the bottom substrate after all minnow traps were lifted.

Round Goby abundance was sampled using five GoPro HERO 3® cameras (www.gopro.com). Each camera was mounted to a steel rod camera frame (height = 60 cm; base = 0.5 m^2) with a quad-pod type base to increase stability when lowered to the lake bottom (Chapter 3). Cameras were secured to the frame and positioned so that they faced downward.

Each camera frame was baited with previously collected, frozen, and thawed Lake Trout eggs (~30 g). The mesh bag containing the Lake Trout eggs was suspended approximately 5 cm from the substrate in the center of the photoquadrat. All five cameras were individually buoyed and positioned 10 m apart at each depth. The cameras were set to take one photograph per minute for 20 minutes. Round Goby present in each image were counted. If at least 50% of a Round Goby was visible in the viewing area, the Round Goby was included in the count. Similar to the handheld cameras in 2012, if more than ten Round Goby were seen in the image or if it was difficult to identify an individual, the photograph was opened in Windows Paint at 150% zoom. Each fish was then marked with a black line on their dorsal side, and all black lines were totaled for the image. Two people independently analyzed images in the laboratory, and any discrepancies were settled by a third person. The maximum number of Round Goby recorded during the 20 minute period was used for analysis (Willis et al. 2000; Cappo et al. 2006; Chapter 3). Any other species seen in the photoquadrats were identified and counted.

We calculated average percent of habitat type (e.g., sand, gravel, cobble, boulder), live mussels (*Dreissena* spp.), dead mussels, and aquatic macrophyte cover by analyzing the photoquadrat images using Image-Pro Plus 7.0 software for every depth. We assumed dead mussels covered sand substrate in photos based on knowledge obtained from scuba diving all sites. Data from Week 1 and Week 2 were averaged per depth (n = 5-10; $\bar{n}$ = 8.85) to determine estimates.

Lake Trout egg deposition data was obtained from the Michigan Department of Natural Resources after their fall sampling in 2012 and 2013 to determine the start and end dates of spawning. Lake Trout eggs were collected through egg funnels or egg bags (Barton et al. 2011) on all six spawning reefs. The average start date for all six reefs was calculated based on when the eggs were collected during sampling.

Statistical Analysis

We regarded the six sites to be our true replicates; therefore, all data for each gear type were averaged by depth within each site. For the 2012 underwater drop camera data, the maximum counts of Round Goby from videos and still images were combined to complete the statistical analysis. To determine the relative measure of abundance over time in the minnow traps, the catch-per-unit-effort (CPUE) was calculated for each trap by dividing the total number of Round Goby captured by the amount of time fished (2012: 1 day; 2013: 1.5 hours). Two-sample t-tests were used to determine differences between the catches of small and large minnow traps as well as to compare the total lengths (mm) of Round Goby captured for each trap type. For each gear, linear mixed effects models were used to examine Round Goby distribution over time and depth. We used models in which time (sampling week) and water depth were represented as fixed factors, and site was represented as a random factor to account for variability among sites. Data were log-transformed if assumptions of normality or homogeneity were not met. All statistical analyses were performed in R using version 2.14.1 (R Development Core Team 2011). All tests were considered to be significant at $P \leq 0.05$.

Results

Using multiple gear types, we monitored Round Goby seasonal distribution over various depths and interstitial habitat use on nearshore spawning reefs in northern Lake Michigan. Round Goby abundances fluctuated over time in both years, with peak relative abundances occurring in mid-October. Interstitial habitat use on the spawning reefs was highest in early November when epibenthic abundance was relatively low.

Field Sampling 2012

A total of 1,675 Round Goby were caught in the minnow traps from July-December 2012. In addition to Round Goby, the minnow traps caught three different species of crayfish and five different species of native fish, though Round Goby made up 93.2% of all fish captured (Table 1.1). Round Goby total length (TL) ranged from 20 to 164 mm (2 m TL: 78 mm ± 0.89 (mean ± SE); 6 m TL: 69 mm ± 0.85; 9 m TL: 67 mm ± 0.66; Appendix A). Minnow trap CPUE was 1.21 Round Goby·trap^{-1}·day^{-1} ± 0.10 (mean ± SE; Figure 1.2). A total of 1,227 Round Goby were captured in the small minnow traps, and 448 Round Goby were captured in the large minnow traps (*t*-test; $t_{184.81}$ = -5.46, P < 0.001). The total lengths (mm) of Round Goby caught in the small minnow traps (72.73 mm ± 0.63) did not differ significantly from those caught in the large minnow traps (67.26 mm ± 1.02) (*t*-test; $t_{48.53}$= -1.82, P = 0.07).

There were significant differences in minnow trap CPUE over time (χ^2 = 28.29, df = 8, P < 0.001) but not by depth (χ^2 = 4.74, df = 2, P = 0.09); there was no significant interaction between time and depth in the 2012 minnow trap catches (χ^2 = 13.21, df = 16, P = 0.66). The highest relative abundance for all three depths occurred during the sampling week beginning on October 16 (Figure 1.2). Although highly variable throughout the sampling period, the relative abundance of Round Goby on 14 October was highest at the 9 m depth, followed by the 2 m and 6 m depths, respectively (Figure 1.2). Round Goby abundances were relatively low during the last sampling week beginning 26 November, with the lowest abundances occurring during the week of 17 September (Figure 1.2).

A total of 102 Round Goby were captured in the egg bags throughout the ten sampling weeks. In addition to Round Goby, three native fish species, one native crayfish species, and one invasive crayfish species were collected from the egg bags on the spawning reefs (Table 1.1). Although there was no difference in the egg bag densities over time ($\chi^2 = 17.27$, df = 10, $P = 0.07$), average relative densities were lowest during the week of 17 September (0.03 Round Goby·egg bag^{-1} ± 0.03 SE) and highest during the week of 26 November (0.38 Round Goby·egg bag^{-1} ± 0.16; Figure 1.2). Round Goby retrieved from the egg bags ranged in total length from 21 to 93 mm, with an average total length of 51 mm ± 1.79 (mean ± SE; Appendix B). The average length of Round Goby captured during the sampling week of 26 November was 58 mm ± 3.69, which differed significantly from the average total length of Round Goby captured from the minnow traps that same week (86.2 mm ± 3.35; $P < 0.0001$, t-test).

A total of 1,539 1-minute videos were recorded using the Seaviewer® underwater drop camera in 2012; however, 36 of those videos were deemed unusable due to file corruption, camera malfunction, or low visibility throughout the recording. In addition to the underwater drop camera videos, a total of 181 still images were captured using the handheld camera on the shallowest reef sites when necessary.

Table 1.1. Bycatch abundance by gear type from July-December 2012 and September-December 2013 in Grand Traverse and Little Traverse Bays, Lake Michigan. Abundances are total abundance for each species within the sampling period: 2012 minnow traps (24 hour period), 2012 egg bags (2 week period), 2012 underwater video (1 minute period), 2013 minnow traps (1.5 hour period), and 2013 baited photoquadrats (20 minute period).

Common Name	Scientific Name	2012 Minnow Traps	2012 Egg Bags	2012 Underwater Video	2013 Minnow Traps	2013 Baited Photoquadrats
Rusty Crayfish	*Orconectes rusticus*	325	169	1	65	—
Northern Clearwater Crayfish	*Orconectes propinquus*	3	2	—	—	—
Virile Crayfish	*Orconectes virilis*	18	—	—	—	—
Lake Chub	*Couesius plumbeus*	23	—	—	—	—
Emerald Shiner	*Notropis atherinoides*	—	2	—	—	—
Largemouth Bass	*Micropterus salmoides*	2	—	—	—	—
Rock Bass	*Ambloplites rupestris*	62	1	—	3	16
Smallmouth Bass	*Micropterus dolomieu*	11	2	37	1	37
Bluegill	*Lepomis macrochirus*	—	—	—	—	1
Spottail Shiner	*Notropis hudsonius*	17	—	—	1	—
Cyprinid spp.		8	—	6	—	47

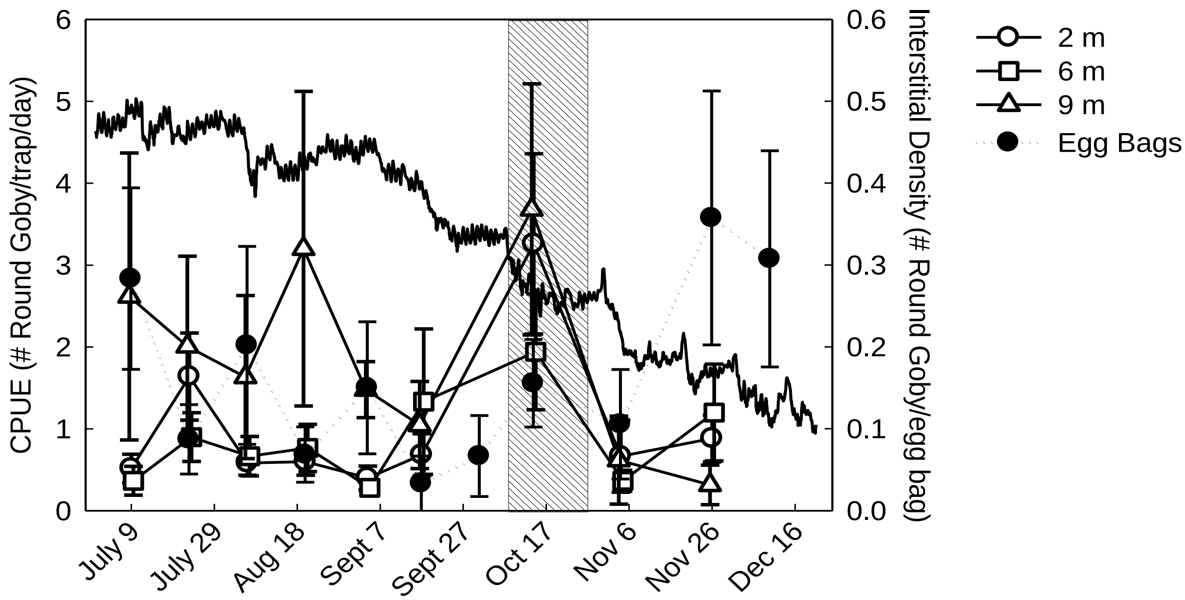

Figure 1.2. Round Goby catch-per-unit-effort (number of individuals per minnow trap per day; CPUE ± SE) and interstitial habitat use (number of individuals per egg bag; density ± SE) from July – December 2012 in Grand Traverse and Little Traverse Bays, Lake Michigan. Minnow traps were set at depths of 2 m, 6 m, and 9 m. Egg bags were buried into reef habitat at 2 m depth. Sampling dates represent the first day of the sampling week. Hatched box represents estimated Lake Trout (*Salvelinus namaycush*) spawning period. Water temperature (°C) is represented by the declining solid line.

The average maximum number of Round Goby present in the videos was 2.96 Round Goby·m^{-2} ± 0.46 (mean ± SE) for the 2 m depth, 10.97 Round Goby·m^{-2} ± 1.45 for the 6 m depth, and 8.86 Round Goby·m^{-2} ±1.84 for the 9 m depth (Figure 1.3). We found a significant difference in Round Goby maximum density over time ($\chi^2 = 48.53$, df = 9, $P < 0.0001$) and by depth ($\chi^2 = 44.89$, df = 2, $P < 0.0001$) as well as a significant interaction between time and depth ($\chi^2 = 46.89$, df = 18, $P < 0.001$). The relative densities of Round Goby observed in the cameras were lowest for all three depths during the sampling week beginning 26 November (2 m: 0.22 Round Goby·m^{-2} ± 0.10; 6 m: 1.08 Round Goby·m^{-2} ± 0.80; 9 m: 1.13 Round Goby·m^{-2} ± 1.11;

mean ± SE); however, all three depths differed in the timing of their peak densities (Figure 1.3). The highest density for the 2 m depth occurred during the sampling week beginning 4 September (5.79 Round Goby·m^{-2} ± 2.73), while the highest density for the 6 m depth occurred during the sampling week beginning 17 September (27.18 Round Goby·m^{-2} ± 6.65; Figure 1.3). Maximum Round Goby density reached the highest for the 9 m depth the earliest, which occurred the week of 6 August (19.67 Round Goby·m^{-2} ± 13.03; Figure 1.3).

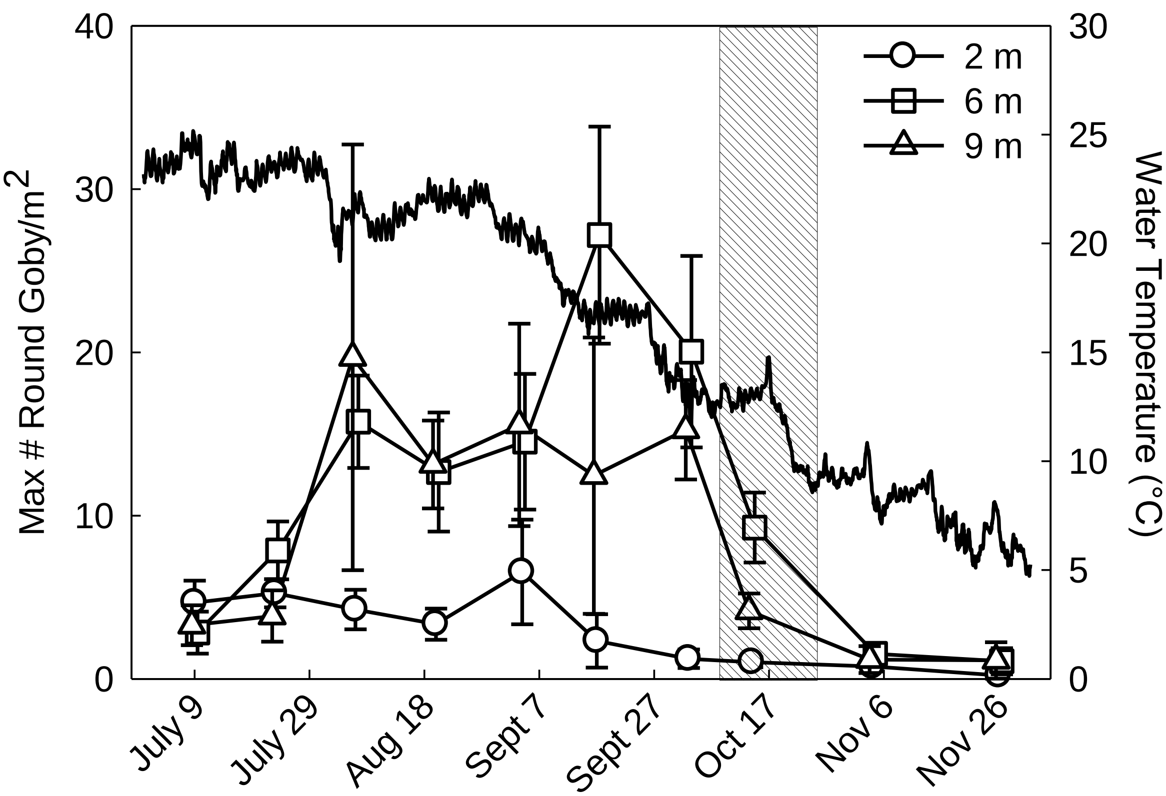

Figure 1.3. The maximum density of Round Goby (maximum number of individuals per m^2; max density ± SE) observed in the underwater video in 2012 at 2 m, 6 m, and 9 m depths in Grand Traverse and Little Traverse Bays, Lake Michigan. Sampling dates represent the first day of the sampling week. Hatched box represents estimated Lake Trout (*Salvelinus namaycush*) spawning period. Water temperature (°C) is represented by the declining solid line.

Based on egg deposition data from all of the spawning reefs, Lake Trout spawning started as early as 8 October 2012. However, by averaging the spawning start dates of all sites, we can estimate an overall start date of 13 October 2012. Since Lake Trout spawning typically lasts for a period of ten days (Wasylenko et al. 2014), we assumed spawning ended around 23 October 2012 (refer to hatched box in Figures 1.2-1.5).

Field Sampling 2013

A total of 2,805 Round Goby were caught in the minnow traps from September-December 2013. Minnow traps also captured one species of invasive crayfish and four species of native fish, though 99.8% of fish captured were Round Goby (Table 1.1). There was a significant difference in minnow trap CPUE over time ($\chi^2 = 62.47$, df = 4, $P < 0.0001$) and by depth ($\chi^2 = 10.27$, df = 3, $P = 0.02$), but the interaction term was not significant ($\chi^2 = 8.80$, df = 11, $P = 0.72$). The highest relative abundance for the 2 m and 6 m depths occurred during the sampling week beginning on 14 October, whereas the highest relative abundance for the 9 m and 15 m depths occurred during the first week of sampling that began on 4 September (Figure 1.4). The lowest abundances for all four depths occurred during the last two weeks of sampling, with nearly zero Round Goby captured at any sites (Figure 1.4).

Mean CPUE for all minnow traps was 2.08 Round Goby·trap^{-1}·day^{-1} ± 0.14 (mean ± SE), and the number of Round Goby caught in the small traps did not differ from the number caught in the large traps (*t*-test; $t_{134.45} = -1.72$, $P = 0.09$). Small minnow traps captured 1,638 Round Goby, while large minnow traps only captured 1,167 Round Goby. The range of Round Goby total length was 20 mm to 147 mm, with an average total length of 65 mm ± 0.31 (mean ± SE; Appendix C). For the small minnow traps, the average total length of Round Goby was 66 mm ± 0.40 (mean ± SE) and 64 mm ± 0.52 for the large minnow traps.

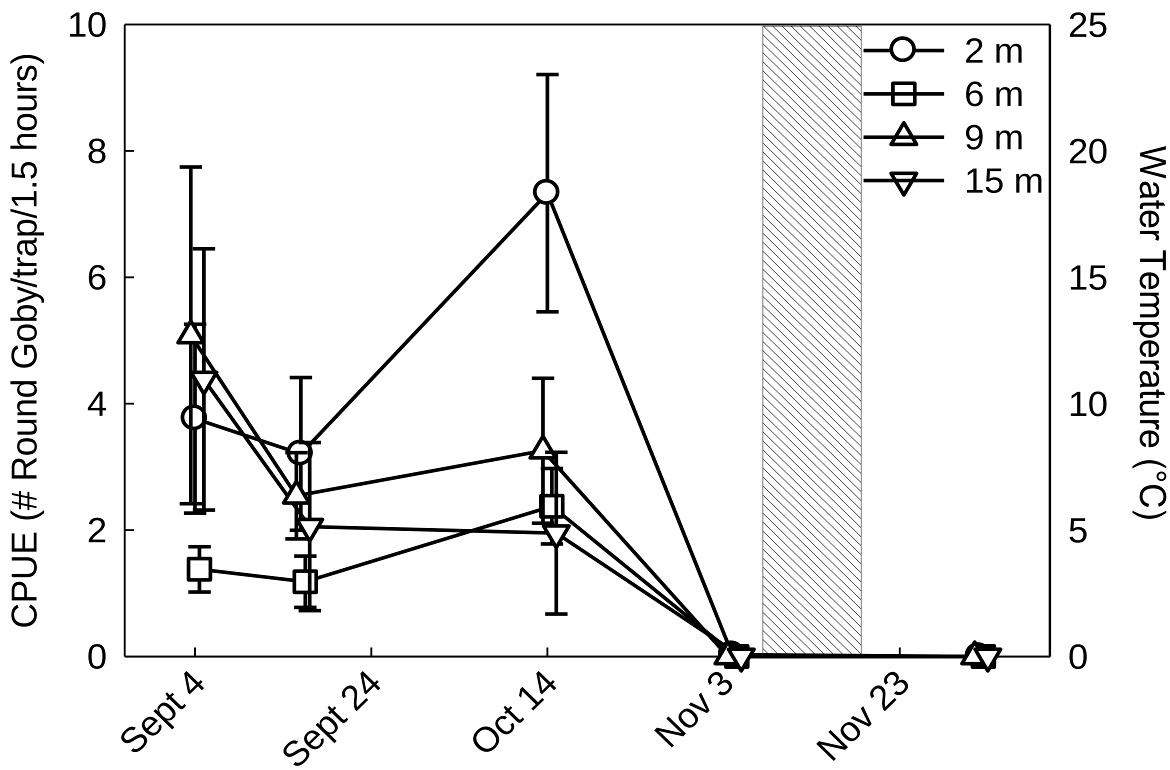

Figure 1.4. Round Goby catch-per-unit-effort (number of individuals per minnow trap 1.5 hours; CPUE ± SE) from September – December 2013 in Grand Traverse and Little Traverse Bays, Lake Michigan. Minnow Traps were set at depths of 2 m, 6 m, 9 m, and 15 m. Sampling dates represent the first day of the sampling week. Hatched box represents estimated Lake Trout (*Salvelinus namaycush*) spawning period. Water temperature (°C) is represented by the declining solid line.

In 2013, there was a total of 449 camera drops done with the GoPro® cameras, which resulted in 8,466 images analyzed. We found a significant difference in Round Goby maximum density over time ($\chi^2 = 254.57$, df = 4, $P < 0.0001$) but not by depth ($\chi^2 = 1.01$, df = 3, $P = 0.80$). Additionally, there was no significant interaction between time and depth ($\chi^2 = 14.66$, df = 12, $P = 0.26$). The relative densities of Round Goby observed in the cameras were lowest for all four depths during the sampling week beginning 2 December (Figure 1.5). The highest density for the 2 m depth occurred during the sampling week that began on 14 October (106.92 Round Goby·m^{-2} ± 19.23), while the highest densities for the 6 m, 9 m, and 15 m depths occurred during the week of 4 September (Figure 1.5). Round Goby density was 102.4 Round Goby·m^{-2} ± 13.20 (mean ± SE) for the 2 m depth, 111.52 Round Goby·m^{-2} ± 16.76 for the 6 m depth, 160.96 Round Goby·m^{-2} ± 30.73 for the 9 m depth, and 161.6 Round Goby·m^{-2} ± 33.96 for the 15 m depth (Figure 1.5).

Based on egg deposition data from all of the spawning reefs, Lake Trout spawning started as early as 29 October 2013. However, by averaging the spawning start dates of all sites, we estimated an overall start date of 7 November 2013 and assumed spawning ended around 17 November 2013 (refer to hatched box in Figures 1.2-1.5).

Habitat type at the 2 m depth consisted primarily of cobble and boulder substrate, and the 6 m depth was composed primarily of boulders and aquatic vegetation (Table 1.2). The 9 m depth was primarily boulders and aquatic vegetation, while sand and aquatic vegetation where found throughout the deepest depth at 15 m (Table 1.2).

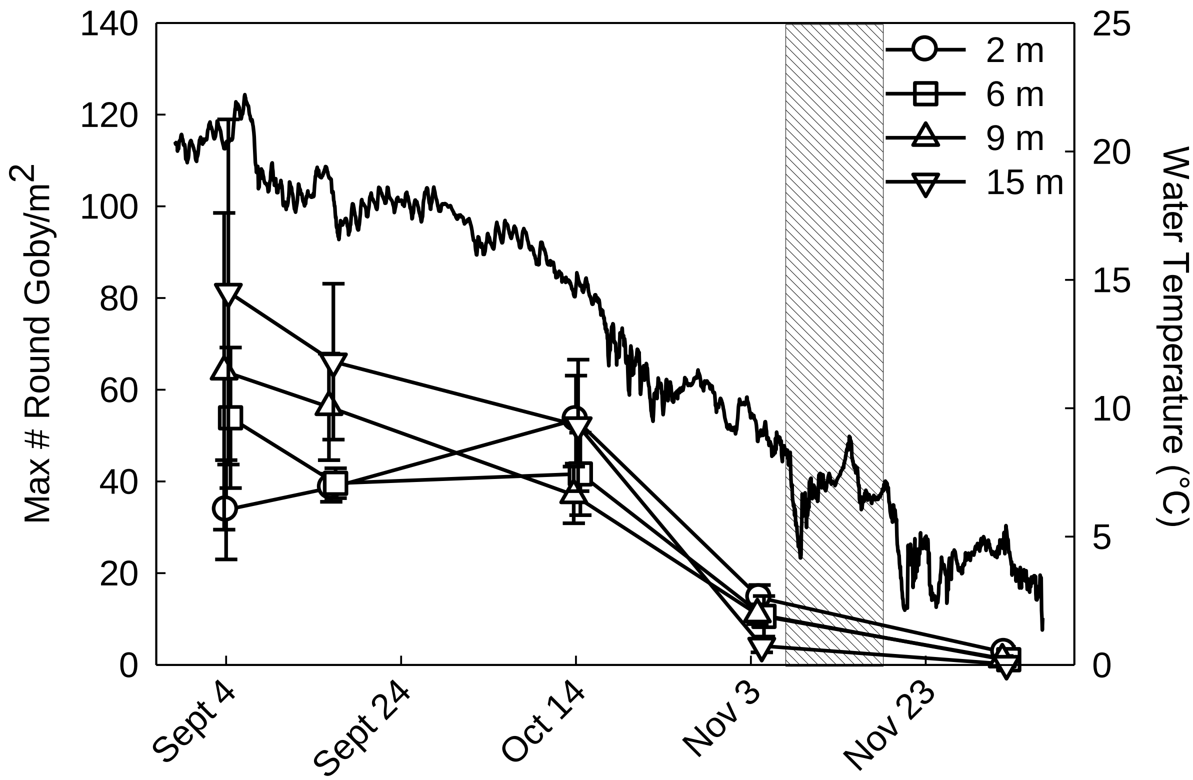

Figure 1.5. The maximum density of Round Goby (maximum number of individuals per m^2; max density ± SE) observed in the baited photoquadrats in 2013 at 2 m, 6 m, 9 m, and 15 m depths in Grand Traverse and Little Traverse Bays, Lake Michigan. Sampling dates represent the first day of the sampling week. Hatched box represents estimated Lake Trout (*Salvelinus namaycush*) spawning period. Water temperature (°C) is represented by the declining solid line.

Table 1.2. Average characteristics of the six spawning reefs (2 m) and offshore depths (6, 9, and 15 m) in Grand Traverse (GTB) and Little Traverse Bays (LTB), Lake Michigan. Mean (± SE) percent habitat type, mussel coverage (*Dreissena* spp.), and aquatic vegetation coverage were estimated using underwater photoquadrat images.

Site Depth (m)	Sand (%)	Gravel (%)	Cobble (%)	Boulder (%)	Live Mussels (%)	Dead Mussels (%)	Aquatic Vegetation Coverage (%)
2	0	2.65± 1.17	22.50 ± 6.09	22.5 ± 5.42	6.85 ± 1.60	2.97 ± 1.50	14.82 ± 6.06
6	0	0.54 ± 0.31	8.70 ± 3.10	17.03 ± 5.25	5.38 ± 1.88	8.99 ± 2.33	32.89 ± 7.38
9	0	0.36 ± 0.26	1.90 ± 1.48	13.06 ± 5.27	3.14 ± 0.97	3.89 ± 0.78	49.12 ± 7.48
15	100	0	0	0	1.31 ± 0.40	0.30 ± 0.07	22.96 ± 6.49

Discussion

The Round Goby invasion in the Great Lakes strongly influenced the benthic community structure and the overall dynamics of the aquatic ecosystem (Kuhns and Berg 1999; Kipp and Ricciardi 2012; Kornis et al. 2012). The purpose of this study was to quantify the spatiotemporal distributions and interstitial habitat use of Round Goby by employing multiple gear types. While there were differences in densities among depths during sampling, we did not document offshore migration from our shallow to deep depths, even though an offshore migration was likely occurring in December. Despite low numbers of Round Goby on the reefs at the end of sampling, a portion of the population did remain behind in the interstitial spaces. These findings have implications for the management and conservation strategies targeting native fish that utilize these nearshore reefs for spawning in late fall.

Minnow traps were an important gear type utilized in this study, particularly because they allowed us to capture individuals and collect biological data (i.e., total length) that was not possible with the underwater video or baited photoquadrats. Round Goby catch rates were low in the 2012 catches relative to the 2013 catches in minnow traps, which could have been the result of the changes made to the sampling methodology (Chapter 3). Zero-inflation is often a concern when employing trapping techniques or measuring catch-per-unit-effort (CPUE) of a species (Maunder and Punt 2004; Bacheler et al. 2013). In order to manage the high proportion of zero catches encountered, we averaged the CPUEs of all ten traps for each depth since there was no significant difference between the small and large trap types (Chapter 3). By aggregating the data for each depth (Maunder and Punt 2004), we were more likely to separate out the “true zeros” (i.e., Round Goby were targeted but no catch was made) from the “false zeros” (i.e., zero catches from non-targeted effort) (Winker et al. 2013). Although the minnow traps did not give us a true measure of Round Goby abundance, we believe that they still successfully evaluated the relative measure of abundance throughout the season.

The egg bags used in this study were essential for examining the interstitial habitat use of Round Goby over time, as they indicated that interstitial habitat use on the spawning reefs was highly variable and relatively low from July through October. We observed no significant difference in Round Goby interstitial habitat use among the sampling weeks, which suggests that Round Goby were using the interstitial reef habitat from July through December. Variability in Round Goby habitat use may be influenced by abiotic gradients like dissolved oxygen, pH, water clarity, or alkalinity (Cooper et al. 2009). Intraspecific or interspecific competition with benthic species that use habitats similar to Round Goby, like the invasive Eurasion Ruffe (*Gymnocephalus cernuus*), may also impact their eventual range and habitat use (Bauer et al. 2007). Other species, such as Blue Gill (*Lepomis macrochirus*), have been found to alter their foraging strategies and habitat use in small Michigan lakes based on energetic gain and predation risk (Mittelbach 1981). Perhaps these factors related to potential growth are also influencing Round Goby interstitial habitat use over time, and they may even account for the variability observed among the different spawning reefs.

Surprisingly, in late November and early December, relatively high interstitial densities of Round Goby were observed on the reefs; however, overall density remained low. During a period of time when Round Goby were previously thought to move offshore (Charlebois et al. 1997; Sapota and Skóra 2005; Pennuto et al. 2010), we determined that some individuals remained on the reefs and stayed in the substrate, which suggests a trade-off associated with the individuals moving deeper into the substrate instead of moving offshore. Theoretical frameworks have suggested that seasonal fish migrations are associated with trade-offs between predator avoidance and growth (Werner and Gilliam 1984; Brönmark et al. 2008). Therefore, we can hypothesize that any Round Goby settling into the spawning reefs at this time were most likely using the interstitial spaces for foraging and shelter from abiotic factors (e.g., colder temperatures), physical forces (e.g., wave action), or predators. The timing and extent of seasonal migration patterns may be size-specific in some species, where smaller individuals have tended to migrate more than larger individuals in some cases (Skov et al. 2008). It is possible that the observed size-differentiated migration patterns where smaller Round Goby were not moving offshore as early as larger individuals are explained by avoidance of open water predators.

In the 2012 underwater videos, we detected relatively low densities of Round Goby on the spawning reefs compared to the deeper depths. We observed peak densities at the 6 m depth occurring in mid-September, which is almost four weeks earlier than the peak abundances from the 2012 minnow traps. Additionally, trends from the 2013 photoquadrats are also different from those observed with the minnow trap gear. For example, the 2013 photoquadrats show trends that are consistent with a more gradual decline in density without any large peaks occurring in mid-October. Although not statistically different, there was an increase in density at the shallowest depths in mid-October, which is consistent with the increase in the 2013 minnow traps. We also found greater differences in abundance among the depths earlier in the sampling season. Most likely, this is occurring since all depths were close to zero density in December because many individuals had already moved offshore.

Although the 2012 underwater video provides a good estimate of relative abundance, we encountered some issues with this particular gear type. For example, we had concerns about the independence between each camera drop, the set time, and the avoidance behavior due to the size of our camera frame. However, we were resistant to changing the methods during the sampling season because we still felt that the underwater video gave us a relative measure of abundance. To manage the high proportion of zeros encountered, we again averaged the densities for each depth so that we could tease apart the "true zeros" from the "false zeros" (Winker et al. 2013). As we moved into our 2013 sampling period, we altered the underwater video frame structure and sampling protocol to incorporate still image photoquadrats instead of videos (Preskitt et al. 2004; Van Rein et al. 2011). Although other studies have incorporated underwater video into sampling freshwater systems (Johnson et al. 2005; Chidami et al. 2007; Ebner et al. 2009; Ellender et al. 2012), we believe that the photoquadrat methodologies used in 2013 resulted in more accurate densities and overall descriptions of the spatiotemporal distributions of Round Goby (Chapter 3).

In both years, there were apparent differences between the abundance trends from the underwater cameras and minnow traps. These gear type discrepancies may be the result of size- or species-selectivity (Willis et al. 2000; Wells et al. 2008). While the minnow traps rely on the target species encountering, entering, and remaining in the trap (Hubert et al. 2012), the underwater video and photoquadrats only require the intended species to encounter the gear and come into view of the camera. Therefore, the underwater video and photoquadrats are able to capture all sizes that may otherwise escape the minnow traps (Bacheler et al. 2013). Despite the differences between the gears (Chapter 3), they are complementary to each other because one gear can collect biological data and quantify effort (Hubert et al. 2012), while the other may index fish abundance more accurately (Bacheler et al. 2013). We found that both gear types were useful in this study and should be combined for future sampling methodologies examining spatial distributions of benthic fish.

Peak abundances of Round Goby occurred mid-October in both 2012 and 2013 for the shallowest depths, which coincided with Lake Trout spawning. We estimated an average spawning start date of 13 October and 7 November in 2012 and 2013, respectively. These findings are consistent with Dawson et al. (1997), which showed that average peak spawning activity of Lake Trout occurs at the end of October. Typically, Lake Trout spawn on rocky reefs where their negatively buoyant eggs remain in the interstices until hatching (Gunn 1995). Wasylenko et al. (2013) determined that Lake Trout were more likely to spawn on substrate previously used by conspecifics, suggesting that in addition to the physical characteristics of preferred habitat, chemical cues can also influence spawning site location. In addition, Lake Trout egg predators, including Round Goby, sculpin (*Cottus* spp.), and crayfish (*Orconectes* spp.) (Chotkowski and Marsden 1999; Jonas et al. 2005; Fitzsimons et al. 2007), are attracted to spawning sites by chemosensory cues as well (Wasylenko et al. 2014). Perhaps the chemosensory cues associated with Lake Trout spawning prompted the Round Goby to move onto the spawning reefs and the surrounding areas in mid-October. However, this seems unlikely in 2013 because Round Goby peak abundances occurred pre-spawning, which makes us believe that there are other factors initiating Round Goby to move onto the reefs. The same environmental cues that trigger the Lake Trout to spawn (e.g., water temperature, accumulated sunlight, wind direction, or the range of temperature decline (Gunn 1995)) may also be affecting

Round Goby distribution patterns. Insights into the cues that shape spatiotemporal distributions are not only critical for Round Goby, but for understanding other factors that may also influence movement of critical native species.

Conservation strategies and rehabilitation plans for ecologically and commercially valuable species are often modified to account for the variability observed in spatial patterns over time (Cooke 2008; Landsman et al. 2011). For example, identifying the seasonal distribution patterns of native salmonids like Lake Trout in Lake Michigan allows managers to locate and protect specific habitats critical to their restoration initiatives (Schmalz et al. 2002; Adlerstein et al. 2007). Information about the dispersal and return of hatchery-reared Lake Trout can also contribute to future management plans and knowledge about local population densities (Schmalz et al. 2002). Data on seasonal patterns of habitat use can provide predictive tools to estimate abundance, migration patterns, and habitat preferences for a range of spatial scales, which can have implications for conservation efforts (Bradford et al. 1997; Flitcroft et al. 2014).

In addition to native species, understanding movement and seasonal distribution shifts has been important for Great Lakes invaders like Round Goby (Pennuto et al. 2010; Lynch and Mensinger 2012) and Rusty Crayfish (Taylor and Redmer 1996; Byron and Wilson 2001; Chapter 2). Interstitial egg predators can greatly affect egg mortality on spawning reefs (Jones et al. 1995; Savino et al. 1999; Claramunt et al. 2005); therefore, understanding the overlap between Round Goby presence on these spawning reefs and the affect they are having on native fish recruitment is valuable. Knowledge of invasive species life history traits and spatial patterns will allow managers to develop effective management strategies and ultimately prevent future invasions of nuisance species (Mack et al. 2000; Sakai et al. 2001; Lodge et al. 2006). The present study asked questions related to the basic ecology of a benthic egg predator in order further understand how they can impact a system. Future studies should aim to incorporate aspects of Round Goby spatial and temporal ecology when designing and implementing control efforts, especially on critical nearshore spawning reefs in the Great Lakes.

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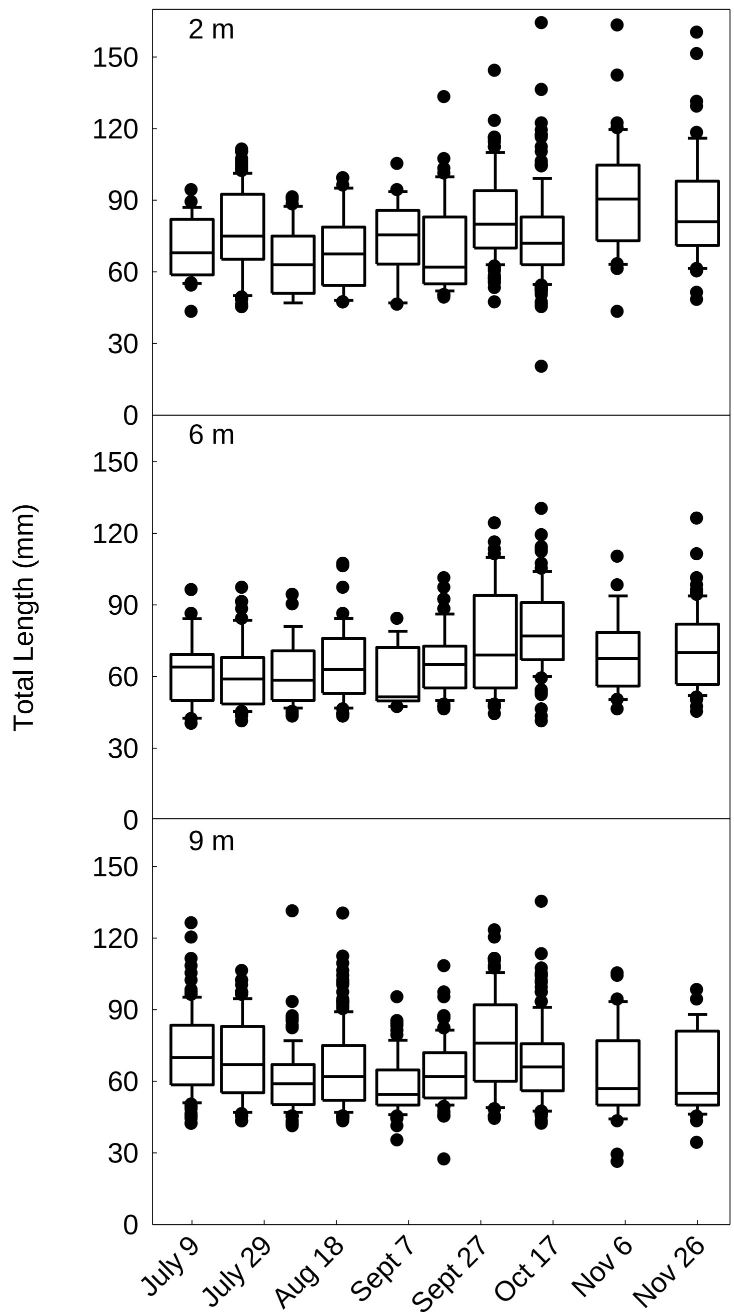
APPENDICES

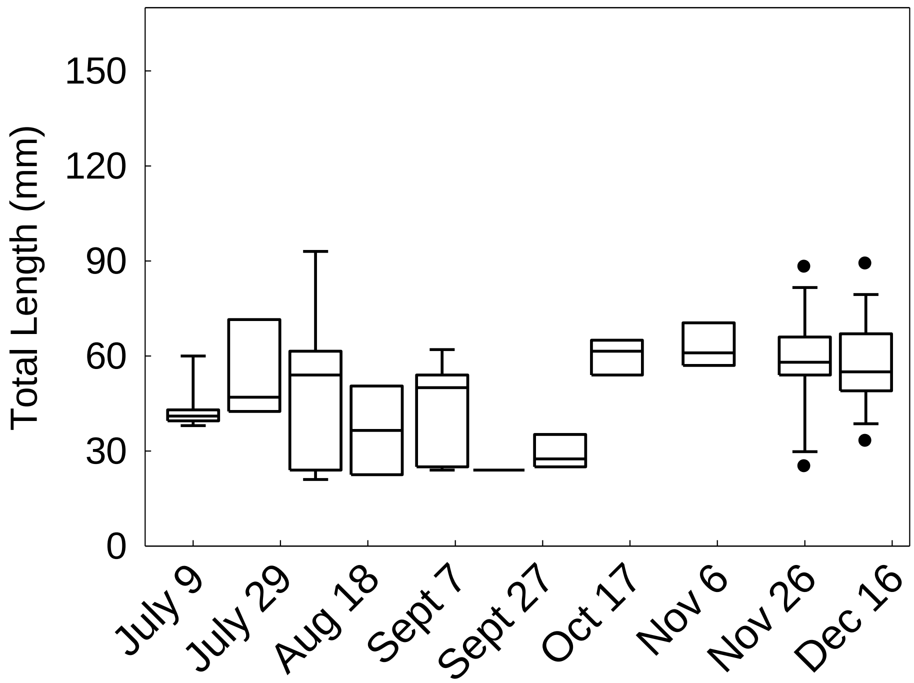
APPENDIX A

BOXPLOTS OF ROUND GOBY TOTAL LENGTH (MM) FROM MINNOW TRAPS IN 2012 AT ALL DEPTHS (2 M, 6 M, AND 9 M). LARGE AND SMALL MINNOW TRAPS WERE COMBINED, AND TOTAL LENGTHS WERE AVERAGED ACROSS SAMPLING SITES FOR EACH WEEK. FILLED CIRCLES REPRESENT OUTLIERS.



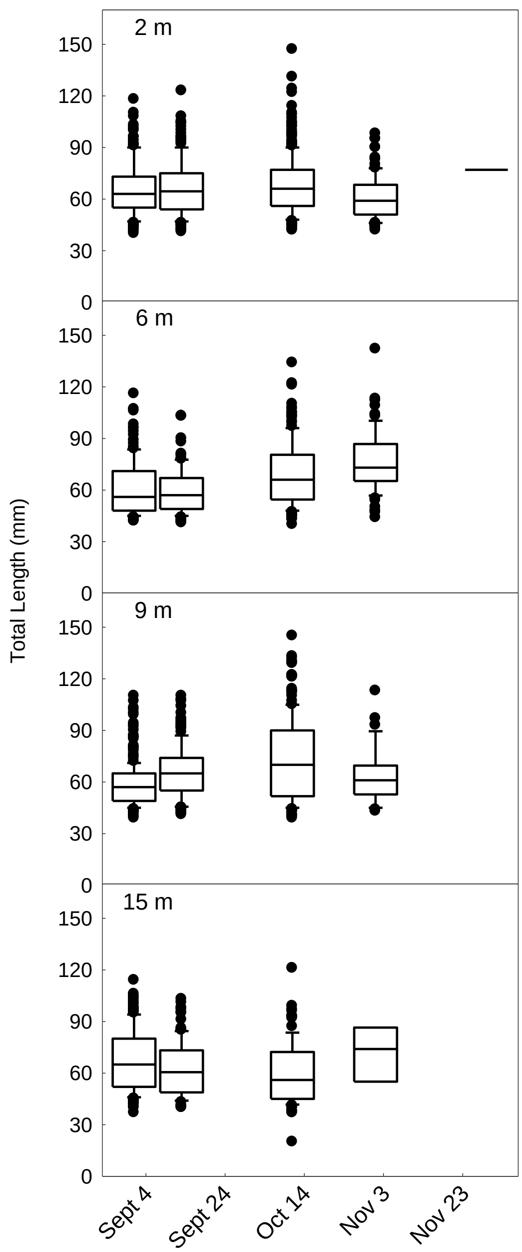
APPENDIX B

BOXPLOTS OF ROUND GOBY TOTAL LENGTH (MM) FROM EGG BAGS IN 2012. TOTAL LENGTHS WERE AVERAGED ACROSS SAMPLING SITES FOR EACH WEEK. FILLED CIRCLES REPRESENT OUTLIERS OUTSIDE OF THE AVERAGES.



APPENDIX C

BOXPLOTS OF ROUND GOBY TOTAL LENGTH (MM) FROM MINNOW TRAPS IN 2013 AT ALL DEPTHS (2 M, 6 M, 9 M, AND 15 M). LARGE AND SMALL MINNOW TRAPS WERE COMBINED, AND TOTAL LENGTHS WERE AVERAGED ACROSS SAMPLING SITES FOR EACH WEEK. FILLED CIRCLES REPRESENT OUTLIERS. NO INDIVIDUALS WERE CAPTURED IN THE MINNOW TRAPS DURING THE SAMPLING WEEK BEGINNING 2 DECEMBER 2013.



CHAPTER II

SPATIAL AND SEASONAL DISTRIBUTION OF THE INVASIVE RUSTY CRAYFISH (*ORCONECTES RUSTICUS*) ON CRITICAL NEARSHORE SPAWNING REEFS IN NORTHERN LAKE MICHIGAN

Introduction

Invasive species are one of the most important threats to biodiversity, ecological processes, and ecosystem functioning in an aquatic environment (García-Berthou 2007; Gozlan et al. 2010; Strayer 2010). Biological invasions not only affect native species through increased predation, competition, and habitat modification, but there are tremendous economic costs associated with implementing management strategies and loss of ecosystem services (Perrings 2002; Lovell and Stone 2005; Pimentel et al. 2005; Gozlan et al. 2010). The negative effects following the introduction and establishment of an invasive species can be influenced by their life history traits and spatial ecology (Lodge et al. 1998; Mack et al. 2000; Sakai et al. 2001; Allendorf and Lundquist 2003). Recent studies have focused on specific characteristics of invasive species to determine which life history traits contribute to their success (Kolar and Lodge 2002; Marchetti et al. 2004; Jeschke and Strayer 2006; Hayes and Barry 2008; Larson and Olden 2010). A comprehensive understanding of the life history traits of invasive species allows for more accurate predictions of potential invaders and can lead to more effective control measures (Lodge et al. 1998; Mack et al. 2000; Sakai et al. 2001; Larson and Olden 2010). Although there are detailed studies regarding the life history traits and characteristics of invasive freshwater fishes (Winemiller and Rose 1992; Kolar and Lodge 2002; Jeschke and Strayer 2006), there are limited data on the life histories of invasive freshwater crayfish and other invertebrates (Butler and Stein 1985; Moore 2013).

Crayfish in particular have become one of the most established invertebrate species in freshwater systems around the globe due to their widespread introductions (Hobbs et al. 1989; Gherardi 2010). As the largest invertebrates found in these systems, they can create extensive ecosystem-level effects (Covich et al. 1999; Lodge et al. 2000). By definition, ecosystem engineers like crayfish indirectly or directly control resources by modifying biotic or abiotic materials in a given habitat (Jones et al. 1994; Crooks 2002). Similar to other invaders, crayfish possess the ability to change the native community structure through their aggressive behaviors and ability to adapt to new benthic environments (Capelli and Munjal 1982; Mather and Stein 1993; Lodge et al. 1994; Morehouse and Tobler 2013; Morse et al. 2013). Food web dynamics (Lodge et al. 1994; Dorn and Wojdak 2004; Geiger et al. 2005; Hansen et al. 2013), nutrient cycling (Covich et al. 1999; Gherardi 2010), and sediment mixing (Covich et al. 1999; Nogaro et al. 2006) can be impacted by the presence of invasive crayfish in lake systems. Examining the movement and spatial distribution patterns of these crayfish can have implications for understanding the life history traits, habitat use, and future invasion rates of non-native crayfish (Gherardi et al. 2000; Byron and Wilson 2001).

Rusty Crayfish (*Orconectes rusticus*) originated from the Ohio River basin and spread to Wisconsin by the 1970's primarily through bait bucket introduction (Creaser 1931; Capelli and Munjal 1982; Taylor and Redmer 1996; Phillips 2010). This invasive species plays a significant role in trophic interactions by replacing its congeners and reducing benthic macroinvertebrate and macrophyte populations (Capelli 1982; Olsen et al. 1991; Mather and Stein 1993; Lodge et al. 1994; Taylor and Redmer 1996; Wilson et al. 2004; Phillips 2010). Although highly active, Rusty Crayfish exhibit high site affinity and are less likely to move outside of their original habitat (Byron and Wilson 2001). Currently, the large-scale spatial and temporal distributions of Rusty Crayfish remain unclear in many freshwater systems, although they occupy a wide range of habitats (Kershner and Lodge 1995; Byron and Wilson 2001; Hein et al. 2007). Rusty Crayfish generally associate with complex cobble substrates due to the shelter it provides during periods of high predation risk (Kershner and Lodge 1995; Taylor and Redmer 1996). However, in addition to refuge, they are also exploiting cobble habitats for prey items like substrate-bound fish eggs (Capelli 1982; Jonas et al. 2005). As benthic egg predators, Rusty Crayfish are negatively affecting the recruitment success of various substrate-nesting fishes in freshwater environments (Dorn and Mittelbach 1999; Dorn and Wojdak 2004; Jonas et al. 2005; Baldridge and Lodge 2013; Morse et al. 2013). The predation pressure on native fish eggs may be influenced by the distribution of Rusty Crayfish over space and time, especially at larger spatial scales. To fully understand the role of Rusty Crayfish in the Great Lakes nearshore community, it is critical to assess their spatial and temporal patterns over a variety of habitats.

The objective of this study was to quantify the spatial and temporal distribution of Rusty Crayfish in northern Lake Michigan. Specifically, the objectives were to (1) determine if and how Rusty Crayfish distribution changed over time and water depth, and (2) quantify Rusty Crayfish interstitial habitat use over time on nearshore spawning reefs. The present study will have critical implications for fisheries management, especially for the restoration initiatives aiming to increase recruitment and survival of native fish eggs. Findings from this study will also help managers better understand seasonal abundance shifts in order to develop effective management strategies targeting Rusty Crayfish.

Methods

Study Sites

Sampling was conducted in Grand Traverse and Little Traverse Bays, Lake Michigan, from 9 July 2012 to 30 November 2012 and 9 September 2013 to 2 December 2013. Both bays are located in northeastern Lake Michigan, with Grand Traverse Bay separated into eastern and western arms by Old Mission Peninsula (Figure 2.1). Six study sites were evaluated for changes in Rusty Crayfish abundance over time and depth. Three study sites (North, Central, and South) were located on a spawning reef complex (44°54’N, 85°25’W) in the eastern arm of Grand Traverse Bay near Elk Rapids, Michigan, and one study site (Ingalls Point) was located in the western arm of Grand Traverse Bay near Ingalls Bay (45°04'N, 85°34'W) (Figure 2.1). Of the two study sites located in Little Traverse Bay, one site (LTB Crib) was located in northern Little Traverse Bay near Harbor Springs, Michigan (45°25'N, 84°56'W), and the other site (Bay Harbor) was located in southern Little Traverse Bay near Bay Harbor, Michigan (45°22'N, 84°59'W). The Grand Traverse Bay South site was not sampled in 2013.

All sites are active spawning reefs (Michigan Department of Natural Resources, unpublished data) that are similar in depth (1.85 ± 0.04 m, mean ± SE) and distance from shore (Barton et al. 2011). The primary habitat type on the reefs consisted of a cobble-rubble rock mixture comprised of substrate approximately 10-20 cm in diameter (Barton et al. 2011). To determine changes in Rusty Crayfish abundance over depth in 2012, each site consisted of one spawning reef depth (2 m) and two offshore depths (6 m and 9 m). The 6 m and 9 m depths for each site were determined by moving offshore from the spawning reef until the appropriate depth was located. All depths remained fixed for the entire sampling period and were chosen regardless of substrate type. In 2013, a 15 m offshore depth was added to every site except the Grand Traverse Bay North site.

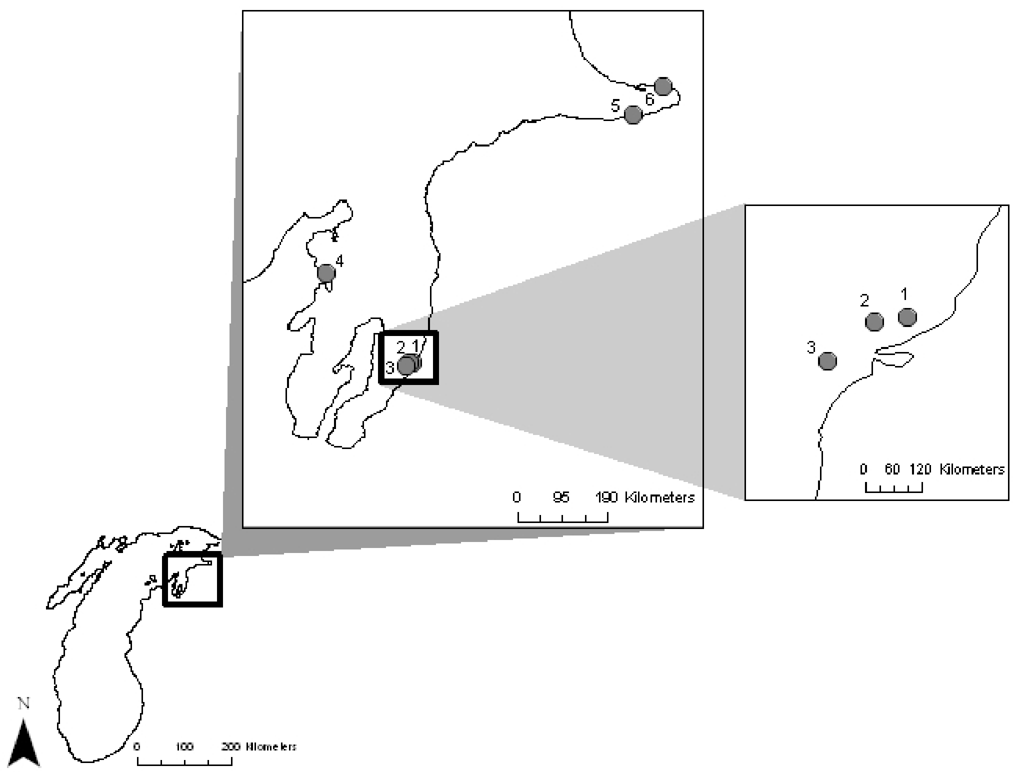


Figure 2.1. Location of the six spawning reefs (2 m depth) in Grand Traverse and Little Traverse Bays, Lake Michigan where Rusty Crayfish spatial and temporal distribution was evaluated. Site key: 1 = North, 2 = Central, 3 = South, 4 = Ingalls Point, 5 = Bay Harbor, and 6 = LTB Crib.

Field Sampling 2012

Rusty Crayfish were sampled using standard Gee minnow traps (23 cm x 45 cm with 0.64 cm steel wire mesh) with either 3 cm ("small" hereafter) or 6 cm ("large" hereafter) entrance openings. Ten traps, alternating small and large entrance openings, were placed 1 m apart on a trap line. Each trap was tagged and baited with previously collected, frozen, and thawed Lake Trout (*Salvelinus namaycush*) eggs. Lake Trout eggs (~30 g) were placed in 8 cm x 13 cm mesh bags and suspended in the middle of each trap. One trap line was set at each depth. Traps fished for 24 hours biweekly throughout the sampling period. All Rusty Crayfish collected were immediately measured for carapace length (mm) and euthanized. Any other fish species captured were identified, measured, and released. Round Goby (*Neogobius melanostomus*), another invasive egg predator on the spawning reefs, were measured for total length (mm) and euthanized if caught in the minnow traps. Water temperature (°C) was taken at each depth by lowering a temperature probe to the bottom substrate after all minnow traps were lifted.

Egg bags (similar to Barton et al. 2011 and Claramunt et al. 2005) were used to quantify interstitial habitat use. Each egg bag was approximately 50 cm deep with a mesh size of 0.16 cm. Scuba divers buried 10 egg bags 1 m apart along a single transect at the 2 m depths of each site. Egg bags were retrieved every two weeks by removing any substrate from inside the egg bag and cinching the tops closed with cable ties to decrease the chance of any Rusty Crayfish escaping (Fitzsimons et al. 2007; Barton et al. 2011). Any losses from the egg bags were noted by divers and included in the abundance estimates. New egg bags were buried into the same locations as the ones previously removed. All samples were processed within 24 hours, and any Rusty Crayfish collected were measured and euthanized. Any non-target species that were captured were handled similarly to the minnow traps catches.

Field Sampling 2013

Standard Gee minnow traps with small and large entrance holes were used to sample Rusty Crayfish abundance at different depths in 2013. Ten traps were deployed at each depth (2 m, 6 m, 9 m, and 15 m). Each trap was baited with Lake Trout eggs (~ 30 g). Traps were individually buoyed and set 10 m apart to ensure that each sample was independent (Robinson, unpublished data). All traps fished for 1.5 hours approximately every three weeks throughout the sampling period. Similar to 2012, all Rusty Crayfish collected were measured for carapace length (mm) and euthanized. Any other fish species captured were identified, measured, and released. Round Goby were measured for total length (mm) and euthanized if caught in the minnow traps. Water temperature (°C) was taken at each depth by lowering a temperature probe to the bottom substrate after all minnow traps were lifted.

Rusty Crayfish abundance was sampled using five GoPro HERO 3® cameras (www.gopro.com). Each camera was mounted to a steel rod camera frame (height = 60 cm; base = 0.5 m^2) with a quad-pod type base to increase stability when lowered to the lake bottom (Robinson, unpublished data). Cameras were secured to the frame and positioned so that they faced downward. Each camera frame was baited with previously collected, frozen, and thawed Lake Trout eggs (~30 g). The mesh bag containing the Lake Trout eggs was suspended approximately 5 cm from the substrate in the center of the photoquadrat. All five cameras were individually buoyed and positioned 10 m apart at each depth. The cameras were set to take one photograph per minute for 20 minutes.

Rusty Crayfish present in each image were counted. Two people independently analyzed images in the laboratory, and any discrepancies were settled by a third person. If at least 50% of a Rusty Crayfish was visible in the viewing area, the Rusty Crayfish was included in the count. The maximum number of Rusty Crayfish recorded during the 20 minute period was used for analysis (Willis et al. 2000; Cappo et al. 2006). Any other species seen in the photoquadrats were identified and counted.

We calculated average percent of habitat type (e.g., sand, gravel, cobble, boulder), live mussels (*Dreissena* spp.), dead mussels, and aquatic macrophyte cover by analyzing the photoquadrat images using Image-Pro Plus 7.0 software for every depth (Table 2.2). We assumed dead mussels covered sand substrate in photos based on knowledge obtained from scuba diving all sites. Data from Week 1 and Week 2 were averaged per depth (n = 5-10; $\bar{n}$ = 8.85) to determine estimates.

Lake Trout egg deposition data was obtained from the Michigan Department of Natural Resources after their fall sampling in 2012 and 2013 to determine the start and end dates of spawning. Lake Trout eggs were collected through egg funnels or egg bags (Barton et al. 2011) on all six spawning reefs. The average start date for all six reefs was calculated based on when the eggs were collected during sampling.

Statistical Analysis

We regarded the six sites to be our true replicates; therefore, all data for each gear type were averaged by depth within each site. To determine the relative measure of abundance over time in the minnow traps, the catch-per-unit-effort (CPUE) was calculated for each trap by dividing the total number of Rusty Crayfish captured by the amount of time spent fishing (2012: 1 day; 2013: 1.5 hours). Two-sample t-tests were used to determine differences between the catches of small and large minnow traps as well as to compare the total carapace lengths (mm) of Rusty Crayfish captured for each trap type. We used models in which time (sampling week) and water depth were represented as fixed factors, and site was represented as a random factor to account for variability among sites. Data were log-transformed if assumptions of normality or homogeneity were not met. All statistical analyses were performed in R using version 2.14.1 (R Development Core Team 2011). All tests were considered to be significant at $P \leq 0.05$.

Results

Using multiple gear types, we monitored Rusty Crayfish seasonal distribution over various depths and interstitial habitat use on nearshore spawning reefs in northern Lake Michigan. We determined that Rusty Crayfish abundances fluctuated over time in both years, with peak relative abundances occurring in mid-October. Interstitial habitat use on the spawning reefs was highest in mid-October then decreased as temperatures cooled in November and December.

Field Sampling 2012

A total of 325 Rusty Crayfish were caught in the minnow traps from July-December 2012. In addition to Rusty Crayfish, the minnow traps caught six different species of fish and two different species of native crayfish (Table 2.1). Rusty Crayfish carapace length ranged from 13 to 78 mm (mean ± SE; 2 m: 35 mm ± 0.60; 6 m: 34 mm ± 0.74; 9 m: 36 mm ± 0.88; Appendix D). Minnow traps captured 126 females and 193 males over the ten week sampling period. Mean minnow trap CPUE was 0.26 Rusty Crayfish$\cdot$trap$^{-1}\cdot$day^{-1} ± 0.03 (mean ± SE) (Figure 2.2). A total of 213 Rusty Crayfish were captured in the small minnow traps and 112 Rusty Crayfish were captured in the large minnow traps (*t*-test; $t_{223.42} = 1.80$, $P = 0.07$).

There were significant differences in minnow trap CPUE over time ($\chi^2 = 89.13$, df = 8, $P < 0.0001$) and depth ($\chi^2 = 8.18$, df = 2, $P = 0.017$); however, there was no significant interaction between time and depth in the 2012 minnow trap catches ($\chi^2 = 14.84$, df = 16, $P = 0.54$). The highest relative abundance occurred for all three depths during the week beginning on October 16, with the highest relative abundance at the 2 m depth, followed by the 6 m and 9 m depths, respectively (Figure 2.2). Round Goby abundances were relatively low from July through September and during the last sampling week, which began on November 26 (Figure 2.2). A total of 169 Rusty Crayfish were captured in the egg bags throughout the ten sampling weeks. In addition to Rusty Crayfish, four fish species and one native crayfish species were also collected from the egg bags on the spawning reefs (Table 2.1). Although there was no difference in the egg bag densities over time ($\chi^2 = 17.66$, df = 10, $P = 0.06$), average relative densities were lowest during the week of September 17 (0.09 Rusty Crayfish·egg bag^{-1} ± 0.03 SE) and highest during the week of November 26 (0.36 Rusty Crayfish·egg bag^{-1} ± 0.15; Figure 2.2). Rusty Crayfish that were retrieved from the egg bags ranged in carapace length from 4 to 40 mm, with an average total carapace length of 24 mm ± 0.54 (mean ± SE; Appendix E).

Field Sampling 2013

A total of 65 Rusty Crayfish were caught in the minnow traps from September-December 2013. Minnow traps also captured five species of fish (Table 2.1). Mean CPUE for all minnow traps was 0.06 Rusty Crayfish·trap^{-1}·day^{-1} ± 0.001 (mean ± SE), and the number of Rusty Crayfish caught in the small traps did not differ from the number caught in the large traps (*t*-test; $t_{160.79} = 1.69$, $P = 0.09$). Small minnow traps captured 19 Rusty Crayfish, while large minnow traps captured 46 Rusty Crayfish. The range of Rusty Crayfish total carapace length was 24 mm to 45 mm, with an average total carapace length of 36 mm ± 0.63 (mean ± SE; Appendix F). For the small minnow traps, the average total carapace length of Rusty Crayfish was 33 mm ± 1.13 (mean ± SE) and 37 mm ± 0.70 for the large minnow traps.

Table 2.1. Bycatch abundance by gear type from July-December 2012 and September-December 2013 in Grand Traverse and Little Traverse Bays, Lake Michigan. Abundances are total abundance for each species within the sampling period: 2012 minnow traps (24 hour period), 2012 egg bags (2 week period), 2013 minnow traps (1.5 hour period), and 2013 baited photoquadrats (20 minute period).

Common Name	Scientific Name	2012 Minnow Traps	2012 Egg Bags	2013 Minnow Traps	2013 Baited Photoquadrats
Round Goby	*Neogobius melanostomus*	1,675	102	2,805	88,887
Northern Clearwater Crayfish	*Orconectes propinquus*	3	2	—	—
Virile Crayfish	*Orconectes virilis*	18	—	—	—
Lake Chub	*Couesius plumbeus*	23	—	—	—
Emerald Shiner	*Notropis atherinoides*	—	2	—	—
Largemouth Bass	*Micropterus salmoides*	2	—	—	—
Rock Bass	*Ambloplites rupestris*	62	1	3	16
Smallmouth Bass	*Micropterus dolomieu*	11	2	1	37
Bluegill	*Lepomis macrochirus*	—	—	—	1
Spottail Shiner	*Notropis hudsonius*	17	—	1	—
Cyprinid spp.		8	—	—	47

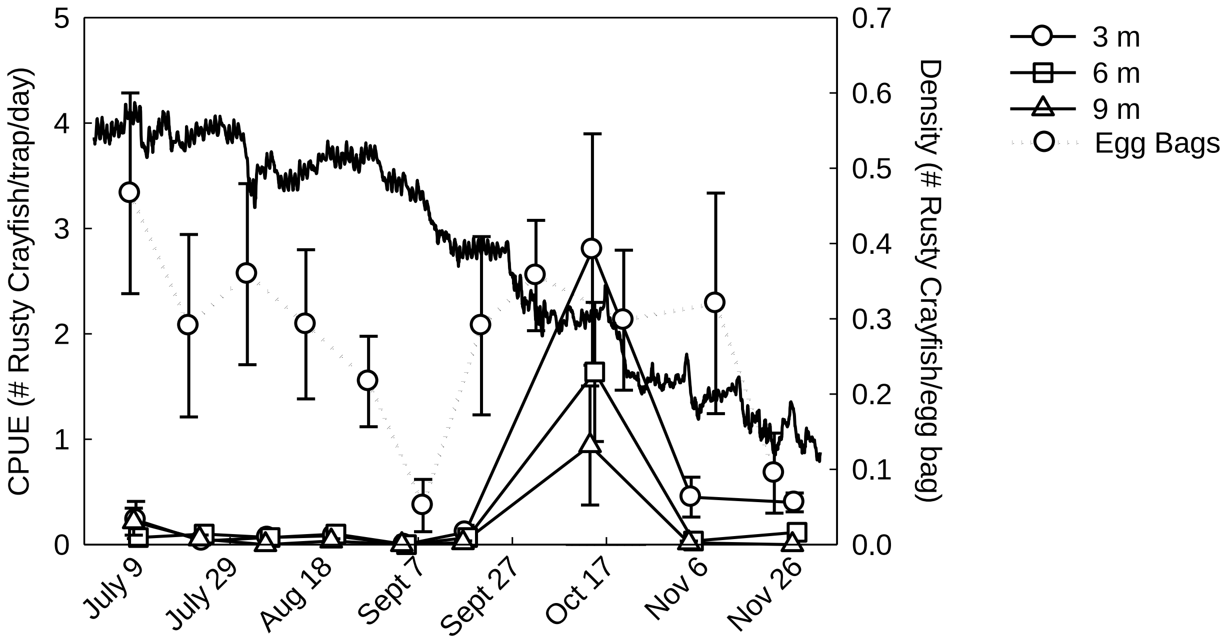


Figure 2.2. Rusty Crayfish catch-per-unit-effort (number of individuals per minnow trap per day; CPUE ± SE) and interstitial habitat use (number of individuals per egg bag; density ± SE) from July – December 2012 in Grand Traverse and Little Traverse Bays, Lake Michigan. Minnow Traps were set at depths of 2 m, 6 m, and 9 m. Egg bags were buried into reef habitat at the 2 m depth. Sampling dates represent the first day of the sampling week. Hatched box represents estimated Lake Trout (*Salvelinus namaycush*) spawning period. Water temperature (°C) is represented by the declining solid line.

There was a significant difference in minnow trap CPUE over time (χ^2 = 37.97, df = 4, *P* < 0.0001), but not by depth (χ^2 = 7.12, df = 3, *P* = 0.07). The interaction term between week and depth was also not significant (χ^2 = 13.80, df = 12, *P* = 0.31). We did not catch any Rusty Crayfish in our 15 m traps. The highest relative abundances for the other depths occurred during the sampling week beginning October 14, with the 9 m depth having the highest abundance, followed by the 2 m and 6 m depths, respectively (Figure 2.3). The lowest abundances for all four depths occurred during the last week of sampling on December 2, with zero Rusty Crayfish captured at any sites (Figure 2.3). We did not catch any Rusty Crayfish in our 15 m traps.

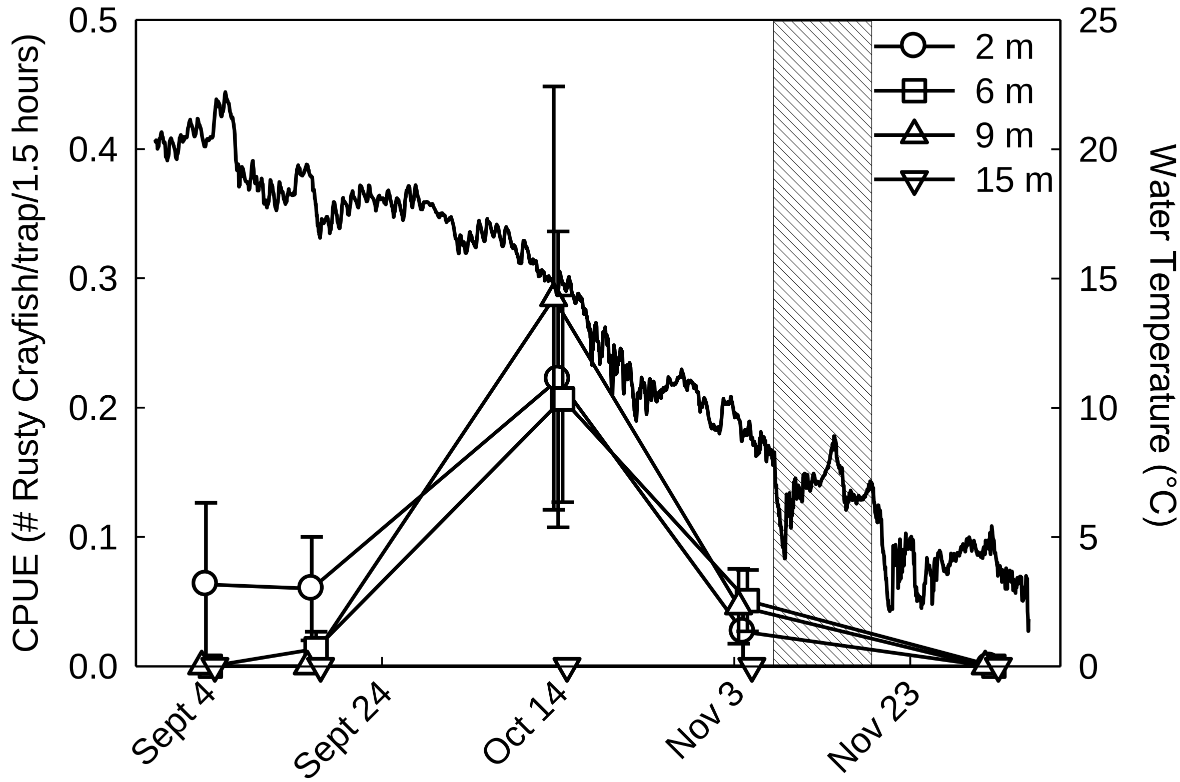


Figure 2.3. Rusty Crayfish catch-per-unit-effort (number of individuals per minnow trap 1.5 hours; CPUE ± SE) from September – December 2013 in Grand Traverse and Little Traverse Bays, Lake Michigan. Minnow Traps were set at depths of 2 m, 6 m, 9 m, and 15 m. Sampling dates represent the first day of the sampling week. Hatched box represents estimated Lake Trout (*Salvelinus namaycush*) spawning period. Water temperature (°C) is represented by the declining solid line.

In 2013, there was a total of 449 camera drops done with the GoPro® cameras, which resulted in 8,466 images analyzed. Rusty Crayfish density was 2.09 Rusty Crayfish·m^{-2} ± 0.33 (mean ± SE) for the 2 m depth, 0.94 Rusty Crayfish·m^{-2} ± 0.22 for the 6 m depth, 0.54 Rusty Crayfish·m^{-2} ± 0.16 for the 9 m depth, and 0 Rusty Crayfish·m^{-2} for the 15 m depth (Figure 2.4). We found a significant difference in Rusty Crayfish maximum density over time (χ^2 = 44.84, df = 4, P < 0.0001) and depth (χ^2 = 55.89, df = 3, P < 0.0001). Additionally, there was a significant interaction between time and depth (χ^2 = 43.67, df = 12, P < 0.0001). Rusty Crayfish were not observed at the 15 m depth. The highest density for the other three depths occurred during the sampling week beginning October 14, with the highest being at the 2 m and 6 m depths, followed by the 9m depth (Figure 2.4). The relative densities of Rusty Crayfish observed in the cameras were lowest for all four depths during the sampling week beginning December 2 (Figure 2.4). Rusty Crayfish were not observed at the 15 m depth.

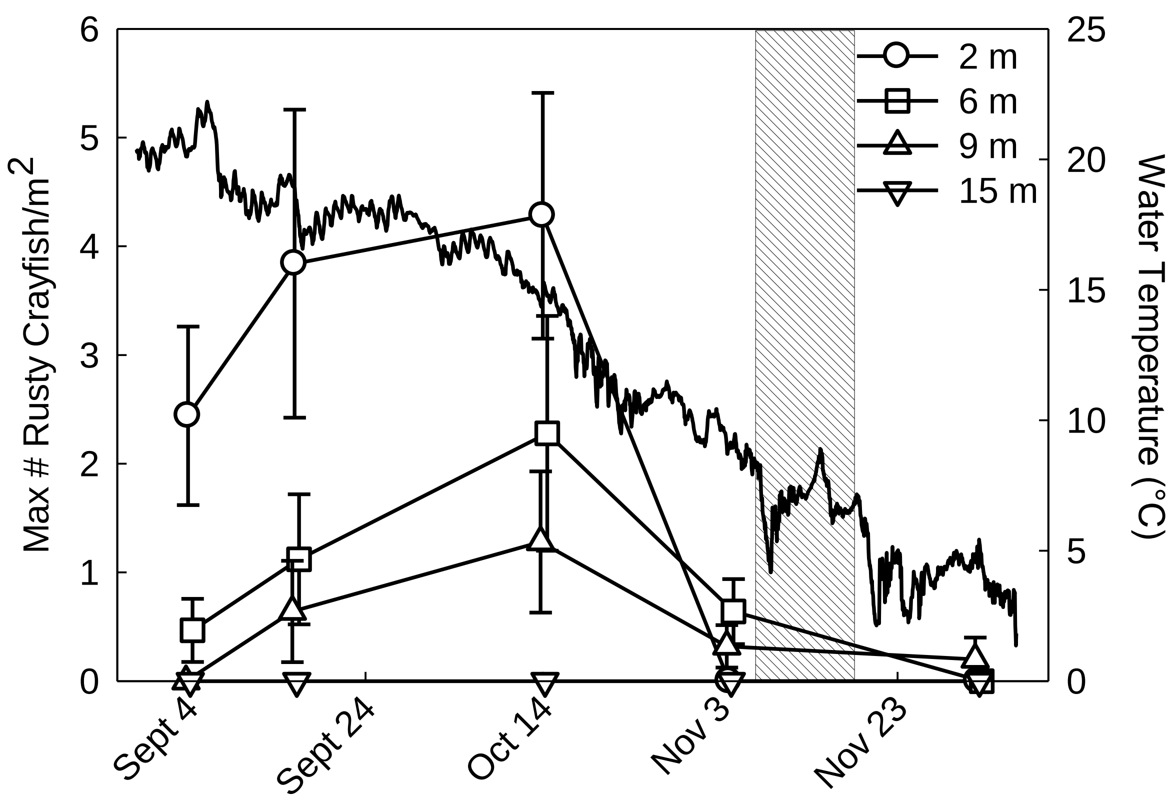


Figure 2.4. The maximum density of Rusty Crayfish (maximum number of individuals per m^2; max density ± SE) observed in the baited photoquadrats in 2013 at 2 m, 6 m, 9 m, and 15 m depths in Grand Traverse and Little Traverse Bays, Lake Michigan. Sampling dates represent the first day of the sampling week. Hatched box represents estimated Lake Trout (*Salvelinus namaycush*) spawning period. Water temperature (°C) is represented by the declining solid line.

Based on egg deposition data from all of the spawning reefs, Lake Trout spawning started as early as 29 October 2013. However, by averaging the spawning start dates of all sites, we estimated an overall start date of 7 November 2013 and assumed spawning ended around 17 November 2013 (refer to hatched box in Figures 2.3-2.4).

Habitat type at the 2 m depth consisted primarily of cobble and boulder substrate, and the 6 m depth was composed primarily of boulders and aquatic vegetation (Table 2.2). The 9 m depth was primarily boulders and aquatic vegetation, while sand and aquatic vegetation where found throughout the deepest depth at 15 m (Table 2.2).

Table 2.2. Average characteristics of the six spawning reefs (2 m) and offshore depths (6, 9, and 15 m) in Grand Traverse (GTB) and Little Traverse Bays (LTB), Lake Michigan. Mean (± SE) percent habitat type, mussel coverage (*Dreissena* spp.), and aquatic vegetation coverage were estimated using underwater photoquadrat images.

Site Depth (m)	Sand (%)	Gravel (%)	Cobble (%)	Boulder (%)	Live Mussels (%)	Dead Mussels (%)	Aquatic Vegetation Coverage (%)
2	0	2.65± 1.17	22.50 ± 6.09	22.5 ± 5.42	6.85 ± 1.60	2.97 ± 1.50	14.82 ± 6.06
6	0	0.54 ± 0.31	8.70 ± 3.10	17.03 ± 5.25	5.38 ± 1.88	8.99 ± 2.33	32.89 ± 7.38
9	0	0.36 ± 0.26	1.90 ± 1.48	13.06 ± 5.27	3.14 ± 0.97	3.89 ± 0.78	49.12 ± 7.48
15	100	0	0	0	1.31 ± 0.40	0.30 ± 0.07	22.96 ± 6.49

Discussion

Rusty Crayfish have negatively impacted the Great Lakes and their surrounding tributaries by reducing resource availability (Bobeldyk and Lamberti 2008), changing sediment dynamics (Nogaro et al. 2006), and altering trophic interactions (Lodge et al. 1994; Roth et al. 2006). The purpose of this study was to quantify the spatiotemporal distributions and interstitial habitat use of Rusty Crayfish using multiple gear types. While there were differences in relative abundance among depths, we did not document an offshore migration from our shallow to deep depths. However, Rusty Crayfish were not present on the spawning reefs or surrounding areas at the end of the sampling period, so an offshore migration was likely occurring in December. Rusty Crayfish interstitial habitat use on the spawning reefs did not change significantly over time, which makes us believe that Rusty Crayfish are continuously affecting these habitats from July until they move offshore in December. Ultimately, the findings from this study will have critical implications for the management and conservation strategies targeting native fish that utilize these reefs for spawning in late fall.

Although some studies suggest that passive gears, such as minnow traps, are not effective for examining crayfish density (Collins et al. 1983; Dorn et al. 2005), other research has shown that minnow traps can be reliable when specifically evaluating Rusty Crayfish abundance in freshwater lakes (Collins et al. 1983; Olsen et al. 1991; Byron and Wilson 2001; Wilson et al. 2004; Hein et al. 2006). For this study, baited minnow traps were used because they allowed us to capture Rusty Crayfish over a range of sizes and collect essential biological data (i.e., total carapace length). In addition to using small Gee minnow traps (3 cm entrance holes), we incorporated modified minnow traps (Somers and Stechey 1986; Byron and Wilson 2001; Wilson et al. 2004) to allow for larger crayfish to enter the traps. We found that some size classes of Rusty Crayfish may not have been represented without the use of our large, modified traps, especially during the peak abundance times in mid-October. In 2012, a sampling method with overnight sets of minnow traps (Collins et al. 1983) was implemented to reflect the nocturnal behavior of Rusty Crayfish (Stein and Magnuson 1976). Despite efforts in choosing the most appropriate gear type, set duration, and bait type, there were many sampling weeks that resulted in low catches. Zero-inflation is often a concern when employing trapping techniques or measuring catch-per-unit-effort (CPUE) of a species (Maunder and Punt 2004; Bacheler et al.

2013). However, based on our experience in the 2012 sampling season, our methods were altered in 2013 in hopes of increasing our catch rates. We recognize that the minnow traps did not give us a true measure of Rusty Crayfish abundance, but we still believe that they evaluated the relative abundance in both years successfully.

In 2012 and 2013, our minnow trap data showed that there was a significant difference in relative abundance over time, and all three depths had clear peaks in abundance in mid-October 2012, with the highest abundance occurring on the spawning reefs themselves. In 2013, we determined that the highest relative abundance for each depth again occurred in mid-October; however, the abundance at the 2 m depth was relatively high throughout September as well (Figure 2.3). This suggests that Rusty Crayfish have a greater presence on the spawning reefs than at the deeper depths throughout early fall. The difference between the depths seen in 2012 and 2013 may be more influenced by crayfish catchability than movement among the depths. Catch rates of crayfish can be influenced by environmental factors such as water temperature (Somers and Stechey 1986), bait type (Kutka et al. 1992), habitat (Stein and Magnuson 1976), and predation risk (Somers and Green 1993). For instance, Stein and Magnuson (1976) demonstrated that in the presence of Smallmouth Bass (*Micropterus dolomieu*), O. *propinquus* prefer substrates that offer interstitial spaces for refuge. Crayfish behavior will most likely change when predators are prevalent in a system, which decreases overall catchability of the crayfish (Somers and Green 1993).

The egg bags used in this study were essential for examining the interstitial habitat use of Rusty Crayfish over time, as they indicated that interstitial habitat use on the spawning reefs was highly variable throughout the sampling season. We observed no difference in Rusty Crayfish interstitial habitat use among the sampling weeks, which indicates that they were present on the spawning reefs from July through December. Rusty Crayfish habitat use can be influenced by the presence of congeners (Hill and Lodge 1994; Peters and Lodge 2013) or predators (Stein and Magnuson 1976; Collins et al. 1983; Mather and Stein 1993; Kershner and Lodge 1995). For instance, Peters and Lodge (2013) documented Rusty Crayfish altering their habitat use in the presence of a native crayfish species, Virile Crayfish (*O. virilus*), by using cobble substrate more frequently and vegetated habitats less. Perhaps the presence of native crayfish on the spawning reefs used in our study (Table 2.1) was influencing the interstitial habitat use of Rusty Crayfish. As an invader, Rusty Crayfish are known to be aggressive and more likely to outcompete their congeners for food and habitat (Capelli and Munjal 1982; Lodge et al. 1994). This aggression, coupled with their use of interstitial spaces and other niche components, may be a reason why we did not see any native crayfish in the egg bags.

The baited photoquadrats provided us with an estimate of relative Rusty Crayfish density at the different depths (2, 6, 9, and 15 m) in 2013. There were no Rusty Crayfish present at the 15 m depth throughout the sampling period, which may have been influenced by the sand habitat prevalent at that depth. Rusty Crayfish generally avoid open sand habitats (Hill and Lodge 1994), which is most likely due to the lack of cover and increased risk of predation (Kershner and Lodge 1995). Peak densities occurred for both the 6 m and 9 m depths in mid-October, similar to the trends observed with the minnow traps. However, different from the minnow traps, the baited photoquadrats documented the highest relative densities of Rusty Crayfish on the spawning reefs throughout September as well as October (Figure 2.4). Underwater cameras and baited videos have recently been thought to be a reliable, non-invasive technique for estimating freshwater crayfish abundance (Fulton et al. 2012). Davis and Huber (2007) and Martin and Moore (2007) both employed 24-hour underwater cameras to evaluate Rusty Crayfish density, activity patterns, social interactions in freshwater systems. Underwater videos and the baited photoquadrats used in the present study have applications for monitoring crayfish as well as other benthic species in freshwater systems (Chapter 3).

Using our methodologies, we documented a pattern of Rusty Crayfish abundance increasing in mid-October on the spawning reefs and then subsequently decreasing to nearly zero in December; however, scuba diving (J. Buckley, unpublished data) demonstrated that Rusty Crayfish are still present on these reefs, albeit burrowed into the substrate. Knowing that Rusty Crayfish remain on these reefs as the temperatures decline suggests that the minnow traps, egg bags, and baited photoquadrats are actually more indicative of behavioral patterns at these low temperatures than true seasonal distribution patterns. Change in water temperature causes a reduction in crayfish activity (Somers and Stechy 1986), which can result in decreased CPUE (Somers and Green 1992) and possibly create a false sense of an offshore migration in December. Understanding the variation among gear types and sampling methods is important for future monitoring studies, especially when making conclusions about shifts in spatiotemporal distributions.

Although there were slight differences between the abundance trends from the baited photoquadrats and the 2013 minnow traps, we believe that using these gears in conjunction with one another is beneficial when evaluating seasonal patterns. The discrepancies between these gear types may have been the result of size- or species-selectivity (Willis et al. 2000; Wells et al. 2008). While the minnow traps rely on the target species encountering, entering, and remaining in the trap (Hubert et al. 2012), the photoquadrats only require the intended species to encounter the gear and come into view of the camera. Therefore, the underwater video and photoquadrats are able to capture all sizes that may otherwise escape the minnow traps (Bacheler et al. 2013). Despite the differences between the gears (Chapter 3), they are complementary to each other because one gear can collect biological data and quantify effort (Hubert et al. 2012), while the other may index abundance more accurately (Bacheler et al. 2013). We believe that both gear types were useful in this study and should be combined for future sampling methodologies examining spatial distributions of benthic species.

Peak abundances of Rusty Crayfish occurred mid-October in both 2012 and 2013 for the shallowest depths, which coincided with Lake Trout spawning. We estimated an average spawning start date of 13 October and 7 November in 2012 and 2013, respectively. These findings are consistent with Dawson et al. (1997), which showed that average peak spawning activity of Lake Trout occurs at the end of October. Typically, Lake Trout spawn on rocky reefs where their negatively buoyant eggs remain in the interstices until hatching (Gunn 1995). Lake Trout are more likely to spawn on substrate previously used by conspecifics, suggesting that in addition to the physical characteristics of preferred habitat, chemical cues can also influence spawning site location (Wasylenko et al. 2013). In addition, Lake Trout egg predators, including crayfish, sculpin (*Cottus* spp.), and Round Goby (Chotkowski and Marsden 1999; Jonas et al. 2005; Fitzsimons et al. 2007), are attracted to spawning sites by chemosensory cues as well (Wasylenko et al. 2014). Perhaps the chemosensory cues associated with Lake Trout spawning prompted the Rusty Crayfish to move onto the spawning reefs and the surrounding areas in mid-October. However, this seems unlikely in 2013 because Rusty Crayfish peak abundances occurred pre-spawning, which makes us believe that there are other factors initiating Rusty Crayfish to move onto the reefs. The same environmental cues that trigger the Lake Trout to spawn (e.g., water temperature, accumulated sunlight, wind direction, or the range of temperature decline (Gunn 1995)) may also be affecting Rusty Crayfish distribution patterns. Insights into the cues that shape spatiotemporal distributions are not only critical for invasive species like Rusty Crayfish, but for understanding other factors that may also influence movement of critical native species.

Conservation strategies and rehabilitation plans for ecologically and commercially valuable species are often modified to account for the variability observed in spatial patterns over time (Cooke 2008; Landsman et al. 2011). For example, identifying the seasonal distribution patterns of native salmonids like Lake Trout in Lake Michigan allows managers to locate and protect specific habitats critical to their restoration initiatives (Schmalz et al. 2002; Adlerstein et al. 2007). Information about the dispersal and return of hatchery-reared Lake Trout can also contribute to future management plans and knowledge about local population densities (Schmalz et al. 2002). Studying the seasonal changes in habitat use by Coho Salmon (*Oncorhynchus kisutch*) in coastal Oregon can provide managers with essential information regarding the importance of coastal streams and tributaries to this economically valuable species (Nickelson et al. 1992; Bradford et al. 1997). These data can provide predictive tools to estimate abundance, migration patterns, and habitat preferences for a range of spatial scales, which can have implications for conservation efforts (Bradford et al. 1997; Flitcroft et al. 2014).

In addition to native species, understanding movement and seasonal distribution shifts has been important for Great Lakes invaders like Round Goby (Pennuto et al. 2010; Lynch and

Mensinger 2012; Chapter 1) and Rusty Crayfish (Taylor and Redmer 1996; Byron and Wilson 2001) in the past. Interstitial egg predators can greatly affect egg mortality on spawning reefs (Jones et al. 1995; Savino et al. 1999; Claramunt et al. 2005); therefore, understanding the overlap between Rusty Crayfish presence on these spawning reefs and the affect they are having on native fish recruitment is valuable. Knowledge of invasive species life history traits and spatial patterns will allow managers to develop effective management strategies and ultimately prevent future invasions of nuisance species (Mack et al. 2000; Sakai et al. 2001; Lodge et al. 2006). The present study asked questions related to the basic ecology of a benthic egg predator in order further understand how they can impact a system. Future studies should aim to incorporate aspects of Rusty Crayfish spatial and temporal ecology when designing and implementing control efforts, especially on critical nearshore spawning reefs in the Great Lakes.

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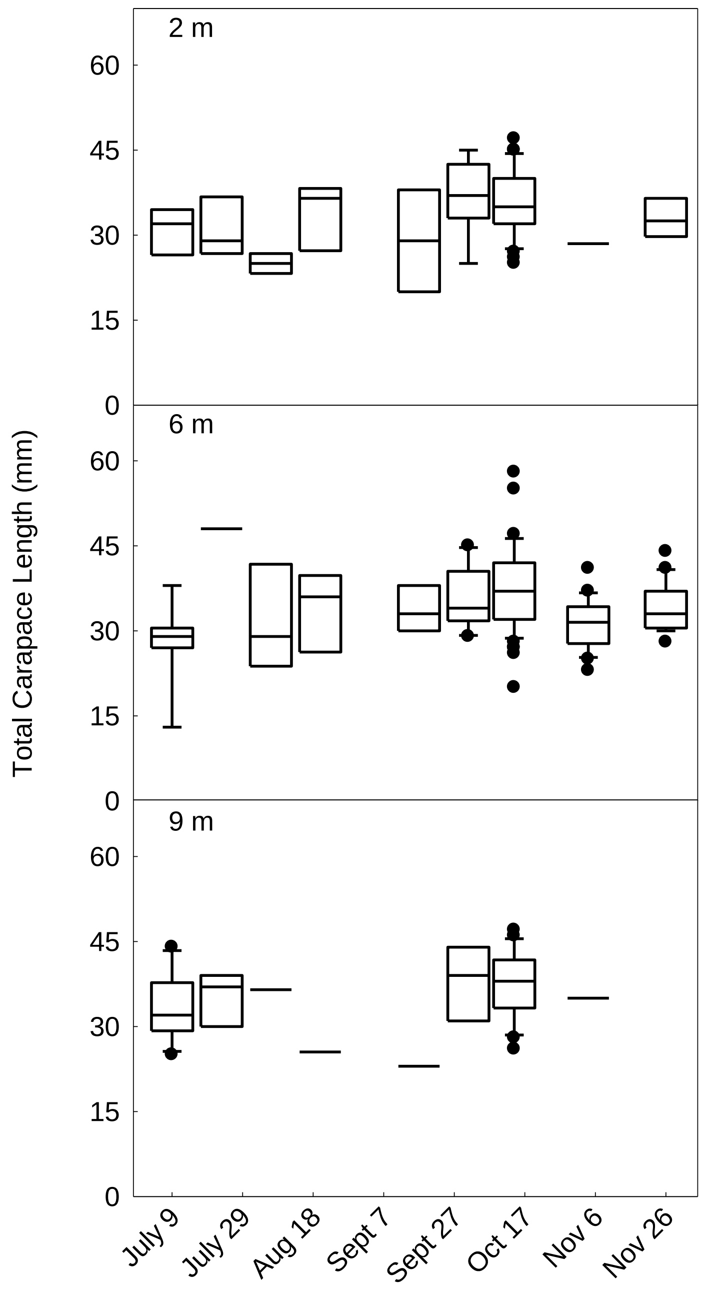
APPENDICES

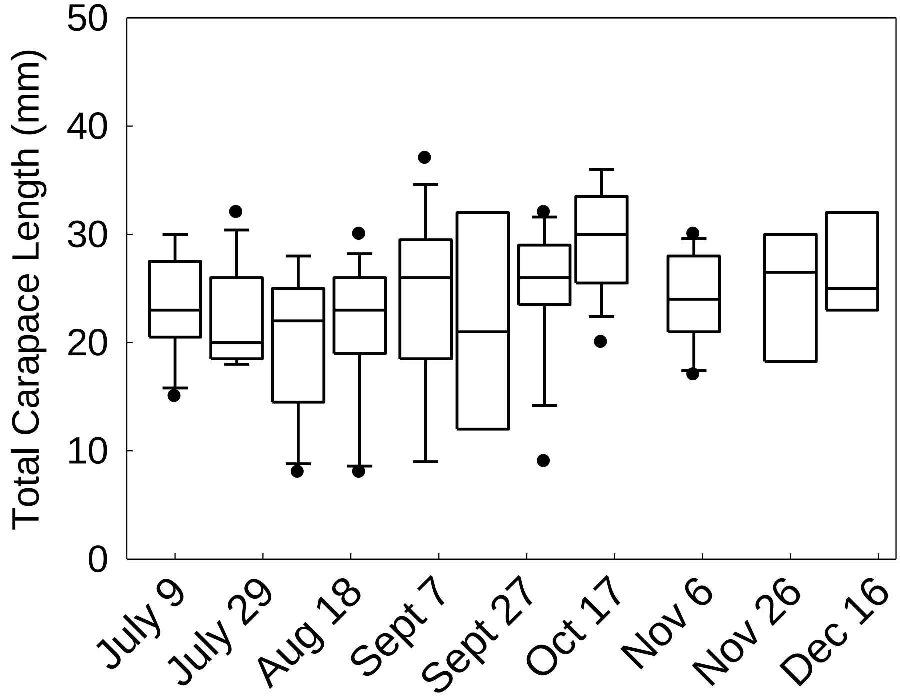
APPENDIX D

BOXPLOTS OF RUSTY CRAYFISH TOTAL CARAPACE LENGTH (MM) FROM MINNOW TRAPS IN 2012 AT ALL DEPTHS (2 M, 6M, AND 9 M). LARGE AND SMALL MINNOW TRAPS WERE COMBINED, AND TOTAL CARAPACE LENGTHS WERE AVERAGED ACROSS SAMPLING SITES FOR EACH WEEK. FILLED CIRCLES REPRESENT OUTLIERS.



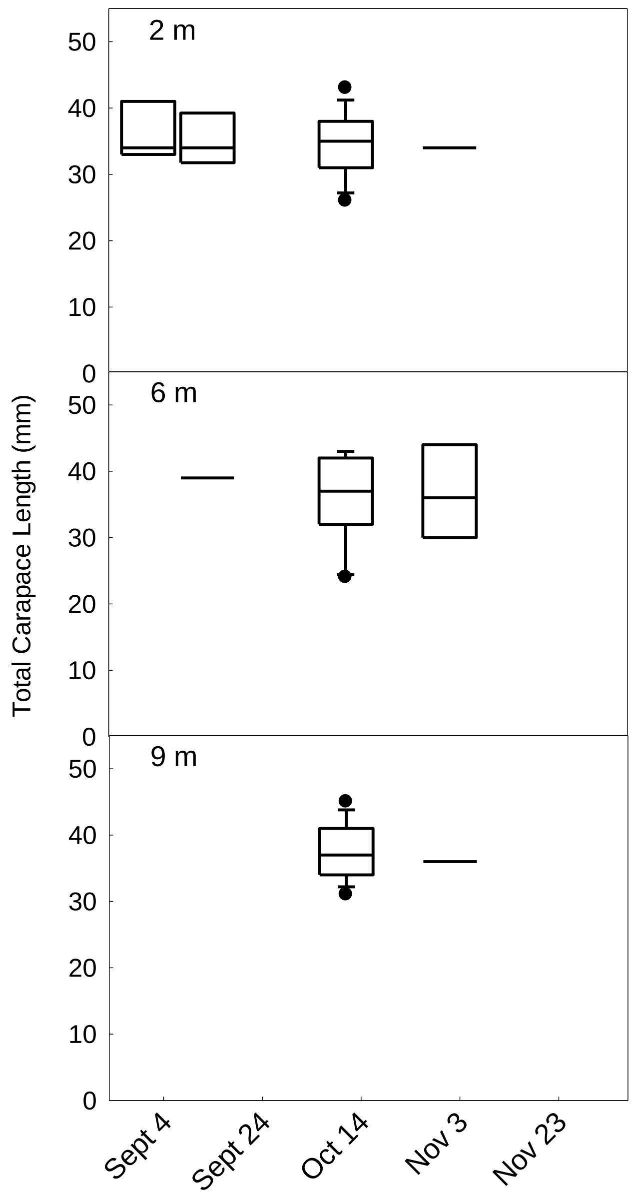
APPENDIX E

BOXPLOTS OF RUSTY CRAYFISH TOTAL CARAPACE LENGTH (MM) FROM EGG BAGS IN 2012. TOTAL CARAPACE LENGTHS WERE AVERAGED ACROSS SAMPLING SITES FOR EACH WEEK. FILLED CIRCLES REPRESENT OUTLIERS OUTSIDE OF THE AVERAGES.



APPENDIX F

BOXPLOTS OF RUSTY CRAYFISH TOTAL CARAPACE LENGTH (MM) FROM MINNOW TRAPS IN 2013 AT ALL DEPTHS (2 M, 6M, 9 M, AND 15 M). LARGE AND SMALL MINNOW TRAPS WERE COMBINED, AND TOTAL CARAPACE LENGTHS WERE AVERAGED ACROSS SAMPLING SITES FOR EACH WEEK. FILLED CIRCLES REPRESENT OUTLIERS. NO INDIVIDUALS WERE CAPTURED IN THE MINNOW TRAPS DURING THE SAMPLING WEEK BEGINNING 2 DECEMBER 2013. THERE WERE NO RUSTY CRAYFISH CAPTURED AT THE 15 M DEPTH DURING SAMPLING.



CHAPTER III

MONITORING SHALLOW BENTHIC FISH ASSEMBLAGES IN THE LAURENTIAN GREAT LAKES USING BAITED PHOTOQUADRATS: AUGMENTING TRADITIONAL FISHERIES MONITORING METHODS

Introduction

The littoral zone is an important component of aquatic ecosystems in both freshwater and marine habitats. Human activities such as pollution (Dudgeon et al. 2006), habitat modification (Loreau et al. 2001; O'Neill et al. 2013), eutrophication (Smith 2003), introduction of non-native species (Mills et al. 1993; Strayer 2010), and overexploitation (Wells and McLain 1973) can impact the ecological functioning of the nearshore community. The use of effective gear types and standardized methods are critical when developing benthic monitoring techniques (Lirman et al. 2007; Van Rein et al. 2011) for littoral zone community assessments. However, due to the structural complexity (Pierce et al. 1990) and heterogeneous nature of fish distributions in nearshore areas, combining multiple gear types is often recommended to effectively characterize benthic fish assemblages across habitat types (Weaver et al. 1993; LaPointe et al. 2006; Ruetz et al. 2007; Eggleton et al. 2010).

To overcome difficulties with sampling diverse benthic habitats, researchers have developed monitoring techniques to sample both soft (e.g., mud, gravel, sand) and hard (e.g., cobble, bedrock, boulders) substrates. In marine systems, fish assemblages in shallow benthic habitats are generally studied with underwater visual census methods using scuba divers (Kulbicki 1998); however, this survey tool introduces bias and can decrease accuracy and precision (St. John et al. 1990; Watson et al. 1995). Other sampling methods in marine environments incorporate the use of stationary photoquadrats (Bohnsack 1979; Roberts et al.

1994; Preskitt et al. 2004; Van Rein et al. 2011) or baited underwater video (Harvey and Shortis 1996; Watson et al. 2005; Cappo et al. 2007; Stobart et al. 2007; Ebner and Morgan 2013) as non-extractive monitoring techniques to allow for more flexibility than traditional trapping, netting, or underwater visual census techniques. The photoquadrat method is a technique used to quantitatively assess the benthic community using a mounted digital underwater camera and is an efficient method for percent coverage of abundant species on coral reefs (Preskitt et al. 2004), but is limited by two dimensionality (i.e., canopy effect) and difficulties identifying species at lower trophic levels (e.g., algae) (Bohnsack 1979; Leonard and Clark 1993; Roberts et al. 1994).

The application of both photoquadrats and baited underwater videos is extensive and includes assessing relative abundance and species richness (Cappo et al. 2007; Ebner and Morgan 2013), evaluating habitat characterization (Haag et al. 2008), reviewing the status of reef communities (Lirman et al. 2007), completing rapid ecological assessments (Preskitt et al. 2004; Schopmeyer et al. 2011), recording spawning behaviors (Esteve et al. 2008), and performing in situ behavioral studies (Chidami et al. 2007). Generally, photoquadrats and baited underwater videos are considered to be efficient gear types because they limit disturbance and size selectivity, while generating permanent visual records that can be stored for future analyses (Preskitt et al. 2004; Cappo et al. 2006). Videos from GoPro® cameras mounted on baited chevron traps resulted in higher frequencies of reef fish occurrence, thus reducing the zero-inflation that is often encountered with trapping techniques (Bacheler et al. 2013).

In freshwater systems, the use of high-definition baited underwater videos or photoquadrats is uncommon (Schill and Griffith 1984; Johnson et al. 2005; Chidami et al. 2007; Ebner et al. 2009; Ellender et al. 2012), with particularly limited use in lakes. The lack of application in freshwater may be due to low water visibility from high turbidity, excessive plankton and algal blooms, high dissolved organic carbon that may be encountered in inland lakes, difficulties in deployment in riverine systems, or confidence that traditional sampling tools (nets and traps) provide an adequate measure of species abundance and diversity. Johnson et al. (2005) and Taraborelli et al. (2009) evaluated Round Goby (*Neogobius melanostomus*) density ($\#/m^2$) using underwater video systems along multiple transects. Although this technique allows for assessment of this benthic species in its natural habitat with limited disturbance, it is very expensive (Johnson et al. 2005) and does not elicit any Round Goby hiding within the substrate. Furthermore, unbaited transects, though efficient for larger individuals, were found to underestimate the densities of smaller Round Goby (Taraborelli et al. 2009).

Most littoral monitoring studies tend to use active gears (Hayes et al. 1996) or passive gears such as gill nets, fyke nets, or minnow traps (Weaver et al. 1993, 1997; Ruetz et al. 2007; Eggleton et al. 2010; Hubert et al. 2012). Passive gears are advantageous for sampling nearshore habitats because they typically capture more mobile fishes than active gears (e.g., seines, trawls, angling, electrofishing) (Weaver et al. 1993; Hayes et al. 1996; Hubert et al. 2012), and the gears are simple and easy to use with quantifiable effort (Hubert et al. 2012). Minnow traps, in particular, are useful when obtaining abundance estimates for benthic communities because they are not only durable and inexpensive (Johnson et al. 2005), but they also have low bycatch and can be used in complex habitats (Diana et al. 2006). Despite the fact that minnow traps have low retention rates and high size selectivity (Johnson et al. 2005; Diana et al. 2006), many researchers have incorporated them into studies targeting benthic invasive species such as Round Goby (Steingraeber et al. 1996; Johnson et al. 2005; Diana et al. 2006; Kornis and Vander

Zanden 2010) and Rusty Crayfish (*Orconectes rusticus*) (Bills and Marking 1988; Wilson et al. 2004; Hein et al. 2006, 2007).

The objective of this study was to examine the effectiveness of baited photoquadrats and minnow traps to sample Round Goby in shallow, littoral, benthic habitats in the Great Lakes. Specifically, the objectives were to (1) determine the effectiveness of baited photoquadrats with different baits, (2) compare catches of minnow traps set along a trap line versus individual trap sets, and (3) evaluate the effect of set time on minnow trap catch rates. Round Goby were the focal species in this study due to their prevalence in the complex habitat of the littoral zone sampled. However, this project has implications for the development of integrated monitoring techniques targeting various benthic organisms in a range of habitats.

Methods

Sampling was conducted on a spawning reef in the eastern arm of Grand Traverse Bay, Lake Michigan (44°54’10”N, 85°25’5”W) near Elk Rapids, Michigan. The spawning reef consisted primarily of cobble substrate (10-20 cm diameter) (Barton et al. 2011) and had a depth of 2.22 m ± 0.04 (mean ± SD).

Photoquadrat Monitoring

Round Goby were sampled using two GoPro® HERO 3 cameras (www.gopro.com) to determine the most effective bait for video monitoring. Five replicates of four bait treatments were used: (1) Lake Trout (*Salvelinus namaycush*) eggs, (2) fish attractant (Atlas Mike’s® Glo Scents in Salmon Egg Oil), (3) Lake Trout eggs plus fish attractant, and (4) no bait. Cameras were mounted onto steel rod camera frames (height = 60 cm; base = 0.5 m^2) with a quad-pod type base to increase stability when lowered to the reef substrate (Figure 3.1). Approximately 30 g of previously collected, frozen, and thawed Lake Trout eggs were used for treatments containing eggs. A small sponge was saturated with the fish attractant added to the mesh bait bag for each treatment containing fish attractant. Cameras were secured to the frame and positioned so that they faced downward. A weighted mesh bait bag was suspended 5 cm off the lake bottom in the center of the camera frame base (Figure 3.1). Treatments were randomly assigned before each camera drop, and a different bait bag was used each time so no cross-contamination occurred and bait freshness was standardized. Cameras captured photographs every minute for a period of 40 minutes.

Figure 3.1. The steel rod photoquadrat frame used in Lake Michigan to assess benthic fish abundance. Each quad-pod frame was baited with Lake Trout (*Salvelinus namaycush*) eggs and had a downward facing GoPro® camera attached to the center.

The total number of Round Goby was counted in each photograph using Windows Photo Viewer. If more than ten Round Goby were seen in the image or if it was difficult to identify an individual, the photograph was opened in Windows Paint at 150% zoom. Each fish was then marked with a black line on their dorsal side, and all black lines were totaled for the image. Two people independently analyzed images in the laboratory, and any discrepancies were settled by a third person. Differences in the maximum number of Round Goby observed among the treatments were analyzed with a one-way analysis of variance (ANOVA) followed by Tukey's post hoc test ($\alpha = 0.05$). In addition, the time at which the maximum number of Round Goby was observed in the images was compared among treatments using a one-way ANOVA followed by Tukey's post hoc test ($\alpha = 0.05$).

Minnow Trap Independence

Round Goby catches from minnow traps on a trap line versus minnow traps set individually apart were examined. Standard Gee minnow traps (23 cm x 45 cm with 0.64 cm steel wire mesh) were used with either 3 cm ("small" hereafter) or 6 cm ("large" hereafter) entrances. All traps were baited with Lake Trout eggs (~30 g) placed in 8 cm x 13 cm mesh bags and suspended in the middle of each trap. Ten traps, alternating small and large entrance openings, were secured 1 m apart on a trap line. Additionally, five small and five large minnow traps were individually buoyed and randomly placed at least 10 m apart. Minnow traps were set for a period of 0.5 hours. The catch-per-unit-effort (CPUE) was calculated for each trap (#Round Goby /hour), and the total length (mm) of each Round Goby captured was recorded. CPUE and total length were $\log_{10}$ transformed to meet assumptions of normality. The effects of entrance size (small versus large), minnow trap independence (trap line versus individually set), and their interaction on CPUE and total length were compared among treatments with a two-way ANOVA followed by Tukey's post hoc test ($\alpha = 0.05$).

Minnow Trap Set Times

To determine the influence of set times on the capture rate of Round Goby, minnow traps were set for six different time periods: (1) 0.5, (2) 1 , (3) 1.5 , (4) 2 , (5) 2.5, and (6) 24 hours. Five small minnow traps baited with Lake Trout eggs (~30 g) were used in each treatment. All minnow traps were randomly placed on the reef at least 10 m apart simultaneously. The CPUE was calculated for each trap (#Round Goby /hour). CPUE and number of Round Goby captured data were $\log_{10}$ transformed to meet assumptions of normality. The effect of set time on CPUE and number of Round Goby captured were compared among treatments with a one-way ANOVA followed by Tukey's post hoc test ($\alpha = 0.05$).

Results

Photoquadrat Monitoring

A total of 1,184 still images were analyzed from the photoquadrats. Round Goby were the only fish identified in the photos (Figure 3.2), with a total of 14,174 Round Goby counted across all treatments. Maximum number of Round Goby differed between the attractant only and no bait treatments ($F_{3,16} = 11.73$, $P = 0.0003$) (Figure 3.3). More Round Goby were attracted to the photoquadrats with the Lake Trout eggs (mean = 20.26, SE = 0.57) or the eggs plus attractant (mean = 14.12, SE = 0.53) than with the attractant only (mean = 10.87, SE = 0.63) or no bait treatments (mean = 0.89, SE = 0.073). Average maximum number of Round Goby captured in the images was highest using Lake Trout eggs only (mean = 39.2, SE = 2.58) compared to the other bait treatments with eggs and attractant (mean = 32.8, SE = 7.15), attractant only (mean = 24, SE = 10.08), and no bait (mean = 5, SE = 1.30). The time at which the maximum number of Round Goby were recorded within a trial did not differ among treatments (mean = 12.7 min, SE = 2.03, $F_{3,16} = 3.06$, $P = 0.06$) (Figure 3.4).

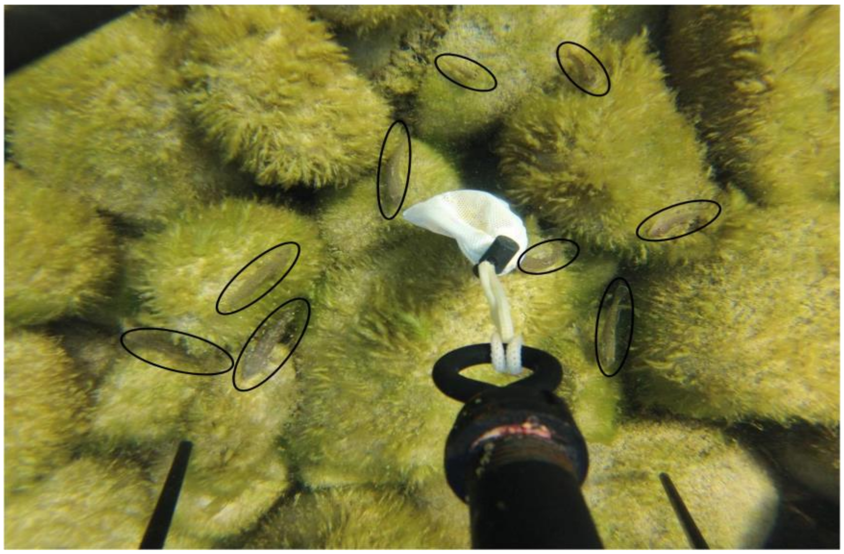


Figure 3.2. A digital GoPro® still image from a baited photoquadrat depicting the activity of Round Goby (circled) on a nearshore reef in Lake Michigan.

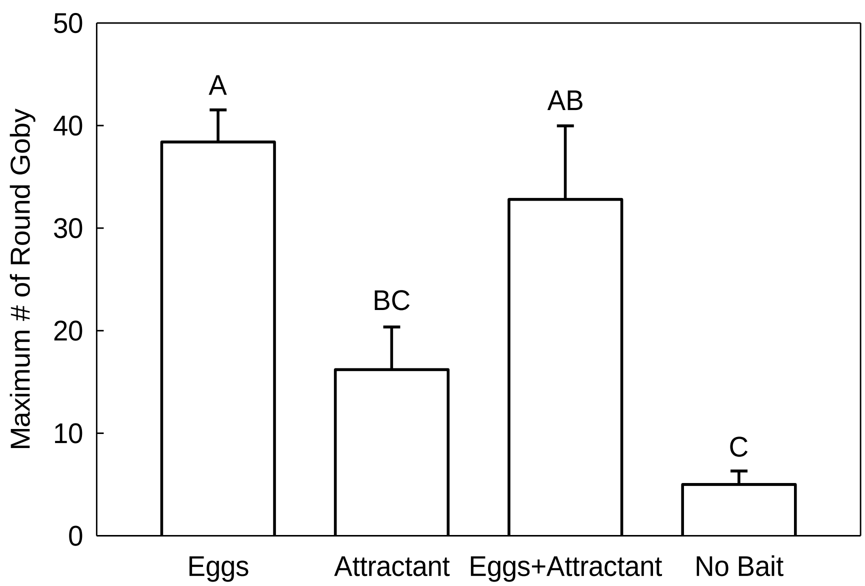


Figure 3.3. Mean (+ SE) maximum number of Round Goby observed in photoquadrats among four treatments: (1) Lake Trout (*Salvelinus namaycush*) eggs, (2) fish attractant, (3) Lake Trout eggs plus fish attractant, and (4) no bait. Treatments with different letters represent significant differences ($P < 0.05$).

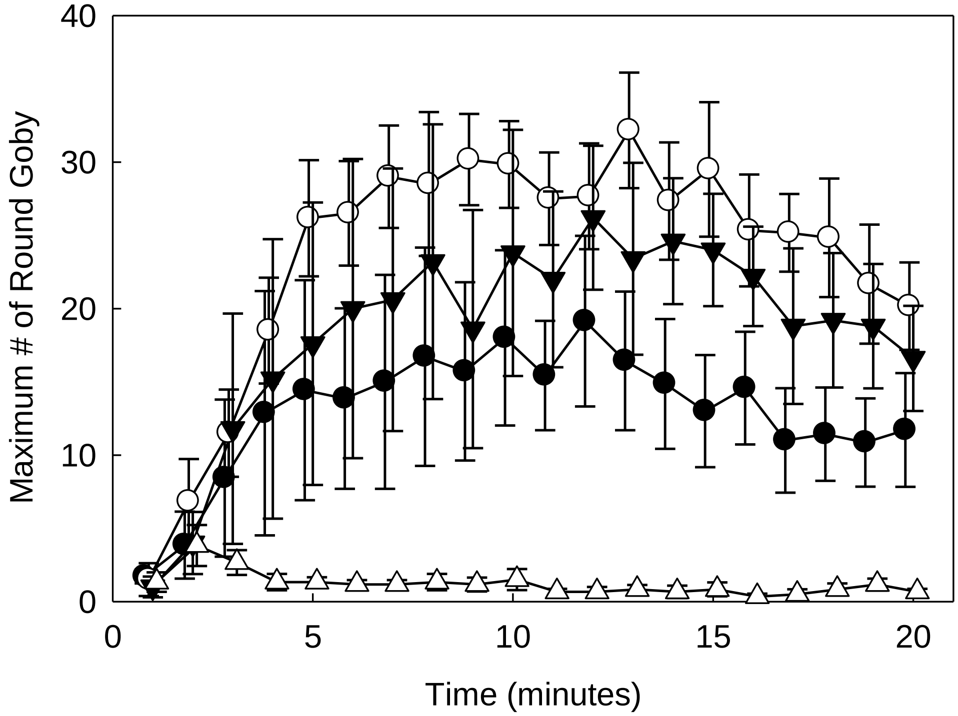


Figure 3.4. Mean (± SE) maximum number of Round Goby observed in the baited photoquadrats over time for each bait treatment (Lake Trout (*Salvelinus namaycush*) eggs: open circles; fish attractant: solid circles; Lake Trout eggs plus fish attractant: solid triangles; no bait: open triangles).

Minnow Trap Independence

The minnow traps also captured Round Goby as well as other species in the benthic littoral zone. Round Goby CPUE was higher in the minnow traps set independently rather than set on a trap line; the entrance hole size did not affect gear efficiency (Independence $F_{1,78}$ = 11.73, P = 0.003; Entrance Size $F_{1,78}$ = 1.29, P = 0.26; Independence x Entrance Size $F_{1,78}$ = 0.05, P = 0.82) (Figure 3.5). Total length of Round Goby did not differ between minnow traps set individually rather than set on a trap line (i.e., independence) or with entrance hole size (Independence $F_{1,56}$ = 0.15, P = 0.70; Entrance Size $F_{1,56}$ = 0.76, P = 0.39; Independence x Entrance Size $F_{1,56}$ = 1.56, P = 0.22).

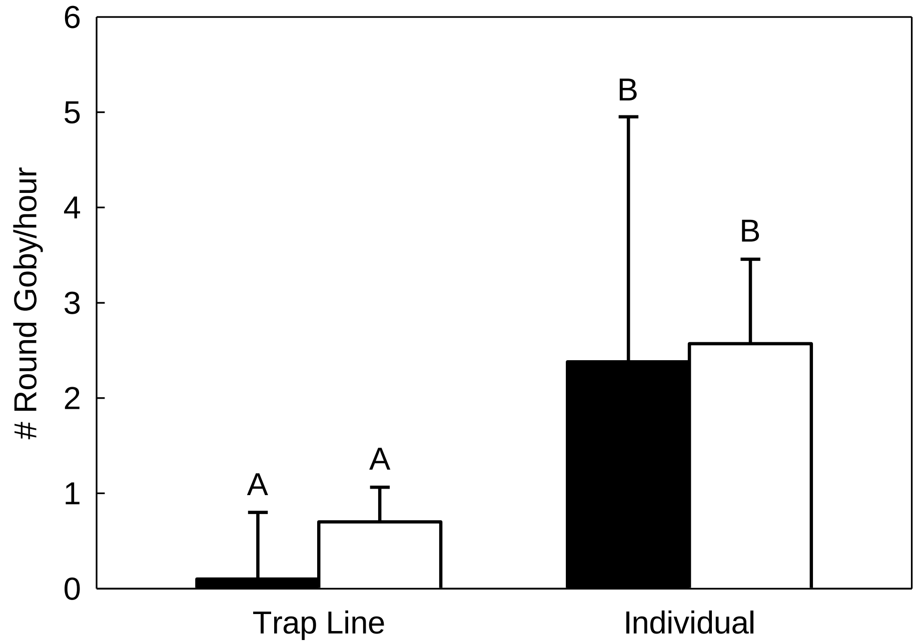


Figure 3.5. Mean (+ SE) catch-per-unit-effort (CPUE) of Round Goby captured from baited minnow traps set on a trap line versus minnow traps set individually apart. Closed bars = small entrance hole sizes and open bars = large entrance hole sizes. Minnow trap types with different letters represent significant differences (P < 0.05). Untransformed data are presented.

Minnow Trap Set Times

Minnow traps captured 410 Round Goby, one Yellow Perch (*Perca flavescens*), and one Rusty Crayfish. Round Goby CPUE did not differ among set times ($F_{5,24} = 0.80$, $P = 0.56$) (Figure 3.6). However, the number of Round Goby captured during the 24 hour (mean = 65.6, SE = 47.5) set was greater than the number of Round Goby captured during the 0.5 (mean = 0.0, SE = 0.0), 1.0 (mean = 1.6, SE = 1.4), 1.5 (mean = 2.8, SE = 1.7), 2.0 (mean = 2.0, SE = 0.9), and 2.5 hour (mean = 4.2, SE = 4.0) sets ($F_{5,24} = 4.94$, $P = 0.003$). Furthermore, the total number of Round Goby caught was highly variable between individual traps across all set times (e.g., range during the hour 24 set: 1-254 Round Goby/trap).

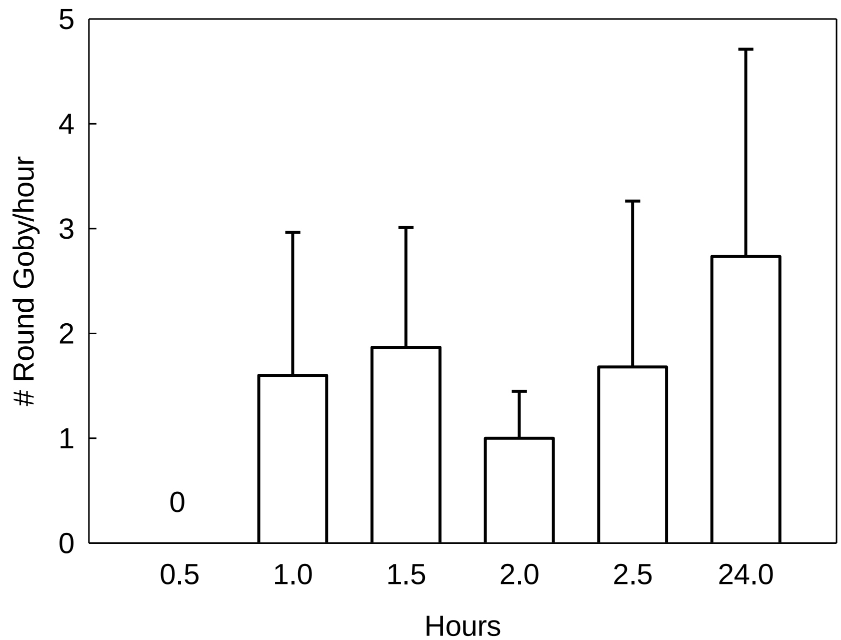


Figure 3.6. Mean (+ SE) catch-per-unit-effort (CPUE) of Round Goby captured from baited minnow traps over six different set times (hours). 0 = no Round Goby captured. Untransformed data are presented.

Discussion

Increasing investment in the restoration of Laurentian Great Lakes littoral habitats and the need to demonstrate measurable progress has increased attention on determining the most efficient techniques for monitoring benthic habitats in the Great Lakes. The results from this study suggest that baited photoquadrats produce a more reliable monitoring tool for Round Goby, the dominant fish species on rocky nearshore reef habitats. Photoquadrats and video techniques have been successful and widespread for species monitoring throughout marine environments (Willis et al. 2000; Cappo et al. 2007; Lirman et al. 2007; Van Rein et al. 2011; Hannah and Blume 2012; Bacheler et al. 2013). However, there is increasing interest in the use of video analysis for sampling freshwater systems (Ebner et al. 2009; Ellender et al. 2012; Ebner and Morgan 2013), and high water visibility found in most of the Great Lakes suggests it has potential to become an important monitoring method for inland fisheries in the region.

Photoquadrats and video surveys provide a logistically simpler alternative to the traditionally labor-intensive methods that rely on netting, trapping, and electrofishing for littoral benthic sampling (Hayes et al. 1996; Hubert et al. 2012). We determined that photoquadrats not only provided an effective means for quantifying Round Goby on reef substrate, but this approach was easy to construct and simple to use. More importantly, the baited photoquadrats required short deployment times (< 1 hour per site), critical when monitoring when weather conditions may produce narrow sampling windows, just as it is an important consideration in marine systems (Willis et al. 2000; Langlois et al. 2010). Ebner and Morgan (2013) targeted marine benthic fish communities using remote underwater video stations, concluding that 20 minutes after deployment was sufficient for maximal species detection. Here, the maximum Round Goby numbers were seen approximately 13 minutes after initial deployment. This finding was consistent with the results of Ebner and Morgan (2013), and we also recommend a 20 minute sampling period to ensure efficiency.

A species-by-species approach to sampling is impractical and can be costly (Andrew and Mapstone 1987); therefore, methodology should focus on practices that allow for multi-species surveys such as visual analyses or digital imagery. In this study, our baited photoquadrats recorded Round Goby, the numerically dominant species present on these reefs, whereas Yellow Perch and Rusty Crayfish were collected in the gee minnow traps (albeit in very low numbers) indicating that other fish species are present on these reef assemblages. Our camera configuration, bait type, and time of sampling may have contributed to our failure to detect other species. We have recorded Rusty Crayfish in ongoing monitoring using this approach (Robinson; unpublished data), and given Round Goby numerical dominance on these reefs, it is possible they are excluding other benthic fish taxa from the camera view. The short camera frame used here was adopted to maximize our ability to count small Round Goby. A lateral camera configuration (e.g., Harvey and Shortis 1996; Cappo et al. 2007) would provide a wider field of view and potential to sample other fish taxa, but this would likely come at a cost of sampling smaller, benthic Round Goby.

Bait type affected densities of Round Goby observed in the photoquadrats, with Lake Trout eggs consistently maximizing the densities overall. Lake Trout eggs are an effective Round Goby attractant (Yavno and Corkum 2011) and an important part of the Round Goby diet in the Great Lakes (Chotkowski and Marsden 1999). Similarly, Lake Trout eggs were an effective bait type for minnow traps since the traps captured Round Goby as well as other species on the reefs. However, CPUE was highly variable among traps irrespective of set times or trap entrance width. Short set times, as well as the 24 hour set time, produced multiple zeros. Although other studies have used overnight sets to target Round Goby with minnow traps (e.g., Diana et al. 2006; Young et al. 2010), sampling over a 24 hour period may pose logistical issues, especially when setting traps out at multiple sites in larger freshwater systems during spring and fall turnover. We recommend using shorter set times (1.5-2.5 hours) to catch Round Goby given these set times produce a relative measure of abundance with standard errors comparable to the 24 hour set times.

Minnow traps may be seen as beneficial since they can be deployed in low visibility environments that are potentially unsuitable for baited photoquadrats. Surprisingly, the entrance hole size of the minnow traps did not affect the catch rates of the minnow traps even though the larger entrance hole size should allow more movement in and out of a trap. As a passive gear, fish are ultimately captured in minnow traps by encountering the gear, entering the gear, and remaining in the gear (Hubert et al. 2012). Although there is likely a threshold where an entrance hole is too large to be effective, our study demonstrated that small and large minnow traps captured similar numbers and sizes of fish despite differences in entrance hole size. Independently set minnow traps had higher catch rates than those set closely together on a trap line, indicating that traps secured on a single line 1 m apart were not acting as true replicates, which is consistent with Young et al. (2010) who set baited minnow traps 10 m apart in their study that targeted Round Goby, given their home range size is approximately 5 m^2 (Ray and Corkum 2001).

Although Round Goby were the only species recorded in our baited photoquadrats due to their predominance in our sampling system, our results have implications for monitoring other species in the Great Lakes. For example, baited photoquadrats may be beneficial to managers examining the nearshore predator-prey dynamics, such as the interactions between Smallmouth Bass (*Micropterus dolomieu*) and invasive species (Steinhart et al. 2004). Besides fish abundances and interactions, however, photoquadrats can also be used as a tool for site descriptions. With the appropriate software, the images collected from the GoPro® cameras can be analyzed for the substrate composition, macrophyte coverage, and *Dreissena* spp. coverage of a given habitat. In addition, although the photoquadrats were used on a nearshore reef in this study, the GoPro® cameras are certified to withstand pressures down to 60 m deep (www.gopro.com). We have recently tested the cameras in depths of 15-25 m in Grand Traverse

Bay, Lake Michigan, in temperatures below 6 °C; the cameras still performed well in low-light conditions. Baited underwater videos and baited photoquadrats are routinely used to sample deep water communities (Roberts et al. 1994; Cappo et al. 2007), and we feel these GoPro® monitoring methods will aid future researchers examining seasonal changes of fish population dynamics as well as determining habitat characteristics at varying depths.

Many studies have recommended incorporating multiple monitoring techniques into sampling practices to provide a more accurate assessment of species composition (Willis et al. 2000; Watson et al. 2005; Ruetz et al. 2007; Bacheler et al. 2013; Ebner and Morgan 2013). The use of baited photoquadrats and minnow traps can be valuable and efficient techniques for sampling over the complex substrates prevalent in littoral zones. Overall, we recommend researchers and managers should augment traditional sampling approaches by incorporating baited photoquadrats. Integrated sampling methodologies that employ multiple gear types will likely provide a more comprehensive understanding of the littoral benthic community in the Great Lakes.

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