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Seasonal Offshore/Inshore Migration of Round Gobies

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SEASONAL OFFSHORE/INSHORE MIGRATION OF ROUND GOBIES

by

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ABSTRACT

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by

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Since the invasion of round gobies (*Neogobius melanostomus*) in Lake Michigan, they have become integrated into both the nearshore and offshore food webs. Round gobies can be found in shallower water (<20 m) during the summer, but they disappear from these depths in early fall. They have been collected, occasionally, offshore in depths greater than 70 m during fall and early spring. These observations and other anecdotal evidence indicate that round goby migrate offshore during the fall and return in the spring. To study this, a large remotely operated vehicle (ROV) was used to conduct video transects offshore at various depths. The offshore sampling showed that round gobies migrated away from nearshore habitat in early October and were almost exclusively found deeper than 20 m by November. The round gobies remained offshore (>30 m) until mid-May, when they began the return to nearshore habitat.

The cues to start the offshore and return migrations were not the focus of this project, but the fall offshore migrations coincided with decreasing temperatures nearshore in the fall, and in spring, the offshore movement of the thermal bar. The offshore migration in fall provide an increase in forage opportunity for deep, cold-water predators such as lake trout, that cannot access nearshore habitat when the lake is stratified because of temperature barriers.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Introduction

Many animals, both terrestrial and aquatic, commit to large movements of population segments or whole populations that are characteristic of migration (Bauer and Klaassen 2013; Dingle and Drake 2007). Migration has been defined as the action of moving from one place to another, or as moving from one habitat to another (Aidley 1981). Migration in fish populations can be for reasons such as spawning, an annual event that can involve long distances traveled to reach suitable breeding grounds to ensure larval fish have increased hatching success and growth rates (Ross 2013). Fish also migrate to new habitats to maximize growth rates while minimizing mortality risks. This can occur across scales, from daily to annual and from short to long distance movements.

Cyclical migration within fish populations is well known for spawning events of mature individuals, and can be separated into multiple categories. Anadromous fish, like salmon and lamprey, will migrate from saltwater into the freshwater streams to spawn (Gross et al. 1988). Catadromous fishes, such as the American and European eel (*Anguilla Anguilla* and *Anguilla rostrata),* the Thinlipp mullet (*Liza ramada*) and flounder (*Plathychtys flesus*) migrate from freshwater to saltwater to spawn (Daverat et al. 2011). Aside from cyclical migrations for reproduction purposes, fish can exhibit diel migrations to follow food sources. Imbrock et al. (1996) showed that European perch (*Perca fluviatilis*) in Lake Constance, in central Europe, would occupy depths up to 30m during the day and at night remain close to the bottom of the lake, but during the evening the fish would move inshore to feed. During this time few individuals were observed deeper than 5m in depth. Diel vertical migration occurs with many larval fish to give them access to plankton they prey on. Adult Bear Lake Sculpin, *Cottus extensus*, (Bear Lake, Utah-Idaho), are strictly benthic and do not migrate into the water column, but the juvenile sculpins (<30mm) will migrate upwards of 30m-40m into the water column to feed. Another factor contributing to seasonal vertical migration was improved growth rates of the juveniles that moved into warmer water to feed (Neverman and Wurtsbaugh 1994). The seasonal migration of species to new habitats at different times of the year varies from the cyclical migrations seen for spawning and the diel movements for food and can occur across a range of age groups or the whole population.

Seasonal migration of fish can occur for a variety of reasons. Roach (*Rutilis rutilus*), in a Swedish lake, were observed migrating into the streams in autumn and overwintering until returning to the lake in spring as a means of predator avoidance (Brönmark et al. 2008). The predators of the roach, northern pike (*Esox lucius*) would remain in the lake system during the winter. By migrating into the streams, the roach were showing a trade-off of growth vs predator avoidance, with the higher benefit coming from predator avoidance during the winter. Smallmouth bass (*Micropterus dolemieui*) were observed migrating downstream from the Embarrass River (Wisconsin) into the Wolf River system in the fall (Langhurst and Schoenike 1990). The trigger that began this migration was related to temperature. When the temperature in the river cooled to 16°C, the fish began to move downstream. In this same study, they observed that the adult fish were the first ones to begin migrating downstream in the fall. This same pattern was observed in spring, were the adult fish moved back upstream and began the spawning process before most of the sub-adults had returned to the area.

Seasonal migration of round goby, *Neogobius melanostomus* was the primary focus of this research project. The round goby was first recorded in the Laurentian Great Lakes watershed in 1990 (Jude et al. 1992; Marsden et al. 1997), likely transported in ballast water from oceanic shipping vessels (Mills et al. 1993; Charlebois et al. 2001). The round goby was first observed in the St. Clair River (Jude et al. 1992) and spread to Lake Michigan by 1994 (Janssen and Jude 2001). Anecdotally, Miller (1986) reported in their native range of the Black and Caspian Seas, round goby migrate from nearshore habitat to offshore sites during the fall and winter to depths of 60 meters. In the Laurentian Great Lakes, round goby are generally found shallower than 20 meters during the summer months (Miller 1986; Jude and DeBoe 1996) where they have been found on a variety of substrate ranging from sand to coarse gravel (Ray and Corkum 2001), but with a preference for rocky habitat (Houghton and Janssen 2015).

The seasonal migration of round goby is poorly documented in the Laurentian Great Lakes, but evidence exists that suggests seasonal migration is occurring. Prior to summer stratification, round goby have been found offshore in Lake Huron at a depth of 73 meters (Schaeffer et al. 2005), and in 130 meters of water in Lake Ontario (Walsh et al. 2007). This is consistent with Miller (1986), that showed round gobies in depths of 50-60 meters during the winter. In Lake Michigan during the late spring and summer, round goby are generally present in high density nearshore in depths between shore and 15 meters (Jude and DeBoe 1996; Houghton and Janssen 2015). The difficulty to perform field research during the five months of winter between November and March, due to ice formation and frequent rough seas, has led to a gap in knowledge to what happens in Lake Michigan and the interaction between round goby and cold-water predators during this timeframe.

Wells (1968) reported, prior to the round goby invasion, research was conducted tracking the seasonal depth distribution of many of the fish species found in Lake Michigan along the eastern shore. In this study, Wells found that bloater (*Coregonus hoyi*), slimy sculpin (*Cottus cognatus*), and trout-perch (*Percopsis omiscomaycus*) all showed evidence of a fall migration to deeper water. This research provided fisheries managers information regarding where certain fish were found throughout most of the year. Determining whether a similar migration, by round gobies, takes place, and the timing of it, would give fisheries managers insight into the potential interactions between the round goby and other fishes. Round goby may provide a substantial, seasonal, offshore food resource to many of the predatory fish, like lake trout (*Salvelinus namaycush*) and burbot (*Lota lota*), during the winter months.

To study the seasonal migration of round goby over a range of depths, temperatures, and substrate types, remotely operated vehicles (ROVs) were used for sampling. The use of ROVs in research has been on the rise since 1985, with the capabilities of ROVs increasing as the technology is improved (Auster 1997). The value of using ROVs to sample benthic fishes has been shown by Davis et al. (1997), where an ROV was used to sample and observe juvenile lake trout for estimates of population densities compared to other methods in a few lakes in Ontario. ROVs have also been used for the collection of benthic fish, slimy sculpin, in Lake Michigan when adapted with electroshocking and vacuum suction capabilities (Janssen et al.

2006; Houghton et al. 2010). I used ROVs to complete my objectives: (1) track the change in depth distribution of round goby as they move offshore in the fall, (2) determine if there is a pattern in the movement to offshore habitat, (3) documenting when round gobies return in the spring to occupy the nearshore habitat.

Methods

This research is broken into a core study with a formal sampling design using the Benthos MiniRover MK II and ancillary studies using diverse ROV and scuba sampling methods.

Study area

Lake Michigan has a surface area of 58,000 km^2, an average depth of 85 m, and a maximum depth of 281 m (Mortimer 2004). The west side of the lake is rocky compared to the eastern side of the lake, which is mainly sandy (Janssen et al. 2005). Sampling for seasonal depth distribution occurred along an East-West transect, N 43° 5’, approximately seven kilometers north of Milwaukee, WI (Figure 1). Sampling dates for the Benthos MiniRover MK II for fall 2018 were: September 17, October 10 and 29, and November 12. Spring of 2019 sampling occurred on April 9, May 10 and 23, and June 7. Sites at 10, 20, 30, and 40 meters were sampled. The substrate was mainly rocky with scattered boulders and gravel, and areas of bare sand and clay. At the deepest site of 40 meters, the bottom substrate consisted of mainly uniform, firm silt covered by scattered quagga mussels (*Dreissena bugensis*).

One additional site at 30 meters on May 10, 2019, that was all sand, was sampled due to a navigational error, this site included for an anecdotal comparison of habitat to the adjacent 30 meter site.

Benthos MiniRover MKII Transects

I used ROVs for the majority of the sampling, collecting video to estimate density. Similar methods have been used in Johnson et al. (2005) and Houghton et al. (2010). Johnson et al. (2005) concluded that ROVs were the most effective method to estimate round goby population size in Lake Erie. The ROV was a Benthos MiniRover MK II, henceforth MiniRover, fitted with a suction sampler and an electroshocking unit (Figure 2); a similar configuration was used in Janssen et al. (2006) and Houghton et al. (2010) for sampling lake trout fry and slimy sculpin. The MiniRover operated within a 30m circle with the center being a lead weight, attached to a steel cable from the support vessel, two to three meters above the bottom. The electroshocking unit was an AbP-2 Dual Channel, battery-powered, pulsed-DC electroshocker developed at the UW-Madison Engineering Technical Services. The unit produced a pulsed-DC current (60 Hz and 244 V). GPS coordinates of the MiniRover were obtained using the TrackLink 1500 series system, the unit accuracy is 0.20 meters and has a working range up to 1000 meters from the ship. A YSI probe (Model: 600XLMD) was attached to the MiniRover to measure temperature and depth.

The anchored support vessel, swung on the designated sampling site. When the MiniRover reached the bottom, its lights are turned on to illuminate the bottom. A compass heading for the first transect was chosen by pilot, based on the estimated longest chord across the circle defined by the 30 meter radius. The actual distance traveled was seldom 30 meters due to the swinging of the ship during a transect. The subsequent transects were based on the pilot's judgment on what would be the longest chord; because starting point and distance was variable, we assumed that transects can be considered operationally random, see Figure 3 as an example. The pilot drove the ROV about 1 meter off the bottom, using the attached lasers to approximate the distance off the bottom, and at a speed around 0.25m/s until the end of the tether is reached. After the MiniRover transects were complete, samples of round goby and slimy sculpin were collected using electro-shocking and suction sampling (Janssen et al. 2006; Houghton and Janssen 2015). This occurred for variable lengths of time.

Video Analysis for MiniRover *transects*

For each transect, the time each transect began and ended was recorded, the GPS location of the start and end of each transect were determined. Once the GPS points were obtained, the transect length, in meters, was determined using the Vincenty Formula (Thomas and Featherstone 2005). Each transect would be viewed again to determine the number of round gobies observed during the transect to calculated the number of round gobies per meter (Figure 4).

Statistical Analysis

Density of round goby was taken as the total number of round gobies observed, divided by the length of each transect. I used a Two-Factor Analysis of Variance (ANOVA) with date and depth as fixed factors and included the (date x depth) interaction. The working hypothesis was that depth distribution would change with the date, hence I tested the null hypothesis of no significant (date x depth) interaction.

To examine whether larger fish were moving offshore first, video from the 20 m and 30 m site on October 10, 2018 was analyzed. To estimate round goby size from the video, I used the ruler tool in Adobe Photoshop (version CC). A reference point would be measured on the video first. The reference distance between two points of light set 10 cm apart from two lasers attached to the ROV was used (Figure 5). All fish sampled were parallel to the reference points in the field of view. The length of the round goby was determined by comparison to the reference distance to the nearest 0.1 mm. A Mann-Whitney U test was used to compare fish sizes at the two depths.

The MiniRover was used during the autumn and spring sampling because of its effectiveness in deep water, collecting capabilities, and can be configured for tracking (Janssen et al 2006; Houghton et al 2010). The R/V Neeskay is limited to operating depths greater than approximately ten meters. However, it is known from previous work in Houghton et al. (2015), that round gobies are present in shallow water up to the shore.

Small ROV Surveys

Shallow water trial observations using small ROV's that had not been previously configured for sampling to perform surveys were used as a complement to the seasonal MiniRover transects.

Small ROV surveys took place on August 8, 2018. The small ROV, VideoRay (Model: Pro 2), was used (Figure 2). A GoPro Hero 5 camera was attached to the underside of the VideoRay. The VideoRay was attached to a 10 meter retractable line which was connected to a weighted, vertical rod one meter in height. This was to allow the VideoRay to remain around a meter off the bottom. A random compass heading was chosen and the VideoRay drove out on that heading until it reached the end of the retractable 10 meter line. The VideoRay would return to the starting point and repeat this process until all the transects were completed.

The OpenROV Trident was used for shallow water surveys, during the spring and summer of 2019 (Figure 2). Seven dates between April and August were surveyed during this project (Table 2). This Trident is equipped is able to record 1080p video at 30 frames per second (fps). It has a top speed of 2 m/s, a tether length of 100 meters, and an approximate battery life of 3 hours. This ROV was operated from a smaller boat at depths ranging from three meters to 20 meters. During dives, the operator drove the Trident along the bottom, searching under rocks and overhangs looking for round goby. The driver would commonly move forward and pause to observe any fish movement within view of the camera. Each Trident dive lasted approximately 10 minutes and was used to record the number of round gobies at each depth.

Scuba Diving/Snorkel Transects

These alternative methods were used as supplemental information to gather data at shallower sites. A pair of scuba divers were used to perform transects at depths of three meters and ten meters at two sites located offshore at N 43° 10' and N 43° 5'. Scuba sampling dates occurred on July 26, 2018 and August 8, 2018. Using the same method used in Houghton and Janssen (2015), divers would descend to the bottom, and using a lead line ten meters in length, would swim with their eyes closed for 20-30 seconds and deploy the line. Divers used a GoPro Hero 5 camera in a waterproof housing and attached to an extendable camera monopod, would follow over the transect line, recording the bottom while staying approximately one meter off the bottom. A one-meter line with a small weight was attached to the monopod to aid the diver in remaining a consistent height off the bottom. The divers performed five to six transects following this protocol at each sampling location and depth.

Snorkel surveys took place in two meters of water offshore of Fox Point and Atwater Beach. Sampling dates took place between July and October 2018 (Table 2). The snorkeler placed a ten-meter lead line on the bottom, and would swim above the line, with the camera remaining about one meter off the bottom. The GoPro Camera setup used in the scuba diving transects, would record the four to six transects to record the number of round gobies observed.

Video analysis for dives, small ROV transects, and scuba/snorkel surveys.

All of the round gobies were counted that were in view of the camera from start to end of the transect line. For the small ROV transects, since a line was not used, all round gobies in frame were counted until the ROV tether was pulled tight. The total number of fish was then divided by the total transect length of ten meters to give the relative density of fish per meter at each depth and time.

Results

Fall MiniRover *transects*

The two-factor ANOVA performed on the log transformed data, $Log_{10}(n+1)$, showed significant differences in the date x depth interaction ($F_{6,60}= 10.25$, $p < 0.001$; Figure 6). Therefore, the round goby depth distribution is dependent on the sampling dates. Consequently, the main effects are generally not interpretable (Zar 2010). For completeness of reporting, the main effect statistics are date ($F_{3,60}= 13.36$) and depth ($F_{2,60}= 3.09$). The nature of the interaction is inherent from Figure 6, in that round gobies disappeared from shallow sites and showed up at the deeper sites in the fall.

Spring MiniRover *Transects*

The 2-Factor ANOVA for the log transformed spring data showed the interaction between the two effects (sampling dates and depth) was significant ($F_{6,60}= 17.43$, $p < 0.001$), indicating that the distribution of round goby at depth is dependent upon the sampling date. Again, the main effect statistics are as follows, sampling dates ($F_{3,60}=19.44$, $p < 0.001$) and depth ($F_{2,60}= 13.46$, $p<0.001$)(Figure 7). The interaction is inherent in Figure 7, showing the round gobies appearing at deeper sites and the leaving deep water sites for the shallow water at the end of the sampling period.

The incidental 30 meter off-transect sampled on May 10 of 2019, had a uniform bottom of sand and firm silt with little structure. No round gobies were seen at this site, while the adjacent 30 meter site (the site sampled the same day and included in the two-factor analysis for spring 2019), located 400 m away, had round goby observed. The site where fish were observed had a heterogeneous bottom, cobble/rocky/sand/clay patches, consistent with what was typically observed at 30 meters throughout the study.

Round Goby Offshore Migration Pattern (size analysis)

A total of 39 fish were measured for the size analysis for the October 10, 2018 sampling date, (26) at 20 meters and (13) at 30 meters. The average length of fish at the 20 meter site was 58.5 mm. Round gobies at the 30 meter site averaged 93.0 mm (Figure 8). The results of the Mann-Whitney U test showed a significant difference in size of the fish between the two sampling depths ($U_{13,26}$=298, P< 0.001).

Scuba Dive/VideoRay/Snorkel Surveys

The scuba dive transects occurred on two dates during the fall of 2018 on July 26, 2018 and August 8, 2018, at 3 meters and 10 meters depth. On July 26 at Fox Point, the average number of fish observed at 3 m (28.33) was higher compared to 10 m (17.33). An unpaired t-test showed a significant difference in the number of fish observed at 3 m compared to 10 m, t_{10}=2.41, p<0.05. The Atwater beach sampling on August 8 showed higher average number of round gobies observed at 3 m (9.2) then 10 m (3.0). The t-test performed showed the difference was significant, t_8=4.14, p<0.05.

The VideoRay transects occurred on August 8, 2018 at the 3 meter and 10 meter site off of Atwater Beach. The average number of round gobies per transect at 3 m (8.9) and at 10 m (1.8) were observed. An unpaired t-test showed a significant difference in the number of fish observed per VideoRay transect at each depth, $t_{11}=3.01$, $p<0.05$.

The snorkel surveys occurred on between July 2018 and October 2018. These dives occurred at 1-2 meters depth. Round gobies were observed at these nearshore sites between July 31, 2018 until October 12, 2018. After this date, no round gobies were seen during the snorkel surveys. Two more surveys were conducted after this date on October 18 and October 24, 2018 to confirm that no individuals were present nearshore.

OpenROV Trident Surveys

The surveys took place between April and August 2019 at depths of three meters and ten meters, round gobies were first observed at ten meters on May 14, 2019 and observed at three meters on May 31, 2019. The number of round gobies observed was highly variable between sampling dates and depths (Table 4).

Discussion

The results can be summarized in three points. 1) Round gobies migrated offshore in the fall and returned to nearshore habitat in the spring. 2) Larger round gobies moved offshore first. 3) The round goby migration in fall may provide a major potential food resource that can be utilized by a variety of species, such as lake trout and burbot, during the winter months.

My results indicate that this migration pattern was occurring at my study area. The round gobies moved away from nearshore habitats to offshore habitat beginning in the early fall

(October) and remained offshore until mid to late spring (April/May). Determination of cues for starting both the offshore and return migration was not a part of my project but need to be explored to explain initiation and timing of movements.

Given the size of the Great Lakes, or the round goby's native waters (e.g. Black Sea), moving to or from deep water a round goby require directional cues. A lack of useful directional cues, perhaps due to differing Black Sea/Great Lakes physical dynamics, may explain findings of round gobies in deep water at times when they should be near shore (Schaefer et al. 2005; Walsh et al. 2007). Assuming Miller's (1986) anecdote regarding movement of Black Sea round gobies to deep water is accurate, then timing and orientation presumably evolved in the Ponto-Caspian region. Orientation cues used by diverse fishes include sun-compass, magnetic, olfactory, and acoustic . We suspect that, given depth and light attenuation, sun compass is not feasible, although photoperiod may be important for timing. We offer no opinion regarding use of the Earth's magnetic field, however, orienting in relation the magnetic field would be in different directions for different coasts of Lake Michigan and individuals would likely have to learn the direction to deep water at the end of their first year. That is they would initially would need to rely on some other cue. For marine reef systems recent work has emphasized odor (Dixson et al. 2014) and sound (Mann et al. 2007).

Regarding sound, round gobies do orient and locate conspecific reproductive sounds and their mating/territorial calls which have peak energy at about 160 Hz with little energy at frequencies greater than 600 Hz (Rollo et al. 2007). Hearing is generally best fishes without swim bladders at less than about 500 Hz and breaking waves have peak energy at about 250-300 Hz (Lugli 2010).

Temperature may be one of the most important cues for the seasonal movement of round gobies. In late September, the bottom temperatures began to drop at my nearshore sites, which could prompt the round gobies that were concentrated at the 10 m site to begin moving to deeper water. This shift to deeper water may allow round gobies to avoid the colder water that is present nearshore during the winter months. In Lake Michigan, the deep water offshore remains warmer than coastal waters, between mid-November through March, while the nearshore water can reach near 0°C (Gottlieb et al. 1989; Janssen et al. 2007).

The shift in depth distribution is common with other Lake Michigan fishes. A study of seasonal movement of fish in Lake Michigan by Wells (1968) found that almost all summer, shallow water, fishes had their depth distribution affected by temperature changes. Fish, such as bloaters and alewives, would move out to deeper waters during the winter as the nearshore temperatures dropped.

For the return migration to nearshore, the process of the thermal bar formation may be a cue round gobies to move back towards shore. The formation of the thermal bar in Lake Michigan occurs as the cold nearshore water warms to 4℃, where water is most dense, and sinks carrying surface water, containing phytoplankton, directly to the bottom (Boyce et al. 1989; Rao and Schwab 2007). This warm water creates a vertical, thermal and density barrier separating nearshore water from the colder offshore water, but is not a barrier for motile animals. As the thermal bar moves offshore, it brings nearshore water that it is comprised of with, which may contain new odors that are detectable by round gobies. The thermal bar begins to move off shore and the warmer water, slides over the colder, more dense, bottom water forming the thermal wedge. This transitions to full, cross-lake, stratification (Mortimer 2004). The shallow, warm water may help create conditions to benefit primary production nearshore during the spring (Millie et al. 2000). In this study during the spring, the water warmed from 2.8°C to 4.3°C at the 30 m site between April and May (Table 3). Coinciding with this change in temperature was the beginning of the return migration of round goby to nearshore habitat to spawn. The earliest spawning that has been reported begins around 9°C (Charlebois et al. 1998).

The increase of primary production and growth of phytoplankton and zooplankton changes the chemical composition of the water. Phytoplankton have been shown to concentrate at thermal fronts, including the thermal bar (Franks 1992). As the thermal bar (and wedge) move offshore, the sinking 4°C water carries with it the scent of phytoplankton. Thus there is a 4°C “coastal curtain” of phytoplankton laden water that, over a period of several weeks (Wang 2013), progresses from shallows to the deep water where the round gobies winter.

While round goby in Lake Michigan, seem to begin their return migration in late April or early May, round goby can also be found offshore on reefs like Julian’s Reef into June when the bulk of the population has returned back to shallow water (<20 m) (personal observations). Julian’s Reef is located at N 42° 13”, W 87° 32” along the 38 m contour line, with a summit at about 27 m (Edsall et al. 1996; Redman et al. 2017). Round gobies were observed and collected, during the spring of 2018, from Julian's Reef using the MiniRover at depths between 30 m and 40 m, these fish did not follow the general migration pattern that other round goby exhibit. One hypothesis is that these fish are actually lost. They move off from nearshore habitat during a past fall and move into deeper water. When spring comes around and the fish are cued to move back to shallow water, these fish followed the slope of these reefs up, but never reach the shallow water or water temperatures they need to spawn. These fish may be trapped until the following fall when the lake mixes again.

Fish that migrate out to deeper water, 50+ m, may never be cued to move back inshore. This could explain the gobies at 73 and 130 meters in lakes Huron and Ontario (Schaeffer et al. 2005; Walsh et al. 2007). In spring, the thermal bar will move out to around 50 m of water before becoming the thermocline (Mortimer 2004). Round gobies deeper than about 50 m may never receive the cue that triggers shallower round gobies to begin moving back inshore. Migration mis-cues, or mis-orientation, also occurs with birds. The birds have normal migration routes, but mis-orientation can cause some birds to be observed up to 5000-7000 km from these migration routes (Alerstam 1990).

When the round gobies began their migration to deeper water, larger fish were the first to move offshore. The reason this occurs may be that the larger fish are more experienced than smaller fish. The average size of these fish was 93 mm which, using length-at-age estimates from Huo et al. (2014), suggests these fish are between 4-5 years of age. The fish that remained shallower averaged 58.5 mm and using the same estimates, would age these fish between 1-2 years of age or younger. These younger fish may still be learning when and where they should go when temperatures drop. Learning migration patterns from adult fish occurred in juvenile French grunts (*Haemulon flavoineatum*) were able to learn the migration routes by following along with the adults (Helfman and Schultz 1984).

In Lake Michigan, larger, experienced fish may move offshore early to take advantage of the quagga mussels that have been growing at deeper depths than round gobies occupy during summer. Round gobies have been shown to effect quagga mussel density through predation in shallow depths (Kuhns and Berg 1999; Barton et al. 2005; Lederer et al. 2006). Studies have shown that round gobies generally begin feed on dreissenids between 60mm-100mm, total length, and primarily feed on mussels between 4.5mm-12.5mm (Andraso et al. 2011), but prefer mussels <10mm (Ray and Corkum 1997; Andraso et al. 2011; Foley et al. 2017). While Lake Michigan is stratified, and round gobies are concentrated near shore, they likely depress the mussel population that are within the smaller size range. Newly recruited mussels occupying deeper sites have had little predation from round gobies for almost half the year and may be a newly available food resource for round gobies large enough to feed on them. Experienced fish would have first access to these mussels by migrating offshore first. Larger adults are also equipped to feed on the wider variety of sizes of quagga mussels found offshore. Larger fish are equipped with molariform pharyngeal teeth that are ideal for feeding on larger mussels, versus the conical pharyngeal teeth found on small round gobies better suited for feeding on non-shelled invertebrates (Andraso et al. 2011). The smaller, inexperienced, fish then follow these adults offshore to gain access to this food source, which would include smaller mussels and other invertebrates.

The offshore migration of round gobies provides a cold season food resource that is available to cold water predators. Throughout the Great Lakes native, warm water, predators have taken advantage of the abundant round gobies available (Crane et al. 2015). In 2004, round goby first began to appear in the diets of smallmouth bass, *Micropterus dolomieu*, in Lake Michigan. By 2005, round gobies were found in the diets of all predatory fish in a survey from Milwaukee, WI (Hirethota 2015). Burbot, *Lota lota*, are known to prey on native fishes and invertebrates and have adapted to feeding on round gobies in the Lake Michigan and Lake Huron (Hensler et al. 2007). The shift in diets to include round gobies has been seen between 16%-33% (Jacobs et al. 2010) and as high as 62% (Hensler et al. 2007) by wet weight. Burbot in Lake Erie have shifted to primarily feed on round goby in offshore habitats (Madenjian et al. 2011). Lake trout, *Salvelinus namaycush*, have also seen a diet shift to include more round gobies (Claramunt 2019). While round gobies did not make up a large percentage, they were 3% of the diet by weight of lake trout in northern Lake Michigan (Jacobs et al. 2010). Lepak et al. (2019) attributed changes in mercury contamination to round goby predation in fall sampled lake trout. In Lake Ontario, lake trout were observed to have seasonal changes in their consumption of round goby, with higher numbers of round gobies found in diets in spring versus the summer (Dietrich et al. 2006).

The preferred water temperature for lake trout is around 12°C, and they generally avoid water temperatures higher than 14°C -15°C (McCauley and Tate 1970; Goddard et al. 1974; Coutant 1977; Bergstedt et al. 2013). This preference of cooler water could be the reason there is a seasonal pattern for predation of round gobies by lake trout. In my study, the nearshore water temperatures were higher than 14°C at 10 m in September, and then cooled into October. The water began warming quickly into June at 10 m, which coincided with when round gobies began moving offshore and back in during this study. During the 4-5 month period between June stratification into fall may minimize round goby predation by lake trout. When this thermal barrier is destroyed by the seasonal mixing, lake trout may begin feeding heavier on round goby during the winter months, but it is little more than conjecture since little research is done during this time.

The results of this study may have management implications when it comes to assessment of round goby populations in the Great Lakes. The US Geological Survey (USGS) conducts annual bottom trawls in the fall at various sites and across depths between 9 meters and 110 meters in Lake Michigan as part of its lake wide prey fish assessment since 1973 (Madenjian et al. 2011). These trawls provide data for the lake-wide predator-prey ratio (PPR) that is used as an indicator for the balance of predators and prey within the lake (Claramunt et al. 2019). From these trawls, the estimate of the round goby and other prey fish populations are determined. A limitation of trawls is that they are unable to be pulled effectively across rocky bottoms, and this causes the surveys to be conducted on less than ideal substrate than round gobies prefer, like sand or clay. This may cause an underestimation of round goby because the bulk of the population may be present on untrawlable substrate. Another issue of trawling in the fall, is that depending on the trawling date, the bulk of the population may be present at 10m and shallower. From my snorkel surveys in fall and OpenROV surveys in spring, I observed many fish shallower than the 10 meters that was sampled during the MiniRover transects, and shallower than the 9 meters that is sampled by USGS. From this study I saw that a large portion of round goby did not move offshore from 10 meters until mid to late October (Table 1). At my study sites in the spring, no round goby were found at shallow depths in April and were detected until early May at 30 meters (Table 1). This means that the majority, if not all, of the population is likely to be present at depths that are trawled by USGS at the sampling sites. A spring trawling survey for round goby may provide a more accurate assessment of the total round goby population residing in Lake Michigan.

The use of ROVs to complete video transects for this study was used as an alternative to scuba diver video transects. Scuba transects have been used in past studies for estimating round goby including, Ray and Corkum 2001, who used scuba transects for estimating round goby during daylight and nighttime over a variety of substrate types. Scuba transects using video cameras were used by Houghton and Janssen (2015) to estimate round goby abundance in rocky substrate and habitat assessment. ROV transects were more beneficial for this study, because it allowed me to follow similar methods that were used in these past studies, while avoiding the limitations of time underwater and the number of dives that can be completed in a single day as a diver would have. I was able to complete a total of 4 dives, one hour or more in length, in a single day, which would be difficult to perform with a typical crew of 2 divers because of general safety and time constraints.

Table 1: MiniRover Round Goby Observations

The number of round goby were counted during the post study video analysis of the large ROV transects in Fall 2018 and Spring 2019. All six transects for each sampling date and depth were combined to reach the total recorded below.

Fall 2018				Spring 2019			
Date	Depth (meters)	Total number observed	Density per meter	Date	Depth (meters)	Total number observed	Density per meter
9/17/18	10	262	1.90	4/9/19	10	0	0.00
	20	122	0.50		20	0	0.00
	30	9	0.04		30	0	0.00
	40	0	0.00		40	0	0.00
10/10/18	10	109	0.89	5/10/19	10	0	0.00
	20	144	0.56		20	14	0.05
	30	107	0.85		30	103	0.46
	40	0	0.00		40	0	0.00
10/29/18	10	31	0.15	5/23/19	10	85	0.47
	20	153	0.60		20	36	0.13
	30	120	0.41		30	54	0.44
	40	0	0.00		40	0	0.00
11/12/18	10	1	0.01	6/7/19	10	267	1.05
	20	1	0.04		20	33	0.12
	30	71	0.23		30	14	0.05
	40	0	0.00		40	0	0.00

Table 2: Dive/Snorkel/VideoRay observations

The total number of round goby observed for all transects for each method was recorded from the video of each dive. Additional snorkel surveys occurred, in about 1 meter of water, but were not recorded because transects did not occur, the video was used for presence and absence.

Date	Location	Method	Depth	# of transects	# Round Goby
7/26/18	Fox Point	Scuba	3m	6	170
7/26/18	Fox Point	Scuba	10m	6	104
7/31/18	Atwater	Snorkel	1m	6	25
7/31/18	Fox Point	Snorkel	1m	5	29
8/8/18	Atwater	Scuba	3m	5	46
8/8/18	Atwater	Scuba	10m	5	15
8/8/18	Atwater	VideoRay	3m	6	51
8/8/18	Atwater	VideoRay	10m	6	11
10/18/18	Atwater	Snorkel	1m	5	0
10/24/18	Atwater	Snorkel	1m	5	0

Table 3: Seasonal Temperature Changes

The bottom temperature was recorded from the CTD aboard the Benthos MiniRover MKII during all sampling dates and at each sampling depth for Fall 2018 and Spring 2019.

	Fall 2018				**Spring 2019**			
	Sept. 17	Oct. 10	Oct. 29	Nov. 12	Apr. 9	May 10	May 23	Jun. 7
Depth (meters)	*°C*	*°C*	*°C*	*°C*	*°C*	*°C*	*°C*	*°C*
10	14.7	11.0	8.9	6.4	2.9	5.0	5.6	9.8
20	11.8	10.3	8.5	6.8	2.48	4.5	4.9	6.2
30	8.1	9.5	6.7	7.0	2.8	4.3	4.7	4.7
40	7.3	8.0	5.6	6.3	2.5	4.4	4.8	4.2

Table 4: OpenROV Trident Surveys

The total number of round goby observed was recorded from the video of each OpenROV Trident Survey.

Date	Location	Depth (meters)	Temperature (°C)	# Round Goby
4/24/19	Atwater Beach	3 meters	8.0	0
4/24/19	Atwater Beach	10 meters	5.5	0
5/3/19	Atwater Beach	10 meters	6.3	0
5/14/19	Atwater Beach	10 meters	*	18
5/21/19	Atwater Beach	10 meters	9.3	15
5/31/19	Atwater Beach	3 meters	11.0	24
5/31/19	Atwater Beach	10 meters	9.0	81
8/9/19	Atwater Beach	3 meters	17.4	150
8/9/19	Atwater Beach	10 meters	15.7	148
8/20/19	Atwater Beach	3 meters	20.9	77
8/20/19	Atwater Beach	10 meters	18.7	126
8/20/19	N42.9834, W87.8362	10 meters	15.8	62
8/20/19	N42.9614, W87.8428	3 meters	*	151
8/30/19	N43.1511, W87.8761	10 meters	8.1	13
8/30/19	N43.1580, W87.8842	3 meters	9.0	1
8/30/19	N43.0992, W87.8726	3 meters	13.0	0
8/30/19	N43.1018, W87.8671	10 meters		5

*Temperatures not recorded

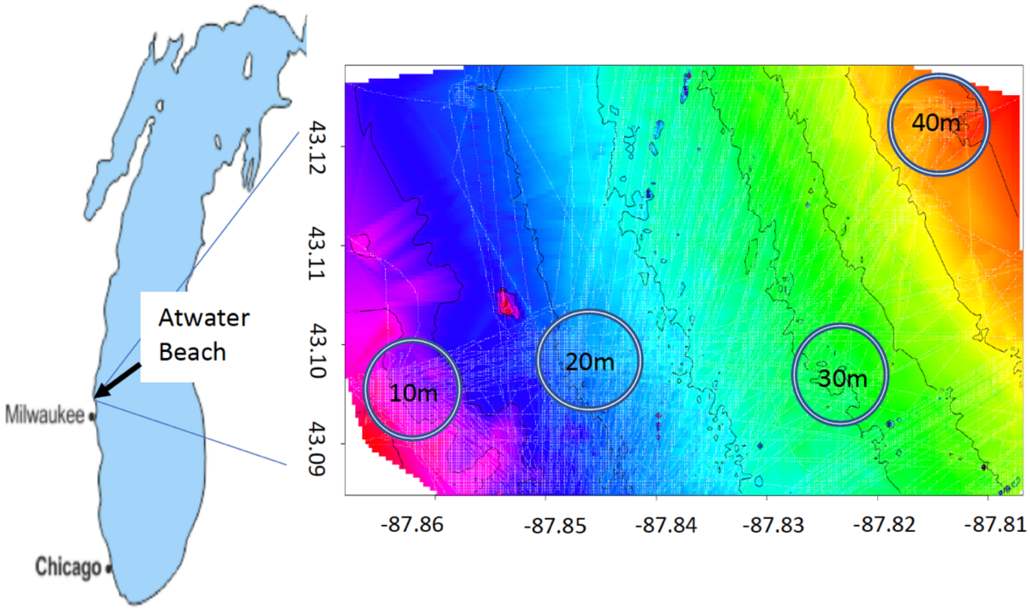
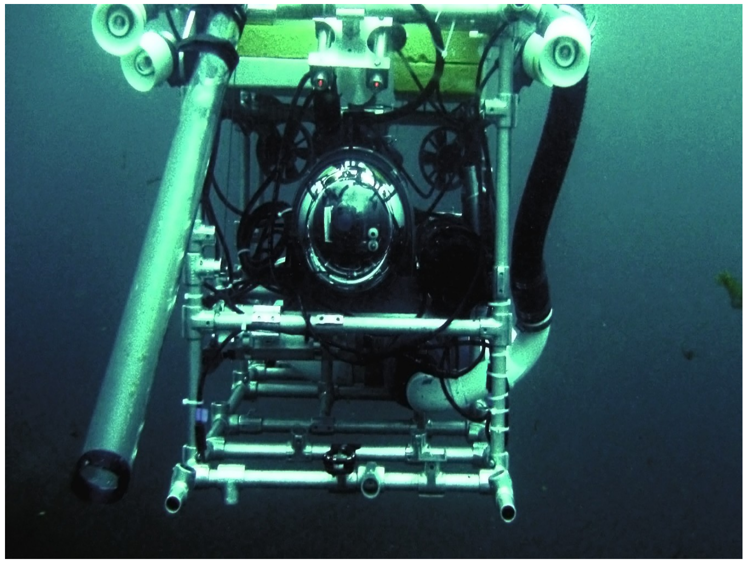
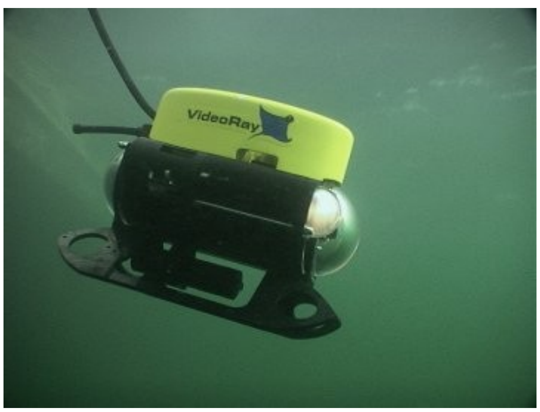


Figure 1. Atwater Beach Study Area

Bathymetric map generated from the R/V Neeskay's sonar of Atwater Beach, located North of the city of Milwaukee, WI. The white circles on the map denote the locations and depths of the four sampling sites.



A)



B) Photo credit VideoRay LLC ®

C)

Figure 2: Remote Operated Vehicles

The following ROVs were used throughout the duration of this study. A) Benthos MiniRover MKII, a large ROV used for the transects off of the R/V Neeskay. B) VideoRay, used in conjunction with the MiniRover dives at the near shore sites (3m and 10m) for sampling. C) OpenROV Trident used in spring 2019 as a quick survey to determine the presence or absence of round goby at various depths.

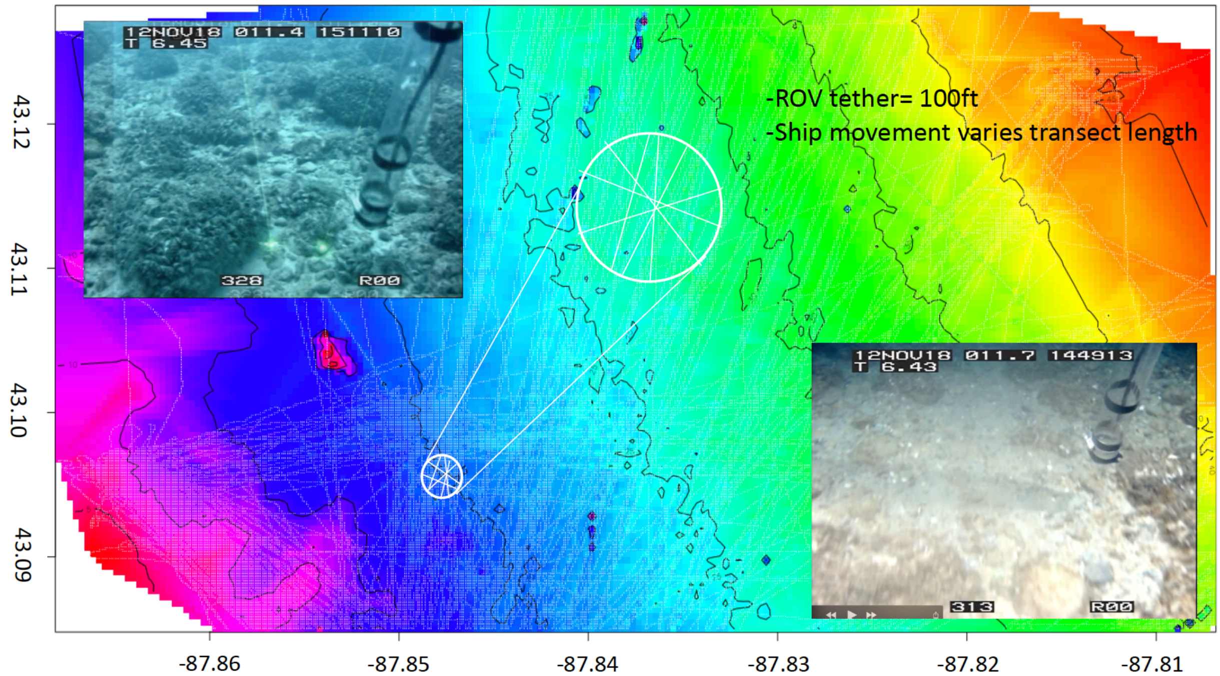


Figure 3: ROV Sampling Transect

Bathymetric map of my sampling area. The enlarged white circle shows the typical coverage by the ROV with a series of transects (6) conducted at a sampling site. The 6 transects within the circle were randomly selected, so the pattern varied at each site. The two pictures imbedded in the figure show the view from inside the support vessel that the crew was able to see.

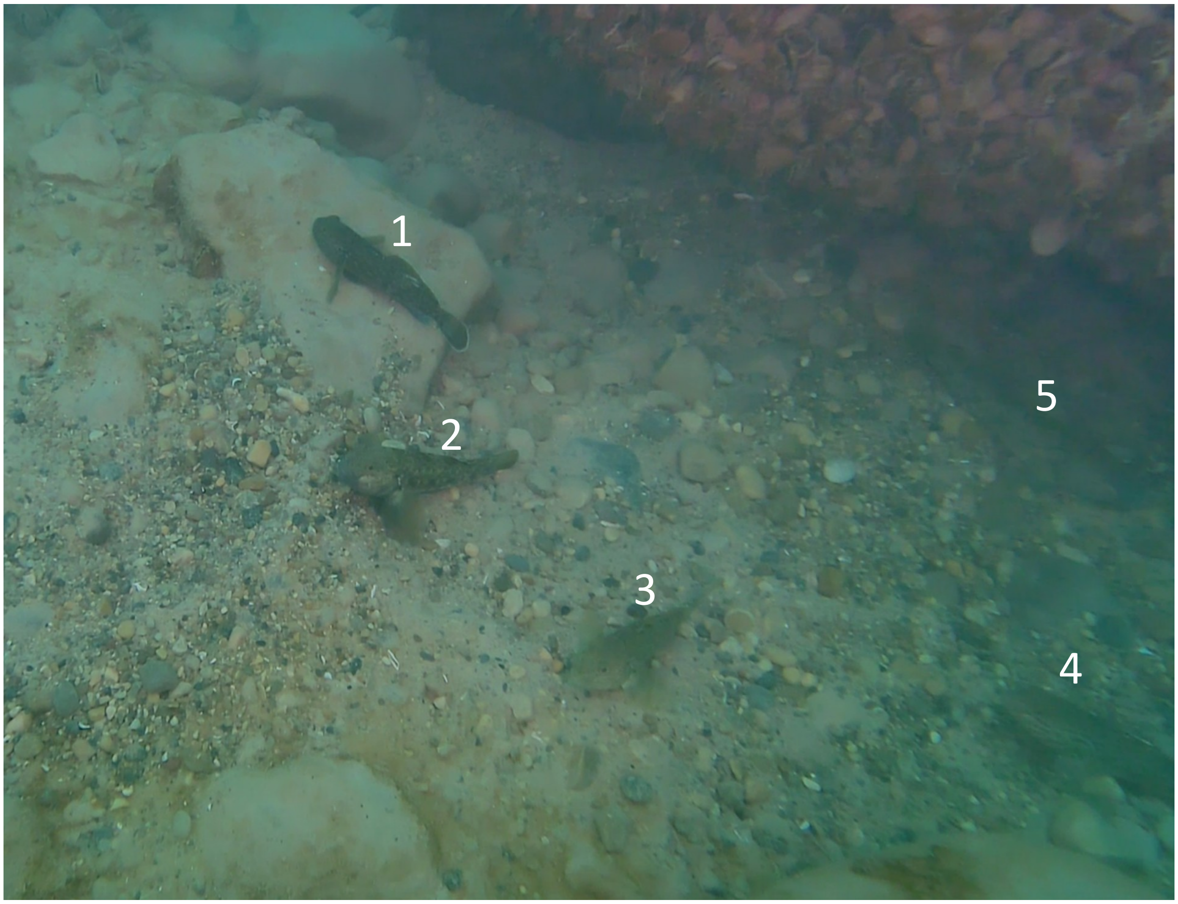


Figure 4: Round Goby Count.

A still frame of a ROV video showing five round goby that would be counted towards the total number of fish seen during the transect. Slimy sculpins were also observed during these transects, but were not counted in the overall total of fish seen during each transect.

Figure 5: Round Goby Size Estimation

The process of estimating the size of the round goby off of the video transects. The reference points are the 2 laser points that are set at 10cm apart (line A). A line is drawn between the two laser points to get a reference length of the laser points, then the round goby total length is measured (line B). The lengths are then converted so the reference line is equal to 10cm, giving an estimated length of the round goby.

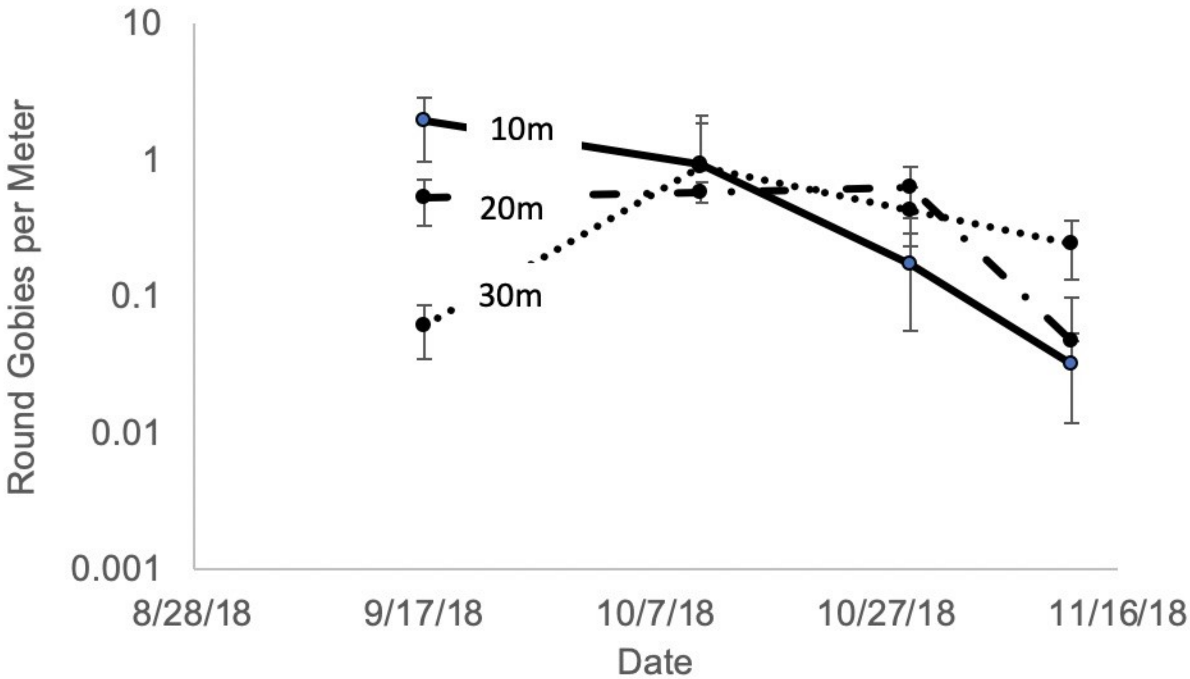


Figure 6: Fall MiniRover Transect Densities

The results from the 2018 fall large ROV transects. The mean number of round gobies per meter were grouped by depth for each sampling date. The error bars represent the standard deviation associated with each data set.

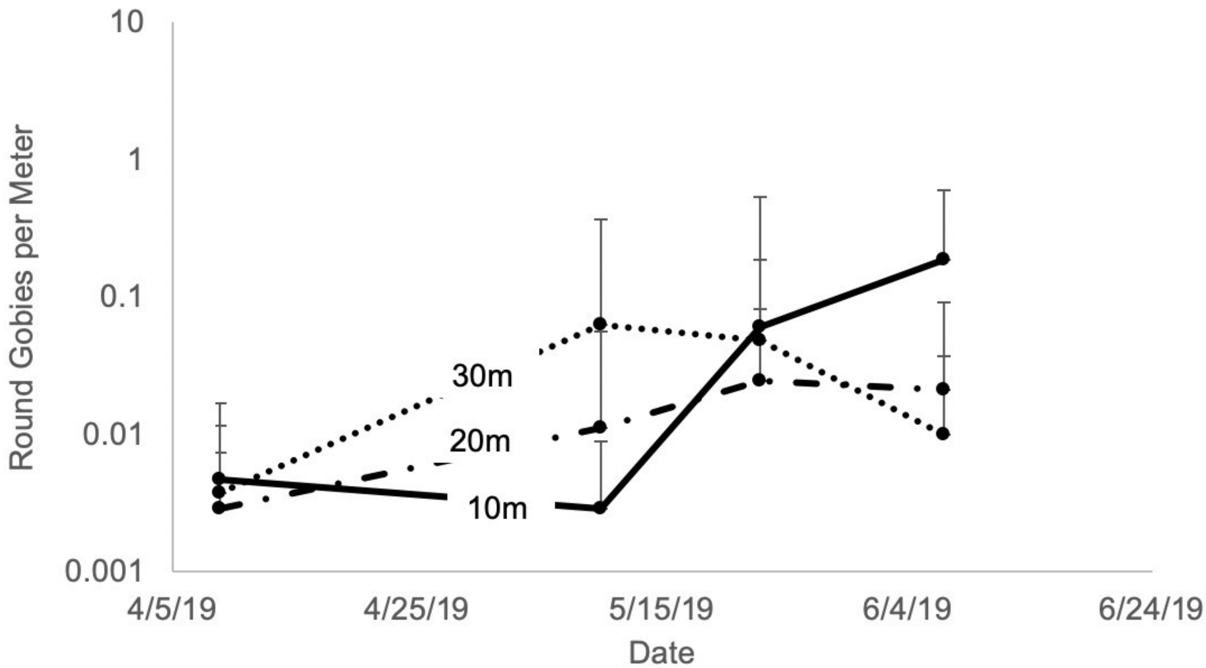


Figure 7: Spring MiniRover Transects Densities

The results from the 2019 spring MiniRover transects. The mean number of round gobies per meter were grouped by depth for each sampling date. The error bars represent the standard deviation associated with each data set.

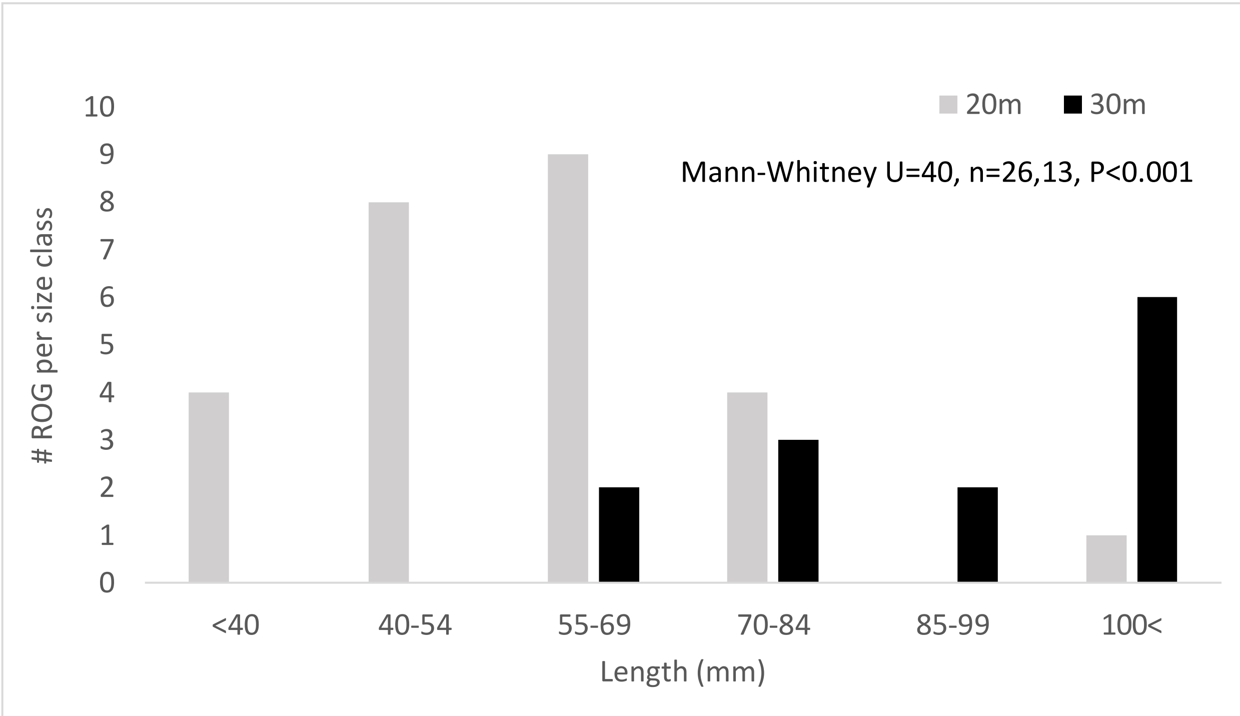


Figure 8: Round Goby Offshore Migration, Size Analysis

The results from the October 10, 2018 comparison of fish sampled at 20 meters and 30 meters. The number of round gobies within each size bin were counted and a Mann-Whitney U-test was conducted to test for differences in sizes between the two depths.

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