Seasonal abundance and movement of the invasive round goby (*Neogobius melanostomus*) on rocky substrate in the Duluth-Superior Harbor of Lake Superior

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CHAPTER 1

A review of round goby (*Neogobius melanostomus*) literature 20 years after introduction to the Laurentian Great Lakes

INTRODUCTION

One of the most significant threats to ecosystems and associated biodiversity is the human-aided spread of species beyond their natural range (Lodge 1993, Vitousek et al. 1997). Although species distributions change naturally over geologic time, human activities have greatly increased the rate and scale of these movements via the global economy (Vitousek et al. 1997). During the past century, the Laurentian Great Lakes have received an influx of alien species from the ballast water of transoceanic ships (Claudi and Ravishankar 2006). These ships take on ballast water in foreign ports to provide stability while crossing the ocean, and discharge it upon arrival to make room for cargo. This represents a significant vector for the dispersal of non-native species. Some of these species now dominate the food web of the Laurentian Great Lakes causing ecological and economic impacts (Ricciardi and MacIsaac 2000).

One species introduced to the Laurentian Great Lakes via transoceanic ballast water is the round goby, *Neogobius melanostomus* or *Apollonia melanostomus* (Neilson and Stepien 2009). The round goby is a soft-bodied benthic fish native to the Ponto-Caspian Region of Eurasia (Black, Caspian, and Azov Seas). In the 20 years since its introduction, this species has become a major component of the Great Lakes ecosystem. Decreases in native benthic fishes (Jude et al. 1995, Lauer et al. 2004), benthic invertebrates (Lederer 2006), dreissenid mussels (Lederer 2006), and predation on smallmouth bass (*Micropterus dolomieu*) (Steinhart et al. 2004a), lake sturgeon (*Acipenser fulvescens*) (Thomas and Haas 2002), and lake trout (*Salvelinus namaycush*) (Chotkowski and Marsden 1999) eggs and fry are impacts associated with the establishment of the round goby in the Laurentian Great Lakes.

NATIVE RANGE

The round goby is native to the Ponto-Caspian Region of the Eurasian steppe. Historically inhabiting the Sea of Azov, nearshore areas of the Caspian Sea, Black Sea, and the Sea of Marmara (Charlebois et al. 1997). Round gobies are also known to inhabit tributaries of the Black and Caspian Seas, including the Dneister and Bug Rivers in Ukraine, and the River Don in Russia (Miller 1986, Charlebois et al. 1997, Simonovicå et al. 2001, Skora and Rzeznik 2001).

INVASIVE RANGE – EUROPE

Human transport through natural and manmade waterways has expanded the range of the round goby in Eastern and Northern Europe (Skora 1996, Simonovicå et al. 2001, Skora and Rzeznik 2001, Corkum et al. 2004, Wiesner 2005). Colonization of the Aral Sea was reported in the 1950’s but this population was subsequently eradicated due to a salinity increase from 11 ppt to 35 ppt caused by the diversion of tributary water for irrigation (Skora 1996). Barges traveling the water routes between the Ponto-Caspian Region and the Baltic Sea have further expanded round goby range into the Danube, Volga, and Moscow Rivers ultimately leading to the establishment of a population in the Baltic Sea's Gulf of Gdansk in 1990 (Simonovicå et al. 2001, Sapota and Skóra 2005, Wiesner 2005).

INVASIVE RANGE – NORTH AMERICA

The first sighting of a round goby in North America was in the St. Clair River in 1990 (Jude et al. 1992). Whether the initial population was introduced as eggs, larva, juvenile or adult fish is not known, but it was likely transported in the ballast water of transoceanic ships originating in the Ponto-Caspian Region and entering the Laurentian Great Lakes through the Saint Lawrence Seaway (Charlebois et al. 1997, Claudi and Ravishankar 2006). Once populations became established they were further spread by additional ballast water imports, recreational fishermen, and natural dispersal (Steingraeber and Thiel 2000). By 1993, round gobies were found at the major shipping ports of Chicago, Illinois; Detroit, Michigan; and Cleveland, Ohio. Five years after the first North American round goby was reported, they had expanded to all five Laurentian Great Lakes with the discovery of a population in the Duluth-Superior Harbor of Lake Superior (Jude 1997). To date, round gobies have been documented in nearshore and offshore areas of Lake Ontario, Lake Erie, Lake Huron, and Lake Michigan while the Lake Superior population has been restricted to the Duluth-Superior, Thunder Bay, and Marquette Harbors (Jude et al. 1995, Clapp et al. 2001, Johnson et al. 2005, Schaeffer et al. 2005, Walsh et al. 2007, Bergstrom et al. 2008). Round gobies have also expanded their range into tributaries and watersheds surrounding the Laurentian Great Lakes including the Mississippi River drainage through the Illinois Waterway (Steingraeber and Thiel 2000, Phillips et al. 2003, Irons et al. 2006, Krakowiak and Pennuto 2008).

PHYSICAL DESCRIPTION

The round goby is a small, benthic, soft-bodied fish with relatively large jaws and a mottled brownish coloration highlighted by dark brown lateral spots and a large, oblong, black spot at the end of the first dorsal fin. During the reproductive season nest guarding males are completely black with yellowish spots on the body and median fins fringed in yellow (Miller 1986). Recent work has identified an alternative parasitic or 'sneaker' male morph without the characteristic nest guarding coloration (Marentette et al. 2009).

Round gobies are distinguished from native North American fishes by their fused pelvic fins (Charlebois et al. 1997). This single fin creates a weak suction between the fish's ventral side and a hard surface, potentially allowing it to maintain position in weak to moderate currents. Round gobies lack swim bladders and are generally poor swimmers, utilizing their oversized pectoral fins to propel themselves with short darting movements.

Male and female round gobies greater than 60 mm in total length (TL) can be differentiated by sexually dimorphic erectile urogenital papilla. The male's papilla is generally longer and pointed, while the female's is shorter and rounded (Charlebois et al. 1997). Adult female round gobies tend to be smaller (mean 90 mm TL) than males (mean 100 mm TL) and the maximum size in the Laurentian Great Lakes tends to be smaller than in their native range with males reported to 250 mm in the Black Sea (Berg 1949, Jude 1997, MacInnis and Corkum 2000b).

FACTORS FACILITATING INVASION

The round goby has several life history traits characteristic of successful invasive species, including wide tolerance of environmental conditions, high productivity, maturity at a young age, rapid dispersal, and a generalist feeding strategy (Charlebois et al. 1997). These traits have presumably led to the high abundance of round gobies in the Laurentian Great Lakes.

HABITAT TOLERANCE

The round goby's native water bodies are characterized by large and rapid water level fluctuations leading to a wide range of historic salinities and temperatures (Dumont 1998) and species adapted to this fluctuating regime of salinity, temperature, and water quality are best suited to survival during transportation to new environments (Ricciardi and MacIsaac 2000). Round goby salinity tolerance is from 0 to 40 ppt, but the likelihood of survival beyond one day is very low in salinities above 30 ppt (Ellis and MacIsaac 2009). Round gobies can also survive substantial temperature fluctuations over short periods of time with a critical maximum temperature of 33°C (Cross and Rawding 2009).

In their native range, round gobies occupy the rocky nearshore habitat of large lakes and rivers (Berg 1949). Although initially restricted to those habitats, round gobies have been found inhabiting a much wider range of environments including small tributary streams (Phillips et al. 2003, Krakowiak and Pennuto 2008, Kornis and Vander Zanden 2010) and offshore areas up to 150 m (Schaeffer et al. 2005, Walsh et al. 2007) in the Laurentian Great Lakes. Round gobies prefer structured habitat such as cobble and rock, but can be found in gravel, sand, clay, and vegetation of both lakes and streams (Jude et al. 1995, Charlebois et al. 1997, Ray and Corkum 2001, Phillips et al. 2003). As round goby density in the most desirable areas increases, continued expansion into novel habitats is expected; potentially leading to a new suite of biological interactions not currently observed.

Population Dispersal

Along with a wide tolerance of environmental conditions, the round goby has utilized a combination of natural and anthropomorphic vectors to rapidly expand its range in both Europe and North America (Steingraeber and Thiel 2000). Natural round goby dispersal may occur in one of several life stages. Although adults lack a swim bladder, larval round gobies are known to exhibit diel vertical migration and at this life stage they could potentially disperse over great distances while suspended in water currents (Hensler and Jude 2007). Adult male round gobies are known to guard nests from April to November and predictably have small home ranges during this time (MacInnis and Corkum 2000b) but immature and non-dominant males may disperse to establish their own territory. In their native range, round gobies are known to move into deeper water during the winter months (Berg 1949). This behavior may provide a mechanism for adult dispersal with imperfect return to previous territories (Wolfe and Marsden 1998).

Several studies have reported changes in the vanguard of round goby populations (Clapp et al. 2001, Schaeffer et al. 2005, Lederer 2006, Bergstrom et al. 2008) with fewer studies addressing the movement of individuals (Wolfe and Marsden 1998, Ray and Corkum 2001, Cookingham and Ruetz 2008). Range expansion estimates have varied from < 1 km yr^{-1} up the Saint Louis River Estuary (Bergstrom et al. 2008) to 14 km yr^{-1} along the Lake Michigan shoreline (Lederer et al. 2008). These estimates provide an approximate rate by which round gobies are colonizing novel areas, however, the described patterns can be the result of insufficient or irregular sampling and shed little information on the pattern or mechanism of spread and studies focusing on individual round gobies suggest adults show a high degree of site affinity (Wolfe and Marsden 1998, Ray and Corkum 2001, Cookingham and Ruetz 2008). SCUBA divers following individual round gobies found them to occupy small home ranges (5 ± 1.2 m^2) (Ray and Corkum 2001) and remote tracking of fish fitted with passive integrated transponder (PIT) tags found similar results (Cookingham and Ruetz 2008). Field studies investigating methods for marking round gobies reported recapture rates as low as 6% (Wolfe and Marsden 1998) and as high as 58% (Ray and Corkum 2001); all of which were taken from the same location as the tagged fish were released. Despite the lack of sampling outside the initial release point, the latter study indicates a large portion of the population may exhibit site affinity.

Diet

Being opportunistic feeders, round gobies will consume a wide range of benthic food items. An ontogenetic dietary shift happens when individuals are approximately 60 mm total length (Jude et al. 1995). Individuals less than 60 mm primarily consume aquatic insects, amphipods, chironomids, and benthic cladocerans (Jude et al. 1995) but adult (>60 mm) round gobies are primarily molluscivores with a diet consisting of an array of bivalves, including: the zebra mussel (*Dreissena polymorpha*) and quagga mussel (*Dreissena bugensis*), two other invasive species from the Ponto-Caspian Region (Ray and Corkum 1997, Lederer 2006). Establishment of the zebra mussel across the Laurentian Great Lakes likely facilitated the establishment of the round goby, as it represents a vast food resource not shared by native benthic fishes (Simberloff and Von Holle 1999). Adult round gobies will also consume an array of macroinvertebrates, fish eggs and fry (Steinhart et al. 2004a, Lederer et al. 2008).

Reproduction

Another factor facilitating the establishment and proliferation of round gobies in the Laurentian Great Lakes is their early maturity and ability to spawn up to five times in one reproductive season, compared to per annum reproduction in native species. Maturation of round gobies in North America occurs at 1-2 years for females and 2-3 years for males (Corkum et al. 1998). Round gobies can spawn between 9 and 26° C and based on this temperature window, round goby reproduction can occur from mid-April to early-November, however, field observations indicate most spawning occurs from mid-

May through the end of July in the Laurentian Great Lakes (MacInnis and Corkum 2000b). This extended spawning season allows gravid females to spawn repeatedly as they produce a new batch of eggs every 18 to 20 days throughout the breeding season (MacInnis and Corkum 2000b). Maximum round goby fecundity recorded in the Laurentian Great Lakes is approximately 600 eggs per female (Corkum et al. 1998). In contrast, the native mottled sculpin, ranges from 10 to 150 eggs per female (Grossman et al. 2002) and may be negatively impacted by round gobies.

REPRODUCTIVE BEHAVIOR

Round goby males establish spawning nests in small crevasses under logs and stones, typically in water depths ranging from 0.2 to 1.5 meters, but can nest in up to 10 meters of water (MacInnis and Corkum 2000b). The general nest requirements are a hard, immobile overhead surface with a single opening (Charlebois et al. 1997). Due to a locally limited number of suitable spawning sites, males compete for these locations and aggressively guard them once established (Janssen and Jude 2001). To attract females, males use a combination of olfactory and acoustic cues and gravid females have been shown to preferentially move toward each of these stimuli (Zielinski et al. 2003, Rollo et al. 2007). Females identify and locate males with desirable spawning sites and deposit their eggs on the ceiling of the males nest. Multiple females will spawn in a single nest resulting in as many as 10,000 eggs being deposited (MacInnis and Corkum 2000b) and males care for the eggs until they hatch into larvae that exhibit diel vertical migration (Miller 1986, Hensler and Jude 2007). This intense caring and guarding effort leads to hatch rates as high as 95 % (MacInnis and Corkum 2000b) but due to the high energetic costs and limited foraging opportunity, male round gobies generally survive only one reproductive season (Corkum et al. 1998).

Environmental Impact

Round goby establishment, proliferation, and expansion has greatly impacted the ecology of the Laurentian Great Lakes. With a western Lake Erie population estimated at 9.9 billion individuals (Johnson et al. 2005) and density estimates as high as 133 individuals/m^2 in southern Lake Michigan (Chotkowski and Marsden 1999), the round goby has clearly become a major component of the food web in several Great Lakes. The round goby's aggressive behavior, habitat requirements, and dietary overlap have put them in direct competition with native benthic fishes including logperch (*Percina caprodes*) (Balshine et al. 2005, Bergstrom and Mensinger 2009), johnny darter (*Etheostoma nigrum*) (Lauer et al. 2004), mottled sculpin (*Cottus bairdi*) (Dubs and Corkum 1996, French III and Jude 2001, Janssen and Jude 2001), slimy sculpin (*Cottus cognatus*) (Bergstrom and Mensinger 2009), and northern madtom (*Noturus stigmosus*) (French III and Jude 2001). Populations of these native species have declined concurrently with rapid increases in round goby populations across the Great Lakes ecosystem (Jude et al. 1995, Janssen and Jude 2001, Lauer et al. 2004).

Round gobies represent both predators and prey of game fish species including smallmouth bass (*Micropterus dolomieu*) (Steinhart et al. 2004a, Steinhart et al. 2004b), lake sturgeon (*Acipenser fulvescens*) (Thomas and Haas 2002), and lake trout (*Salvelinus* *namaycush*) (Chotkowski and Marsden 1999, Dietrich et al. 2006). In areas of high round goby density, reproductive success of these game fish species may be reduced through predation on eggs and fry (Chotkowski and Marsden 1999, Steinhart et al. 2004a). Their affinity for interstitial spaces make round gobies difficult for piscivorous species to capture but with increases in their density, round gobies have become an important component in the diet of piscivorous fish, birds, and the threatened Lake Erie watersnake (Somers et al. 2003, Corkum et al. 2004, Steinhart et al. 2004b, King et al. 2006). With this predation on round gobies, the sole consumers of dreissenid mussels, a trophic link has been added to the Great Lakes food web (Dietrich et al. 2006). The addition of this trophic link connects piscivores species with contaminants previously confined to the dreissenid mussels. This link has been implicated in increasing levels of bio-accumulated mercury (Hogan et al. 2007) and type E botulism outbreaks (Yule et al. 2006) and may also affect phosphorus cycling (Hecky et al. 2004, Bunnell et al. 2005).

The full impact of round goby naturalization in the Laurentian Great Lakes is not yet resolved because changes traceable to the invasion of round gobies continue. With time, the biotic assemblage of the Laurentian Great Lakes may come to a new equilibrium with these Ponto-Caspian invaders; but until then, as densities increase and range expansion continues, more unforeseen consequences may arise from the addition of this species to the Laurentian Great Lakes food web.

CHAPTER 2

Seasonal abundance and movement of the invasive round goby (*Neogobius melanostomus*) on rocky substrate in the Duluth-Superior Harbor of Lake Superior

CHAPTER OVERVIEW

The round goby, *Neogobius melanostomus*, is a benthic fish introduced to the Laurentian Great Lakes from the Ponto-Caspian Region of Eurasia via transoceanic ships in 1990. Despite its small size (adult 60 to 130 mm, TL), and reported home range of 5 m^2, round gobies have quickly become established throughout the watershed. Little information is available, however, on the mechanism of dispersal. This capture-mark-recapture study utilized alphanumeric elastomer tags subcutaneously inserted into round gobies (n = 1,228) along a 550 meter stretch of the Duluth-Superior Harbor shoreline to observe their movement patterns over a 13 month period from July 2009 to July 2010. Recaptured round gobies (n = 415) had a highly leptokurtic movement distribution with 89% of the fish showing no net movement between captures and a maximum displacement of 475 meters between captures. Observed movement events were not correlated with fish size or the month of capture. Our work indicates round gobies (> 50 mm, TL) generally occupy an area less than our minimum sampling interval (25 m); however, occasional movement events up to 50 meters per day could facilitate range expansion in the Laurentian Great Lakes Watershed.

INTRODUCTION

Organisms move to avoid competition and exploit dynamic aspects of their environment, such as changes in food availability, location of mates, and danger from predators. Through this process, species distributions change naturally over time; human activities, however, can greatly increase the rate and scale of these movements (Vitousek et al. 1997). As a result, human-aided spread of species beyond their natural range, is one of the most significant threats to ecosystems and associated biodiversity (Lodge 1993, Vitousek et al. 1997). Most successful species invasions are irreversible, and once introduced, the magnitude of their impact is often directly related to the organism's ability to expand beyond the point of introduction. This highlights the importance of studying natural dispersal patterns as part of invasive species biology.

The discharge of ballast water into the Laurentian Great Lakes by transoceanic ships has led to an influx of alien species from the Ponto-Caspian Region of Eurasia (Claudi and Ravishankar 2006). In the last twenty years, these species have become major components of the food webs and have dramatically impacted the Great Lakes ecosystem (Ricciardi and MacIsaac 2000). One species introduced during this time is the round goby, *Neogobius melanostomus* or *Apollonia melanostomus* (Neilson and Stepien 2009). This species first appeared in the St. Clair River in 1990 (Jude et al. 1992) and through a combination of additional ballast water discharges, recreational fishermen, and natural dispersal, round gobies are now found in all five Laurentian Great Lakes (Jude et al. 1995, Clapp et al. 2001, Schaeffer et al. 2005, Walsh et al. 2007) and have begun to colonize streams and tributaries (Phillips et al. 2003, Krakowiak and Pennuto 2008, Kornis and Vander Zanden 2010).

The round goby's diet and habitat requirements have placed them in direct competition with native benthic fishes (Jude et al. 1995, Dubs and Corkum 1996, Balshine et al. 2005, Bergstrom and Mensinger 2009). The aggressive behavior and reproductive success of round gobies has resulted in population declines in some native species including logperch (*Percina caprodes*), johnny darter (*Etheostoma nigrum*), mottled sculpin (*Cottus bairdi*), and slimy sculpin (*Cottus cognatus*) (French III and Jude 2001, Janssen and Jude 2001, Lauer et al. 2004). Gamefish such as smallmouth bass (*Micropterus dolomieu*), lake sturgeon (*Acipenser fulvescens*), and lake trout (*Salvelinus namaycush*) may also be impacted as a result of round goby predation on their eggs and fry (Chotkowski and Marsden 1999, Thomas and Haas 2002, Steinhart et al. 2004).

Despite their colonization throughout the Laurentian Great Lakes Watershed, little data is available on the movement of round gobies on large spatial or temporal scales. Range expansion estimates have varied from < 1 km yr^{-1} up the Saint Louis River Estuary (Bergstrom et al. 2008) to 14 km yr^{-1} along the Lake Michigan shoreline (Lederer et al. 2008). These rates are confounded, however, by reports of limited movement by individuals. Round goby home range size was estimated at 5 ± 1.2 m^2 by SCUBA divers following eight round gobies over a one hour period (Ray and Corkum 2001) and mark-recapture rates of 6 % (Wolfe and Marsden 1998) and 58 % (Ray and Corkum 2001) have been reported with all but one of the recaptured fish caught within the release location. Although the latter marking study indicates a large portion of the population may exhibit a high degree of site affinity, both studies were confined to a limited area and time (7 to 8 weeks).

Natural round goby dispersal may occur in one of several life stages or seasons. Although adult round gobies are benthic, early juvenile round gobies (7-8 mm) exhibit diel vertical migration in summer, and may disperse while suspended in water currents (Hensler and Jude 2007, Hayden and Miner 2009). Dominant adult males guard nests and presumably show little net movement during the reproductive season, whereas immature and/or non-dominant males may be a significant driver in range expansion as they search for their own territory. Female round gobies spawn multiple times during the breeding season, however, little is known about their behavior or distribution between spawning events. Range expansion also may result from a pattern of seasonal on-offshore migration. In their native range, round gobies move into deepwater (≤60 m) during winter (Miller 1986), and anecdotal reference has been made to this seasonal migration in North America (Pennuto et al. 2010). Our study utilized individual capture-mark-recapture to investigate the pattern of movement by round gobies > 50 mm (total length, TL) in the Duluth-Superior Harbor over a 13 month period.

METHODS

STUDY SITE

The Saint Louis River drains a 5,861 km^2 watershed in western Lake Superior and forms a 4,856 ha freshwater estuary at its mouth. The Duluth-Superior Harbor is located in the lower portion of this natural embayment, and is characterized by a high degree of anthropomorphic change to the shoreline and river channel. Round gobies were first reported in the outer harbor in 1995 and have since expanded throughout the inner and outer harbors (Bergstrom et al. 2008) and were recently discovered 38 km upstream from Lake Superior at the Fond du Lac Dam (Lynch unpublished).

Sampling Methods

Twenty three sampling stations (Figure 1) were established at 25 meter intervals parallel to shore along Rice's Point in the Duluth-Superior Harbor (46°45'12"N; 92°06'27"W). The shoreline in this area is characterized by an array of interstitial spaces created by a manmade backfill of rock, metal, and concrete over a sandy bottom. Stations were located two meters from shore in water depths from 0.5 to 1.5 meters. Two stations, N and V, were located near overhanging willow trees; all other locations were in direct sunlight.

Round gobies were captured using 40.6 cm (0.6 cm square mesh, 3.0 cm diameter opening) galvanized minnow traps baited with previously frozen fish (Lake Superior Fish Company, Superior, WI, USA). The study period was from July 1st, 2009 to July 22nd, 2010. Two traps were set at each station and sampled 24 and 48 hours after deployment before being removed until the next sampling period. Trapping was done weekly for the first 10 weeks and biweekly during the remaining ice free months of the study. Surface water temperature was recorded at site M on every sampling date.

MARKING METHOD

The Schnabel multiple census method described by Ricker (1975) allowed round gobies to be marked and monitored repeatedly throughout the sampling period. Round gobies were marked with 1.0 x 2.5 mm visible implant alphanumeric tags (VI Alpha Tags, Northwest Marine Technology, Shaw Island, WA, USA) from July 1st to 29th, 2009 (*n* = 773) and again from March 31st to April 28th, 2010 (*n* = 455) (Table 1). During each of these dates (July 2009, *n* = 9; April 2010, n = 6) twenty round gobies greater than 50 mm (TL) were selected for marking at sites C through U (Figure 1). If fewer than 20 round gobies were captured at a station, all fish > 50 mm (TL) were tagged. VI Alpha tags were implanted subcutaneously in the right cheek and remained externally visible (Figure 2). All tagged fish were also given a rear dorsal fin clip to provide an estimate of tag loss. After tag insertion, fish were allowed to recover in a bucket of fresh harbor water for five minutes. Following the recovery period, all fish (marked and unmarked) were returned to their capture location. On subsequent sampling dates, the total length of all captured fish was measured, and then the fish were sexed, checked for a fin clip or tag and re-released. Males and females were differentiated by urogenital papilla (Charlebois et al. 1997) and gender determination was typically limited to fish over 60 mm (TL).

Additionally, on May 12th and 13th, 2010 a small sample of 47 round gobies (*n* = 23 males, 24 females) were marked and reciprocally transplanted between two sites, G and K, separated by 100 meters (*n* = 31 from G to K and *n* = 16 from K to G [Figure 1]) to determine if they would return to the original site of capture.

STATISTICAL ANALYSIS

Monthly length frequency diagrams were constructed from round gobies captured at all 23 sampling stations to determine seasonal changes in the size distribution of round gobies. It was not unusual to recapture the same tagged fish multiple times within a month which may have led to some sampling bias, however, tagged fish comprised less than 15 % of the catch, and there was no mechanism to determine the recapture rates of untagged fish. Therefore, each capture was treated as a unique fish and monthly changes in the size distribution were analyzed by Kruskal–Wallis one-way analysis of variance (ANOVA) on ranks with subsequent Dunn's post-hoc test for multiple comparisons.

Round goby movement was quantified by recording the displacement distance of individuals between each sequential capture. The general design followed Turchin (1998), creating two-tailed recapture distributions by assigning positive values to easterly moves and negative values to western moves. Following Petty and Grossman (2004), movement was quantified as units of linear distance (m) rather than rate ($m\ d^{-1}$) because distances were not correlated with time elapsed between captures (linear regression, $r^2 = 0.022$, $n = 1{,}320$). Directional (east-west) and gender (male-female) comparisons of movement distributions were performed using the Mann – Whitney rank sum test, and the relationship between size and movement distance was determined using linear regression analysis of initial length by distance moved.

Recapture intervals were highly variable, ranging from 1 to 52 weeks, therefore, to compare temporal patterns in movement within the study period we restricted analysis to 1 to 4 week capture intervals within calendar months. These monthly movement distributions were compared using Kruskal-Wallis one-way analysis of variance (ANOVA) on ranks.

All statistical analysis was performed using SigmaStat (Systat Software, Inc. 2006 version 3.5) with nonparametric tests because the data often failed tests for normality or equal variance (Anderson-Darling test, $\alpha = 0.05$).

RESULTS

SEASONAL ABUNDANCE

The study area was sampled 46 times ($n = 2,116$ traps) during the ice free months from July 2009 to July 2010 and 9,114 fish were captured. Round gobies comprised the vast majority (98.1 %) of this sample, with native species, primarily rock bass (*Ambloplites rupestris*), composing 1.4 % of the catch and two other invasive fishes, the Eurasian ruffe (*Gymnocephalus cernuus*) and tubenose goby (*Proterorhinus marmoratus*) contributing 0.5 %. The only native benthic fish captured was a single logperch (*Percina caprodes*) in June of 2010.

Round gobies were captured in all sampling periods, however, catch rates varied from 10 individuals in the first week of post-ice sampling (March 31st - April 1st) to 957 in late April (April 28th - 29th) (Figure 3).

Round goby median length (TL) was significantly different between each sequential month, except from September to October 2009, increasing from July to October before decreasing from April to July (Kruskal-Wallis, $p < 0.01$; $H = 1,415.6$, df = 7; Figure 4). Throughout the study, males were significantly larger (male 93.0 ± 0.2

mm SE, female 85.0 ± 0.2 mm SE, Mann-Whitney *U* test: $p < 0.01$) and comprised a greater portion of the catch (62%) than females (33%). Small, sexually indeterminate fish were captured throughout the sampling period, but did not significantly differ in median length between sequential months. This was likely due to sexual maturation accompanying growth as nine of the ten round gobies which were sexually indeterminate when tagged showed sexual maturation when subsequently captured.

Tag Return

A total of 1,228 round gobies (July 2009: n = 773, April 2010: n = 455) were marked and released during the study (Table 1). Forty one percent of the 2009 fish and 22 % of the 2010 fish were recaptured at least once. Fourteen percent (n = 111) of the round gobies marked in July 2009 were captured in the following year. Of those, 36 fish (4.7 %) were not initially recaptured until 2010, including one individual first recaptured 364 days after tagging. Over 50 % of round gobies tagged in 2009 greater than 80 mm (TL) were recaptured at least once during the course of the study (Table 1). Many round gobies were recaptured on multiple occasions with fish marked in 2009 recaptured a mean of 3.6 (± SE 0.2) times, including one individual captured 23 times over the 13 month period (Figure 5). Only twelve round gobies were recaptured (mean time since marking ~ 7 weeks) with dorsal fin clips that lacked tags, indicating tag loss was less than one percent.

ROUND GOBY MOVEMENT

Round gobies displayed high site affinity and did not exhibit directional trends in movement within the Duluth-Superior Harbor (Mann-Whitney *U* test: $p > 0.05$, Figure 6). Male and female round gobies exhibited highly leptokurtic movement distributions, accounting for the consistent departure from normal distribution (Anderson-Darling Test: $p < 0.01$). Eighty nine percent (88% males, 91% females) of recaptured round gobies showed no net movement between captures including 60 % of the males ($n = 12$ of 20) and 92 % of the females ($n = 12$ of 13) captured 12 months after marking (Figure 7). This pattern was maintained throughout the study period with no statistical difference in movement distributions between month for male (Kruskal-Wallis, $p > 0.05$; $H = 5.232$, df = 7) or female (Kruskal-Wallis, $p > 0.05$; $H = 12.326$, df = 7) round gobies (Figure 8) and despite the suspension of sampling for five months because of ice, 29 (male $n = 20$ of 21, female $n = 9$ of 10) of the 31 individuals captured during the last sampling period in October were found in the same location the following April.

A large portion of recaptured round gobies exhibited little or no net movement between captures leading to an average movement of only 0.79 (± SE 0.18) meters per day. The eleven percent of this population that showed a net movement was recaptured an average of 68.2 (± SE 8.77) meters from their previous location, moving at 4.0 (± SE 0.85) m d^{-1} with a maximum rate of dispersal of 50 m d^{-1} by a male and 25 m d^{-1} by a female. The greatest net movement observed was 475 m (69 days between capture, 6.88 m d^{-1}) by a male and 225 m (15 days, 15 m d^{-1}) by a female (Figure 6) yet the median distance moved did not differ significantly between genders (Mann-Whitney *U* test: $p > 0.05$). Twelve percent of the male (10 of 84) and 35 % of the female (9 of 26) round gobies that exhibited net movement subsequently returned to their initial location and only three individuals (all males) were observed to continue moving further away from their tagging site (Table 2). The size of fish was not correlated with the distance moved for either gender (Male $r^2 = 0.002$, n = 107; Female $r^2 = 0.012$, $n = 37$; Figure 9).

Reciprocal Transplant

Five round gobies (10.6 %; $n = 4$ male, $n = 1$ female) were recaptured at least once from the 47 fish relocated 100 meters from their capture point. Two showed no net movement but three moved toward their initial capture site including the female, which returned to its original site 43 days after transplantation.

Discussion

The results show round gobies living among rocky substrate in the Duluth-Superior Harbor have high site fidelity and the majority display little net movement. This is the first study to tag and follow a large number of round gobies for an extended time period and presents new insight on the natural history of this species.

Efficacy of VI Alpha Tags and Minnow Traps

The combination of implanted tags and minnow traps was an effective method to monitor the round goby population and its movement throughout the ice free months.

Minnow traps were efficient at capturing round gobies from 38 to 152 mm (TL) and as up to 78 round gobies were caught in a single trap, it is unlikely that occupants impeded further entrance. Previous work using minnow traps upstream in the St. Louis River captured numerous species of native fishes (Lynch unpublished); thus the high percentage (> 98%) of round gobies captured in the Duluth-Superior Harbor was indicative of their local dominance and not sampling bias. VI Alpha tag retention and return was high, as less than 1% of fin-clipped fish displayed tag loss and 41 % of the round gobies marked in July 2009 were recaptured. A laboratory pilot study showed no difference in mortality between tagged and control fish, and field recaptures were readily visible 12 months after implantation with no sign of infection or necrosis at the implant site.

ROUND GOBY SEX RATIO AND LENGTH

A thirteen month sampling period allowed the observation of monthly changes in the Duluth-Superior Harbor nearshore round goby population. During this time, the male to female sex ratio remained constant at approximately 2:1 while median length increased from July to October before decreasing from April to July.

Round gobies spawn multiple times from mid-May through July (MacInnis and Corkum 2000b) and the decrease in median size of male round gobies from spring to mid-summer may be the result of large individuals returning to establish nesting territories after ice out and subsequently becoming less vulnerable to trapping once guarding nests. Although an initial gender bias was expected concurrent with this inshore migration, the later months were expected to be dominated by females. Males of other nest-guarding species in the Batrachoididae family are difficult to trap once they have established nesting territories (Allen Mensinger personal observation) and previous reports indicated male round gobies cease feeding while guarding nests (Miller 1986). Additionally, unlike Batrachoididae fishes, female round gobies will spawn multiple times throughout the spring and summer and the hypothesis was they would be actively moving between spawning bouts and therefore make up a larger portion of the catch. It remains unclear why the round goby sex ratio did not change during the reproductive season and highlights the lack of information on the behavior of females during this time. Using bottom trawls, Bergstrom et al. (2008) found round goby populations in sandy portions of the Duluth Superior Harbor to be female dominated, indicating females may reside in this habitat between spawning bouts. This conclusion was contradicted, however, by the consistent capture of marked females at the same sampling station throughout the study.

While little quantitative data is available on the fate of adult round gobies after the spawn, MacInnis and Corkum (2000a) found only a few female and no male round gobies greater than age two in the Detroit River indicting a short life expectancy. Although it was rare to find dead round gobies, presumably due to both their sinking and high piscivorous and avian foraging, the lack of large round gobies in the catch after the spawning season could result from post-spawn mortality. Miller (1986) indicates high mortality of males in the Black Sea as a result of not feeding while nest guarding. The presence of males displaying characteristic nest guarding coloration in the traps during the spawning season, however, indicates these individuals leave the nest periodically for brief foraging bouts. Also, contrary to the emaciated appearance of other nest guarding species like the toadfish and midshipmen during the reproductive season (Allen Mensinger personal observation), most male round gobies captured during this time appeared in good health.

Winter Habitat Use

Trapping was suspended in mid-October as surface ice prevented trap deployment until spring. The shallow habitat combined with shifting ice precluded the use of alternative sampling gear, and by mid-winter, ice thickness equaled sampling depth. During this period round gobies presumably retreated to deeper water as the sampling area became uninhabitable due to the interstitial spaces freezing solid. This migration would be consistent with behavior reported in the Black Sea (Miller 1986), Lake Erie tributary streams (Pennuto et al. 2010), and the Baltic Sea's Gulf of Gdnask (Sapota and Skóra 2005). The initial sampling in March 2010 following ice out supported this conclusion as only 0.12 fish per trap were captured compared to the 6.23 fish per trap during similar water temperature in October 2009.

Round Goby Movement

Eighty nine percent of recaptured round gobies displayed no net movement between captures. This large portion of the population showing no net movement coupled with occasional dispersals ≥ 25 meters, was consistent throughout the study and led to a leptokurtic two-tailed distribution providing strong evidence for high site affinity and small home ranges.

Both genders showed this leptokurtic distribution, and despite contrasting reproductive behaviors no significant difference was observed between median male and female movement distance. Ray and Corkum (2001) observed round gobies occupying 5 m^2 home ranges in mid-summer and the goal of our study was to examine movement at a greater scale than this previously reported home range. Therefore, the 25 meter trap spacing may have been too coarse to determine the difference in home range between male and female round gobies. Yet, due to the high percentage of both genders remaining in the original capture location, both appear to have home ranges less than the 25 meter trap interval, providing support for small home ranges independent of gender or sampling month.

No consistent relationship was observed between round goby length and distance moved for either gender despite the predicted displacement of small round gobies by aggressive nest-guarding males (Charlebois et al. 1997). Breen et al. (2009) noted the absence of size-specific movement in the anatomically similar mottled sculpin (*Cottus bairdi*) and hypothesized the lack of a strong relationship was an artifact of their inability to mark sculpin < 55 mm (TL) with passive integrated transponder tags. The VI Alpha tag was effective only on round gobies > 50 mm (TL) and may have limited the ability to observe a size-specific relationship, however the range of marked fish (50 to 130 mm, TL) should have represented nest-guarding and non-nest-guarding individuals.

The relationship between length and movement in round gobies may be further confounded by the discovery of an alternative parasitic or 'sneaker' male morph (Marentette et al. 2009). The difference in reproductive behavior between these two morphs may contribute to the lack of a relationship between length and movement as their home ranges may be greatly different. Further work on the behavioral differences between these morphs is necessary to determine the role they play in the population.

The majority of the round goby population did not move more than 25 m; still, a small percentage of the population did exhibit limited movement with net displacement up to 350 meters in a week (50 m d^{-1}). Mechanisms which cause a few fish to move, while most remain within a small home range are unclear, but show adult round gobies are capable of limited dispersal. Highly leptokurtic movement distributions have been observed in similar sized North American benthic species including the mottled sculpin (*Cottus bairdi*) (Petty and Grossman 2004, Breen et al. 2009), Potomac sculpin (*Cottus girardi*) (Hudy and Shiflet 2009), and the Roanoke logperch (*Percina rex*) (Roberts et al. 2008). The biological significance of these leptokurtic movement distributions has been the focus of several review and modeling papers which propose the observed pattern can result from sampling design (Gowan et al. 1994, Rodriguez 2002), consistent behavioral variation among relatively 'static' and 'mobile' subpopulations (Skalski and Gilliam 2000), or temporal variation in the movement behavior of the same individual (Petty and Grossman 2004). Round gobies observed moving ≥ 25 m showed a tendency to stay in their new location and many returned to their initial capture site. Based on this lack of consistent movement coupled with the absence of intrapopulation variation, the impetus to move may be related to seeking new home territories as a result of habitat saturation.

In an area of high round goby density four kilometers from the marking study site, a pilot study was conducted to determine the effect of removing round gobies from a population. In this study, consistent capture rates (~ 7 gobies $trap^{-1}$) were observed from May to October despite the weekly removal of all round gobies captured (Lynch unpublished). This indicates round gobies may readily colonize vacated habitats but are typically sedentary when density is relatively constant across the optimal habitat. No round gobies were removed from the sampling area used in the marking study to emulate natural round goby densities of the Duluth-Superior Harbor, but movement would be predictably different at altered densities and future studies should investigate the effect of artificially increasing and decreasing densities.

Daina et al. (2006) showed baited minnow traps to be a more effective method for capturing round gobies in rocky substrate than trotlines or hook-and-line fishing. Weekly baiting, however, may have reduced natural migration and resulted in unnaturally high site affinity. To minimize this influence, sampling intervals were extended to two weeks in the latter half of the study. Also, if the baited traps were the primary reason for site affinity, individual fish should have been recaptured at every sampling date, yet, no fish were captured in all sampling weeks and capture intervals were highly variable with less than seven percent of recaptured individuals caught in more than five sampling weeks. Additionally, despite 24 weeks between sampling (and baiting), 29 of 31 fish were captured in the same location in mid-October 2009 and early April 2010. Therefore, it appears that other biological or environmental factors were mitigating site selection.

This study was designed to monitor a 550 meter stretch of shoreline at 25 m intervals. Movement outside the area, while possible, was tempered by a large expanse of suboptimal habitat immediately offshore characterized by a sandy bottom and large patches of American wild celery (*Vallisneria americana*). In August 2010, 40, five minute (5.5 m head-rope, 2.5 cm stretch-mesh body, 6.4 mm stretch-mesh cod end) bottom trawls were conducted by the United States Fish and Wildlife Service (Ashland, WI) in conjunction with the 1854 Treaty Authority (Duluth, MN) within the Duluth-Superior Harbor and Saint Louis River Estuary ranging from 30 m to 24 km from our study site (For complete methodology see Bergstrom et al. 2008). None of the round gobies (n = 1,339) captured in these trawls, including the area 30 m offshore from the sampling site, contained tags. Based on the small mean size (67.1 ± SE 1.9 mm, n = 90), absence of round gobies > 90 mm (TL), and lack of tagged fish, it appears the area immediately offshore was utilized differently by adult round gobies and was unlikely to have been a large sink for tagged fish.

Our data showing round gobies (> 50 mm) inhabit a small home range, with only rare movement outside this area, is not consistent with the rapid expansion of round gobies throughout the Laurentian Great Lakes watershed. Growing evidence in the literature points to 7-8 mm juvenile round gobies as a likely vector for range expansion (Hensler and Jude 2007, Hayden and Miner 2009). These fish search for food by vertically migrating in the water column and may be carried over great distances by water currents or ballast/bilge water, yet the movement of these 7-8 mm fish is predicated on suspension in currents and cannot explain recent range expansion up rivers and tributary streams (Phillips et al. 2003, Krakowiak and Pennuto 2008, Kornis and Vander Zanden 2010).

Although our study site was selected to minimize the effect of current, tag returns showed adult round gobies capable of moving up to 50 meters per day in a lentic system. The movement of these extreme individuals indicates this life stage could facilitate population dispersal. Yet, this behavior was rare and there is little evidence round gobies are able to sustain even modest long term swimming rates (Hoover et al. 2003). Therefore, the 0.7 km per year expansion of round gobies in the Duluth-Superior Harbor and Saint Louis River Estuary (Bergstrom et al. 2008) is likely representative of natural adult round goby range expansion. Kornis and Vander Zanden (2010) recently identified round gobies in 26 of 73 Lake Michigan streams including a population 34 km up the Pensaukee River. This observation and our identification of a reproductive population 36 km upstream from Lake Superior in the Saint Louis River, suggest that anthropogenic forces may be behind these extensive upstream colonization events.

The round goby's ability to utilize a combination of natural and anthropomorphic vectors has led to its rapid range expansion in both Europe and North America (Steingraeber and Thiel 2000, Sapota and Skóra 2005, Wiesner 2005). The primary objective of this study was to quantify the overall and intrapopulation variation in the movement of round gobies greater than 50 mm in the Duluth-Superior Harbor. Although eradication of round gobies may be impractical, increased information on life history characteristics will assist mangers in understanding the role this non-native species plays in the environment and may guide future control strategies in more manageable locations such as streams and small lakes. Our results show adult round gobies exhibit little net movement, yet the movements of rare individuals, provide evidence that natural dispersal by this life stage may aid in the rapid expansion of round goby populations in the Laurentian Great Lakes. Further study is necessary to determine the degree to which round goby dispersal is mediated by 7-8 mm juvenile fish and stream based studies to determine mechanisms of population expansion against water currents.

ACKNOWLEDGMENTS

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TABLES

Table 1. The number of round gobies tagged in July 2009 and April 2010 and the percentage of each recaptured at least once before August 2010. Fish were binned into 20 mm intervals based on total length at tagging and grouped by male (M), female (F), and indeterminate (I) gender. All round gobies captured > 80 mm were sexually determinate.

	≤ 59			60-79			80-99		100-119		≥ 120		Sum
	M	F	I	M	F	I	M	F	M	F	M	F	
Marked July 2009	48	26	25	263	154	11	149	56	22	17	2		773
Recaptured	7	6	8	95	53	2	90	29	13	12	1		316
%	14.6	23.1	32.0	36.1	34.4	18.2	60.4	51.8	59.1	70.6	50.0		40.9
Marked April 2010	1		1	16	28	1	100	117	141	18	30	2	455
Recaptured	1		0	1	3	0	29	18	33	6	7	1	99
%	100			6.3	10.7		29.0	15.4	23.4	33.3	23.3	50.0	21.8

Table 2. Number of round gobies observed moving greater than 25 meters and their subsequent behavior.

	Number Moved ≥ 25 m	Not Recaptured	No Further Movement	Returned to Original Site	Moved Partially Back	Continued Moving
Male	84	49	18	10	4	3
Female	26	13	4	9	0	0

FIGURE CAPTIONS

Figure 1. Study area on Rice's Point (46°45'12"N; 92°06'27"W) in the Duluth-Superior Harbor (insert). Trapping stations (A to W) were located 25 meters apart in 0.5 to 1.5 m of water. Round gobies were marked at the middle 19 trapping stations (circles and squares) while the stations at each end (triangles) were used only as recapture stations. In May 2010 round gobies were reciprocally transplanted between stations G and K (squares). Lines indicate water depth contours of 2 meters.

Figure 2. Round goby with Visible Implant Alphanumeric Tag (VI Alpha).

Figure 3. The number of round gobies captured (left axis) is plotted against time of year and water temperature (right axis) in the Duluth-Superior Harbor. Each bar represents the total number of round gobies captured in 46 baited minnow traps on two consecutive days and is subdivided into male (black), female (open) and indeterminate (grey) gender. The shaded rectangle represents the period when sampling was suspended due to surface ice.

Figure 4. Monthly length frequency distribution of round gobies captured in the Duluth-Superior Harbor between July 2009 and July 2010. Data were binned in 5 mm increments and subdivided into male (black), female (open) and indeterminate (grey).

Figure 5. Recapture frequency of the round gobies caught from the July of 2009 marking (n = 415). Includes fish captured twice in one sampling week.

Figure 6. Relative frequency distribution of net distances moved (25 m interval, maximum observable movement of 500 m) by male (solid) and female (open) round gobies between successive captures in the Duluth-Superior Harbor independent of sampling date or capture interval. Easterly and westerly movements are arbitrarily coded as positive and negative, respectively.

Figure 7. Frequency distribution of net absolute distance moved by male (n = 20, solid bars) and female (n = 13, open bars) round gobies captured 12 months after marking in the Duluth-Superior Harbor.

Figure 8. Relative frequency distribution of net distances moved (25 m interval, maximum observable movement of 500 m) by male (solid) and female (open) round gobies between successive captures within the same month. Easterly and westerly movements are arbitrarily coded as positive and negative, respectively.

Figure 9. Relationship between net displacement distance and total length (mm) for male (r^2 = 0.0017, n = 107) and female (r^2 = 0.012, n = 37) round gobies moving ≥ 25 m in the Duluth-Superior Harbor independent of capture interval.

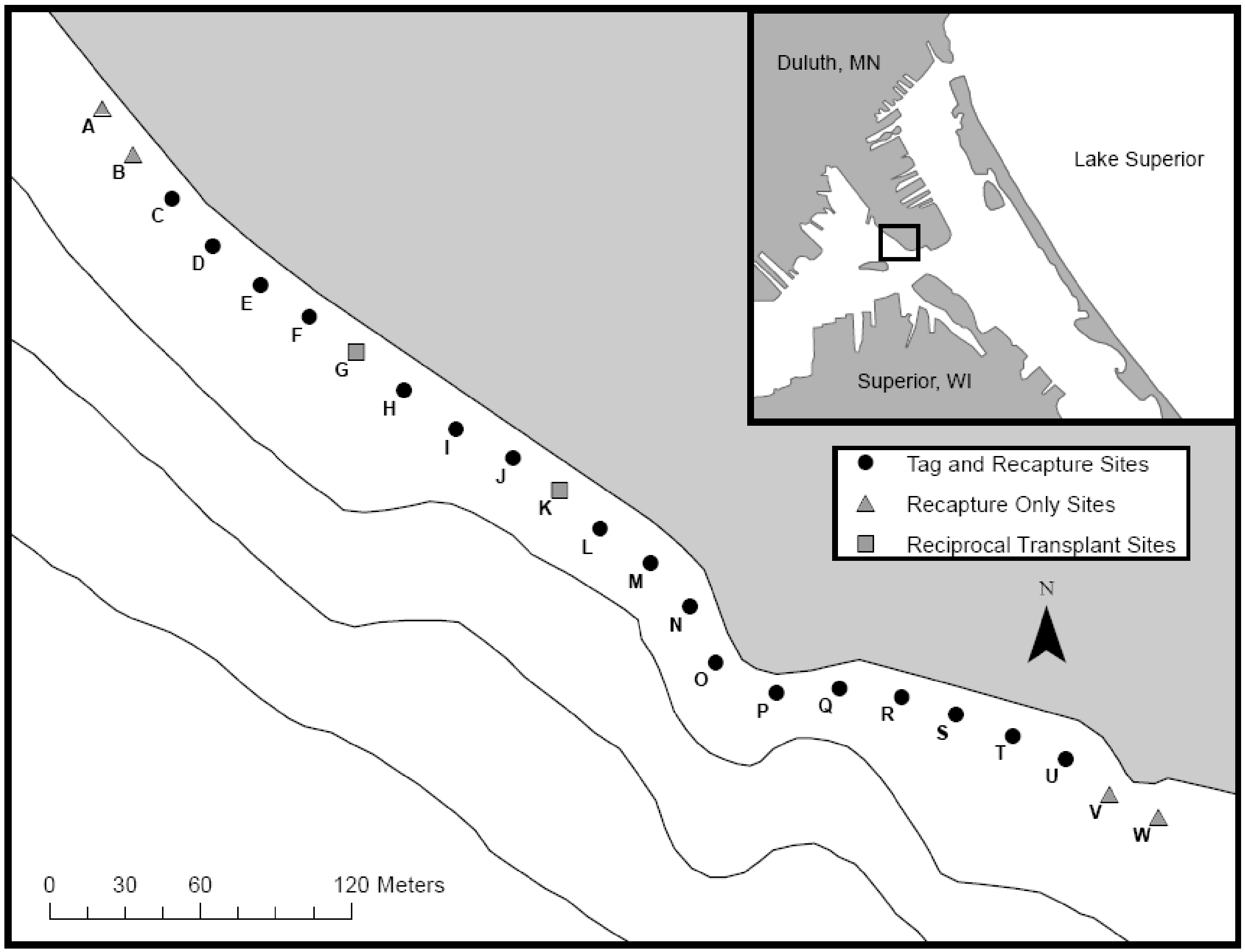

Duluth, MN
Lake Superior
Superior, WI
Tag and Recapture Sites
Recapture Only Sites
Reciprocal Transplant Sites
N
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
0 30 60 120 Meters

Figure 1.

Figure 2.

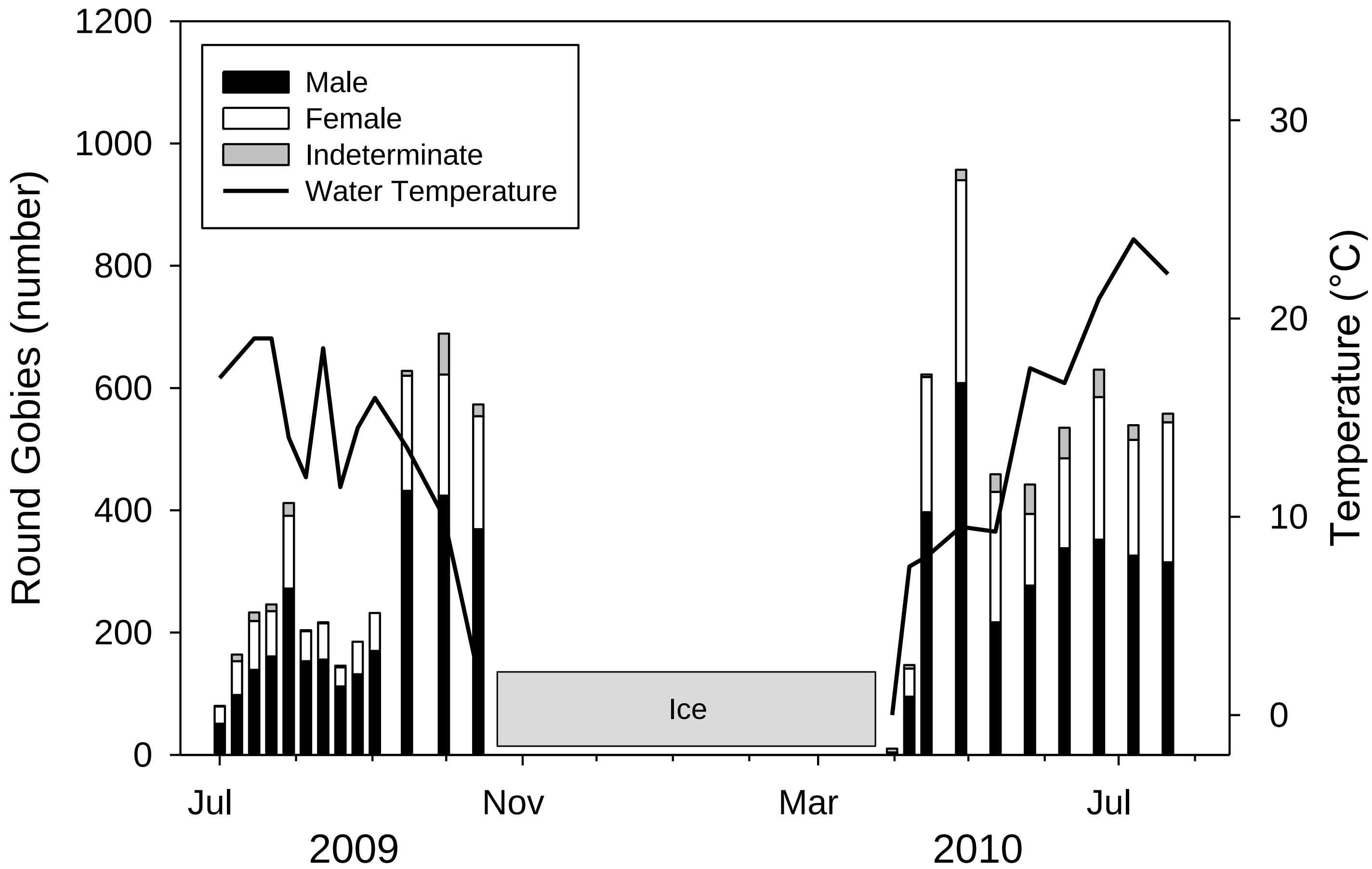

Male
Female
Indeterminate
Water Temperature
Ice
Round Gobies (number)
Temperature (°C)
1200
1000
800
600
400
200
0
30
20
10
0
Jul
Nov
Mar
Jul
2009
2010

Figure 3.

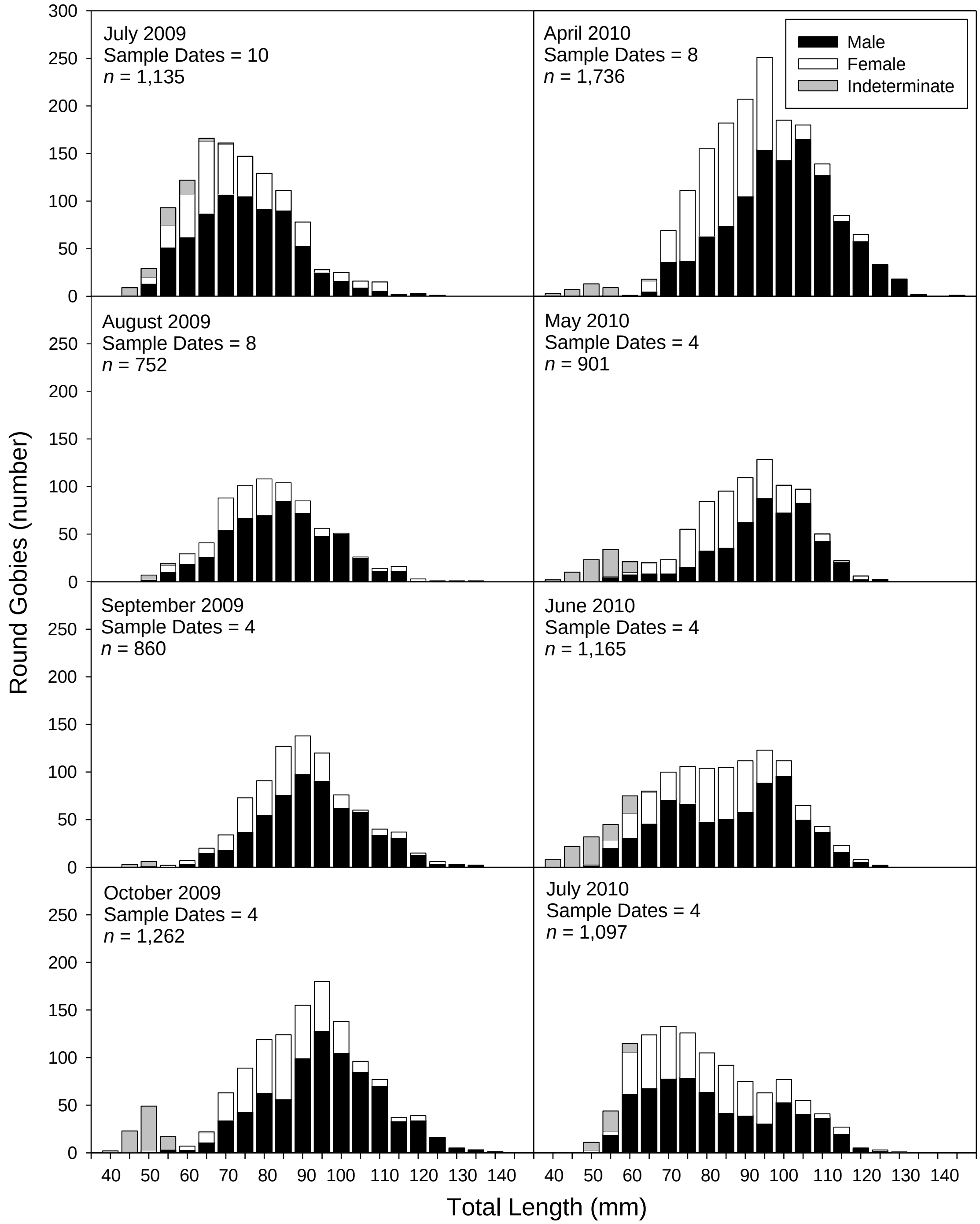

July 2009
Sample Dates = 10
n = 1,135
April 2010
Sample Dates = 8
n = 1,736
Male
Female
Indeterminate
August 2009
Sample Dates = 8
n = 752
May 2010
Sample Dates = 4
n = 901
September 2009
Sample Dates = 4
n = 860
June 2010
Sample Dates = 4
n = 1,165
October 2009
Sample Dates = 4
n = 1,262
July 2010
Sample Dates = 4
n = 1,097
Round Gobies (number)
Total Length (mm)
0
50
100
150
200
250
300
40
50
60
70
80
90
100
110
120
130
140

Figure 4.

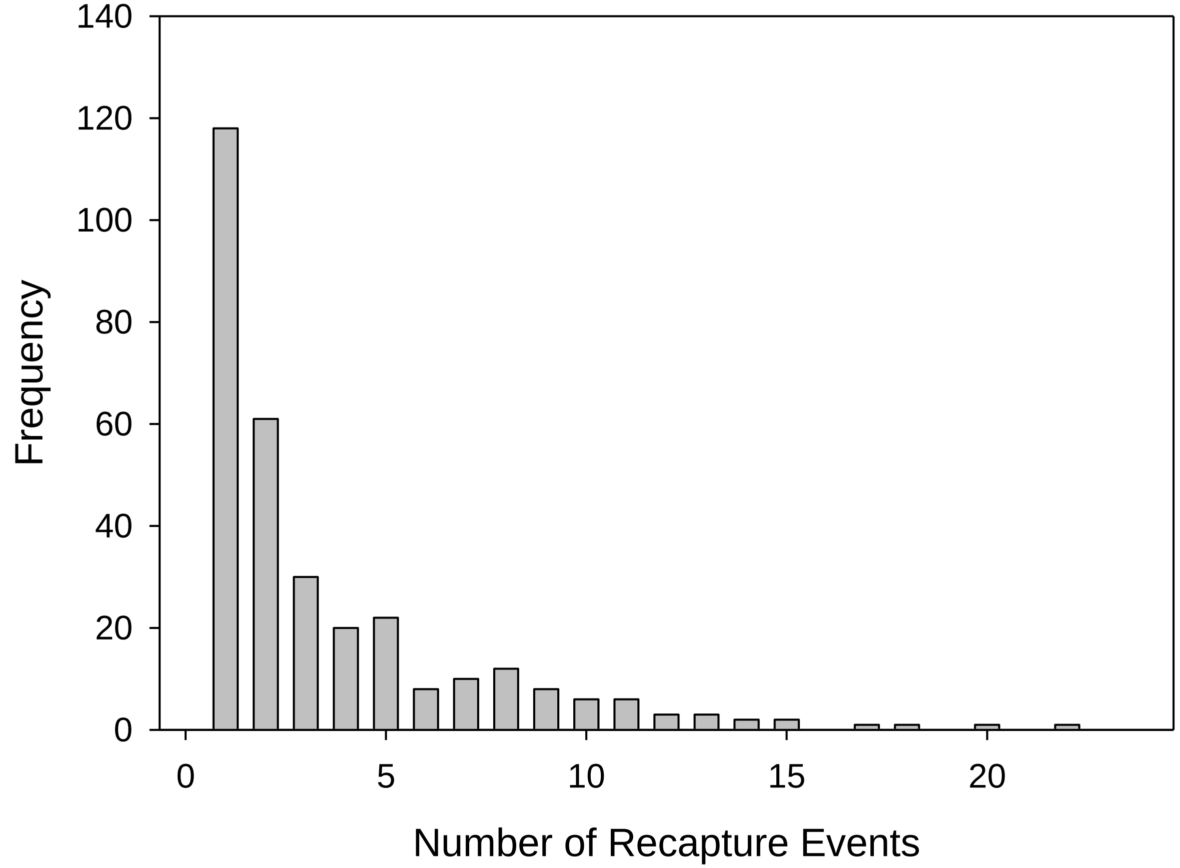

140
120
100
80
60
40
20
0
Frequency
0
5
10
15
20
Number of Recapture Events

Figure 5.

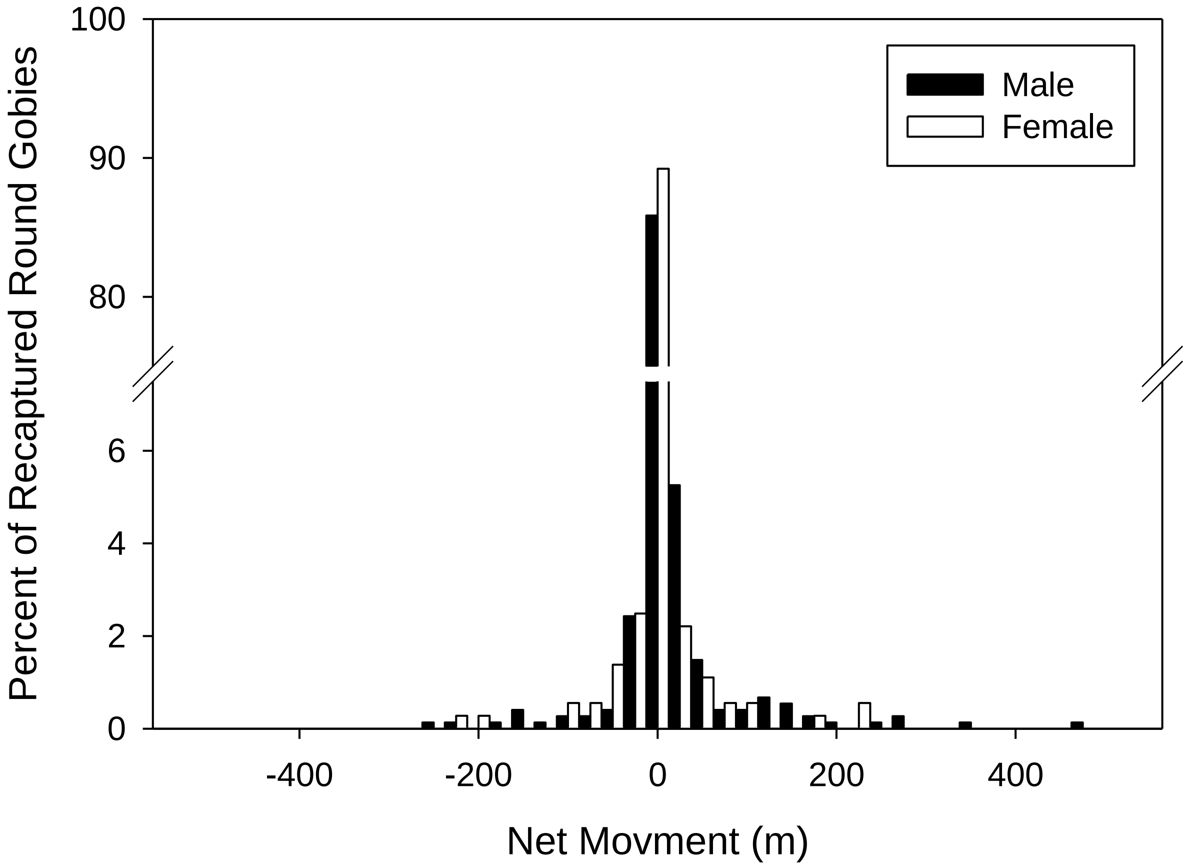
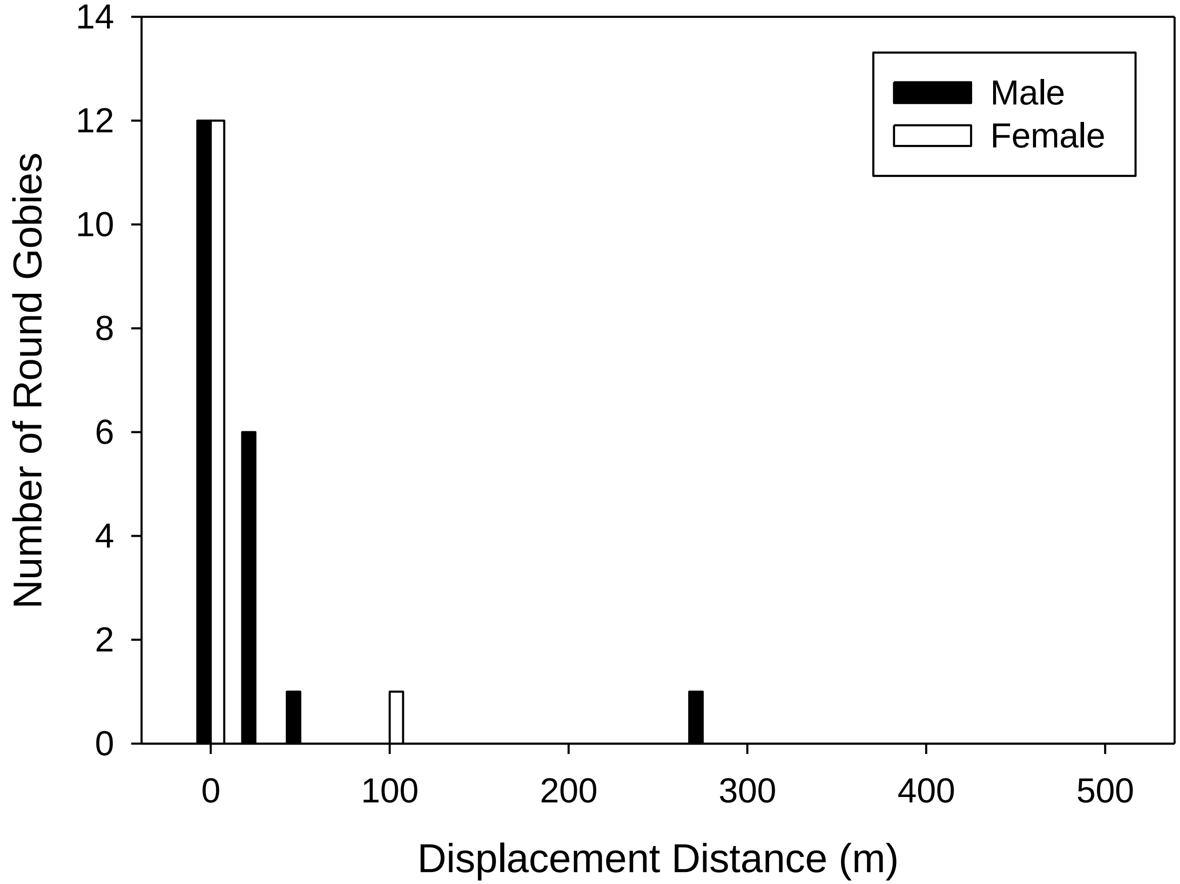
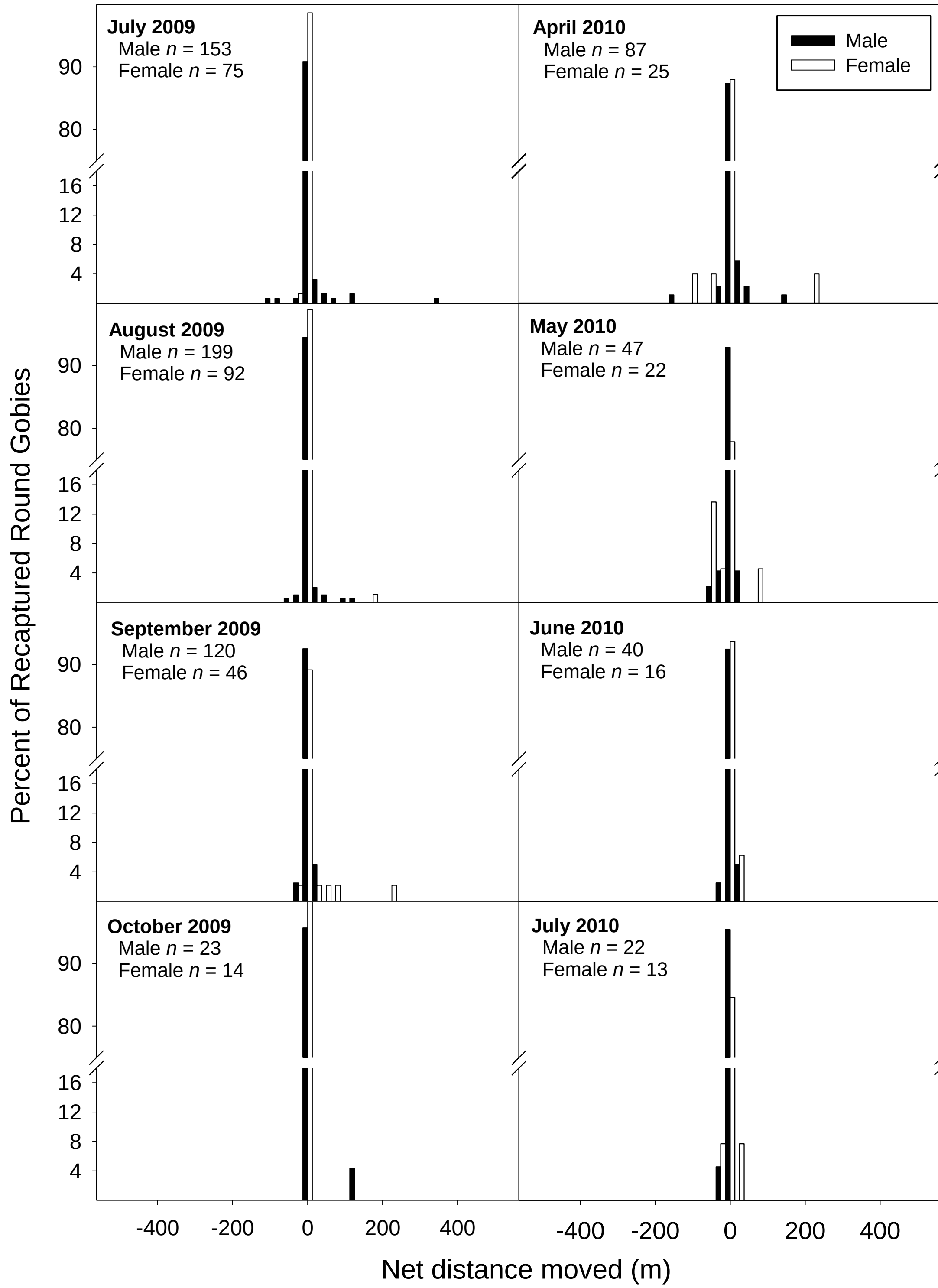

Percent of Recaptured Round Gobies
100
90
80
6
4
2
0
Male
Female
-400
-200
0
200
400
Net Movment (m)

Figure 6.



Number of Round Gobies
14
12
10
8
6
4
2
0
0
100
200
300
400
500
Displacement Distance (m)
Male
Female

Figure 7.



July 2009
Male n = 153
Female n = 75
April 2010
Male n = 87
Female n = 25
Male
Female
August 2009
Male n = 199
Female n = 92
May 2010
Male n = 47
Female n = 22
September 2009
Male n = 120
Female n = 46
June 2010
Male n = 40
Female n = 16
October 2009
Male n = 23
Female n = 14
July 2010
Male n = 22
Female n = 13
Percent of Recaptured Round Gobies
90
80
16
12
8
4
-400
-200
0
200
400
Net distance moved (m)

Figure 8.

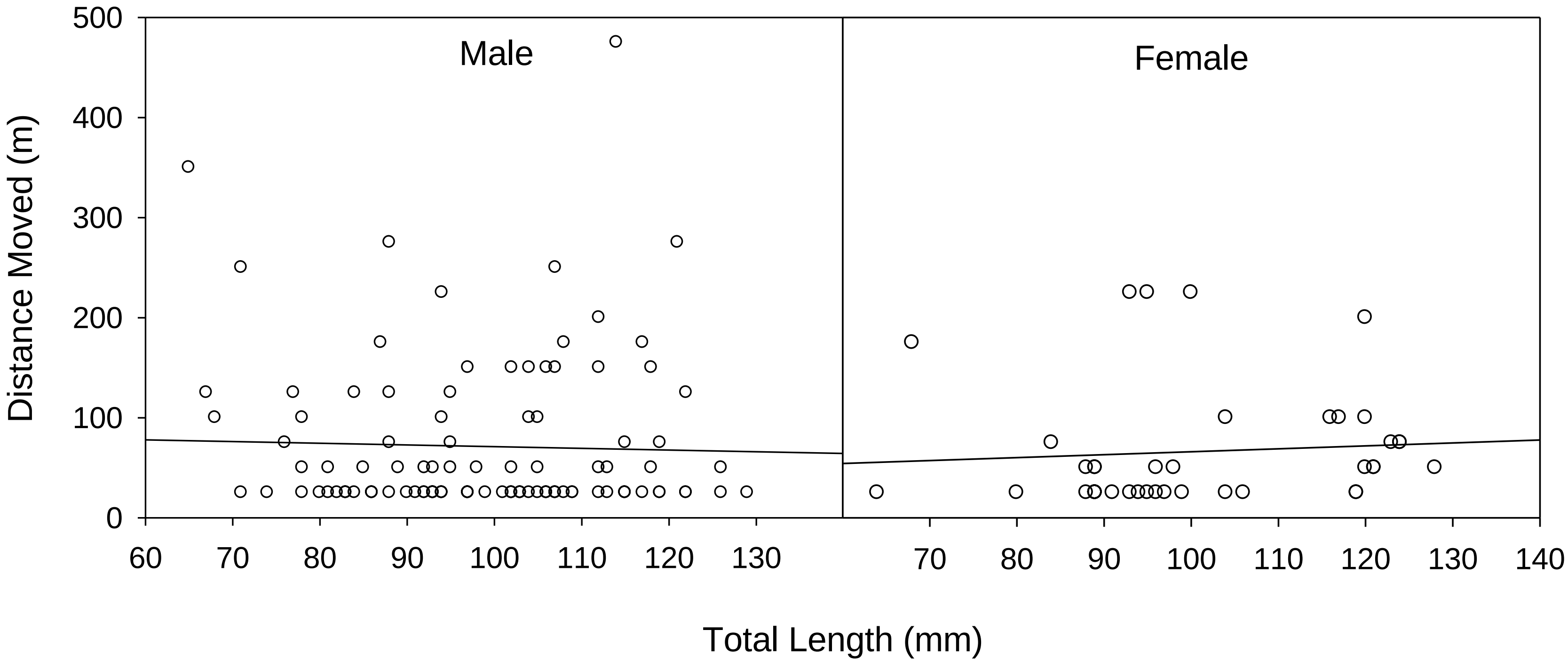

Male
Female
Distance Moved (m)
0
100
200
300
400
500
60
70
80
90
100
110
120
130
70
80
90
100
110
120
130
140
Total Length (mm)

Figure 9.

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