Research Article

Minnow trap styles and baiting strategies on round goby (*Neogobius melanostomus*) capture rates: Lessons from a complex invasion front

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Abstract

The round goby (*Neogobius melanostomus*) invaded the Great Lakes in the 1990s and the species continued expansion into inland bodies of water, raising basin wide concerns for negative ecological impacts. The Lower Fox River (LFR), Wisconsin, USA, is the state's largest tributary linking the Great Lakes to inland Lake Winnebago through a fragmented waterway of eight lock and dam structures across 62.0 river kilometers (RKm). Round goby were detected in the LFR lower river reaches, in the early 2000's below an invasive species barrier (completely sealed structure) located near the midpoint of the LFR (RKm 31.5), but in 2015, the species was observed above the barrier raising concerns for upstream invasion. This discovery prompted the closure of the upper most navigational lock system (Menasha Lock, RKm 62.0) separating the outflow of Lake Winnebago to the LFR. The goal of this study was to assess the distribution and abundance of round goby throughout the entire LFR in 2019–2021 using baited minnow traps. We further evaluate differences in capture rates between combinations of minnow trap styles, bait types, and bait quantities. A total of 1,007 round goby were captured during monitoring surveys throughout the LFR (2019–2021), confirming presence in all river segments with maximum upstream extent reaching Menasha Lock. Highest densities of round goby are found below the invasive species barrier (RKm 31.5), but males and females are present at the current maximum upstream distribution. An additional 834 round goby were captured during the comparison of trapping strategies and suggest round-style minnow traps baited with food (i.e., dog food or hotdog) are successful in capturing round goby and outperform other trap/bait types. Continued monitoring would help describe trends in abundance and adaptive sampling approaches will improve detection.

Key words: invasive species, abundance, trapping and distribution

Introduction

Non-native and invasive species are among the largest threats to natural ecosystems and the ecosystem services they provide (Wilcove et al. 1998). Invasive species have a wide range of physiological tolerances, high reproductive potential, and generalist life history that put them at an advantage to establish and spread (Marchetti et al. 2004). Invasive species outcompete native fauna leading to extirpation, loss of biodiversity, and impaired ecosystem services (Pimentel et al. 2000; Rahel 2002), especially within aquatic ecosystems that are highly connected and have high levels of anthropogenic activity (Harris et al. 2018). The Laurentian Great Lakes, USA and Canada, hosts over 180 non-native species (Sturtevant et al. 2019; Vander Zanden et al. 2010), where highly connected canals, waterways, and tributaries that host large urban centers and heavily trafficked ports, act as high-risk locations for aquatic invasions and vectors between Great Lakes ecosystems and inland waterbodies (Harris et al. 2018; Tucker et al. 2020). Early detection and monitoring are vital to mitigate the risk of invasive species spread to novel ecosystems (Harris et al. 2018).

The round goby (*Neogobius melanostomus*), native to the Black and Caspian Seas, is now a well-established, invasive species in the Great Lakes (Adrian-Kalchhauser and Burkhardt-Holm 2016; Kornis et al. 2012). Round goby were first documented within the Great Lakes basin in the St. Clair River near Detroit, Michigan (outflow of Lake Huron) in 1990 (Jude et al. 1992). The range of round goby has rapidly expanded into Lake Michigan (Clapp et al. 2001), including invasions into the coastal wetlands and slow-moving lotic tributaries located along the shorelines of Lake Michigan (Kornis et al. 2012). The species prefers rocky habitats, exhibits high fecundity, rapid maturation, aggressive behavior, and batch spawning resulting in domination of aquatic resources and outcompeting native benthic fishes (MacInnis and Corkum 2000; Bergstrom et al. 2008). Life history traits of the round goby favor the continued expansion throughout the Great Lakes (MacInnis and Corkum 2000), and potentially to further inland bodies of water that may be more vulnerable to negative ecological impacts (Kornis et al. 2012).

The Lower Fox River (LFR), in Northeast Wisconsin, USA, is a large slow-moving fluvial tributary which flows into lower Green Bay, Lake Michigan. The LFR is the largest tributary flowing into Lake Michigan, originating from its headwaters of Lake Winnebago, and the Upper Fox and Upper Wolf Rivers. The LFR has a series of 8 lock and dam structures dispersed between the outflow of Lake Winnebago (RKm 62.0) and its confluence with lower Green Bay (RKm 0.0) and have been in use since the mid-19th century. In 1988, an invasive species barrier in the form of concrete and sealed steel gate, was installed indefinitely on the LFR (at Rapid Croche Dam, Site RC-B, see Figure 1), located approximately halfway (RKm 31.5) between Lake Winnebago and lower Green Bay. While this permanently sealed lock was originally motivated by the establishment of invasive sea lamprey (*Petrimyzon marinus*) in the Great Lakes, its continued use is reinforced by the presence of round goby throughout the Great Lakes, and to prevent the spread of additional invasive species from Lake Michigan upstream into Lake Winnebago.

A survey of Wisconsin tributaries to Lake Michigan for the presence of round goby was conducted in 2007, using backpack electrofishing and gee-style minnow traps, and the species was confirmed to be present in lower Green Bay and in the LFR ranging upstream to the invasive species barrier

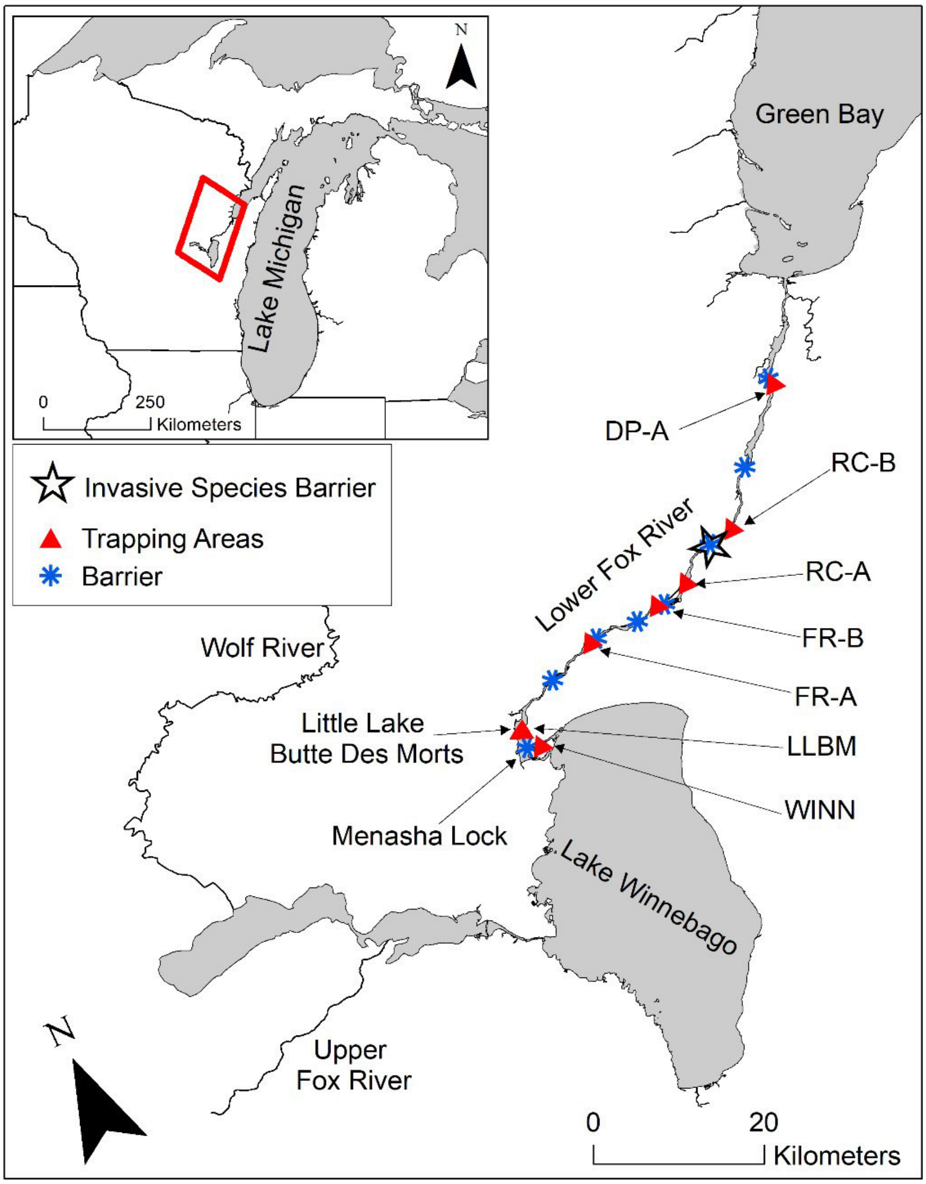

Figure 1. Regional map of Winnebago, Little Lake Butte Des Morts and round goby monitoring reaches throughout the Lower Fox River, Wisconsin, USA

at Rapid Croche Dam (Kornis and Vander Zanden 2010). In August 2015, a single round goby was reported by a recreational angler above the invasive species barrier and verified by the Wisconsin Department of Natural Resources (WDNR), in Little Lake Butte Des Morts (LLBM), below the last barrier (Menasha Lock, RKm 62.0) before entering Lake Winnebago. Confirmation of round goby within LLBM triggered a large-scale sampling response, led by WDNR that confirmed a population was present, prompting concerns that round goby would soon reach the Lake Winnebago watershed. In September of 2015, the WDNR worked with the Fox River Navigation System Authority (FRSNA) to close the Menasha Lock to all vessel traffic until further notice with the exception of limited commercial vessels that must coordinate with the WDNR to follow a decontamination plan to minimize risk of upstream passage during lock operations. Round goby continued to be detected in lower reaches of the LFR, below the invasive species barrier during 2016, using a combination of trapping, netting and seining techniques (De Stasio 2016). In 2017 the WDNR and the United States Geological Service (USGS) conducted environmental DNA (eDNA) sampling at four locations upstream of the final barrier and found no eDNA evidence for round goby presence (Wisconsin DNR report #3200-3900-2023-02). Since 2015, the WDNR has utilized several annual fisheries surveys conducted throughout Lake Winnebago (e.g., trawling, electrofishing, and fyke netting) and surveys conducted by the University of Wisconsin – Green Bay (this study) throughout the LFR, as a means to provide surveillance for round goby, as well as developed a public online reporting tool and public outreach campaigns which presently serve as a system wide round goby monitoring program (Wisconsin DNR report #3200-3900-2023-02). Extensive sampling targeting round goby on Lake Winnebago does not occur on a recurring basis, outside of this study, and sampling in the lower river, below the invasive species barrier, provides limited information to inform trends in abundance, distribution, and demographics throughout the system.

Several different methods can be employed for detecting and monitoring invasive species including eDNA and physical traps (George et al. 2021). Many studies have used a variety of active (e.g., angling, bottom trawls, seining, and electrofishing) and passive (e.g., gillnets and minnow traps) sampling methods for capturing and documenting round goby (Diana et al. 2006; Johnson et al. 2005; Brandner et al. 2013; Kornis and Vander Zanden 2010; Kornis et al. 2012); however, relative efficiency of gears utilized throughout the Great Lakes is widely debated and appropriate methodology should be determined by project objectives and system specific habitat features (i.e., water depth, clarity and substrate; Diana et al. 2006; Kornis et al. 2012; Robinson et al. 2019). Baited minnow traps have been used to successfully capture round goby (Diana et al. 2006; Kornis and Vander Zanden 2010; Kornis et al. 2017; Robinson et al. 2019), and is the gear currently used for monitoring throughout the LFR and Lake Winnebago (See also Wisconsin DNR report #3200-3900-2023-02) Although many studies have used minnow traps for collecting round goby, none have compared variations of minnow trap types amongst one another and comparisons between bait types or amount of bait used within each trap remain limited.

The overall goal of this study was to assess the current distribution and abundance of round goby throughout the entire Lower Fox River and within the waters of Lake Winnebago. The specific objectives were to 1) quantify the differences in capture rates of round goby between single funnel rectangular minnow traps (hereafter box-style) and double-funnel cylindrical minnow traps (hereafter round-style) and, 2) determine the influence of food concentration and bait types on capture rates. This baseline information is necessary to evaluate the previous methods of round goby detection strategies used in the LFR and Lake Winnebago (see

De Stasio 2016 and Kornis and Vander Zanden 2010), as well as propose improved methodology and monitoring protocols (De Stasio 2016) to maximize detection probability using low-cost gear. We hypothesize higher round goby catches will occur in round-style minnow traps and be positively influenced by the presence and quantity of bait within minnow traps.

Materials and methods

Round goby collection

Round goby were sampled in six river reaches within the LFR, and one site near the outflow of Lake Winnebago from June–September of 2019–2021, and Little Lake Butte Des Morts in 2021 (Figure 1). Sampling occurred in a systematic design beginning in Lake Winnebago moving downstream and three to six times annually. Eight to thirty-six, round-style minnow traps were deployed on near shore rocky habitats and baited with 100 g of dry dog food (Country Squire Premium Chunk Dog Food). Eight minnow traps were used in river reaches with known round goby presence, and trap number increased heavily (e.g., N = 36) in Lake Winnebago to maximize trapping effort in areas of unknown round goby presence. Traps were fished on bottom for 24 hours before being pulled and processed the following day (Diana et al. 2006). Round goby were counted and measured for total length (± 1 mm) during all years. Sex was recorded in 2021 and determined by visually examining dimorphic urogenital papilla (Supplementary material Figure S1), following descriptions by MacInnis and Corkum (2000), Marsden et al. (1996) and Charlebois et al. (1997).

Evaluation of trap type and bait on round goby catch

Combinations of minnow trap type and bait type/quantity, were compared during 2020 and 2021 within the river reach located just above De Pere Lock (Site DP-A, Figure 1). This location was selected as the study site due to the known high round goby abundance documented in previous surveys (De Stasio 2016; Kornis and Vander Zanden 2010). Three designated trapping areas (Blocks), were selected within the study area (Figure 2) based on the identification of habitats such as shallow, rocky shorelines which are reported as preferred by the round goby (Ray and Corkum 2001; Bauer et al. 2007).

During 2020, specific study goals were to address capture differences based on trap style (i.e., round-style vs. box-style) and bait quantity. To evaluate this, paired minnow traps, 1 round-style and 1 box-style (black in color), were baited with 50 g, 100 g or 200 g of dog food (Figure 3A) at three standardized locations ~ 75 m apart within each block and deployed biweekly June–September. Paired traps were tied to a single line 1 m apart and sank to the bottom with small weights. All traps were deployed within

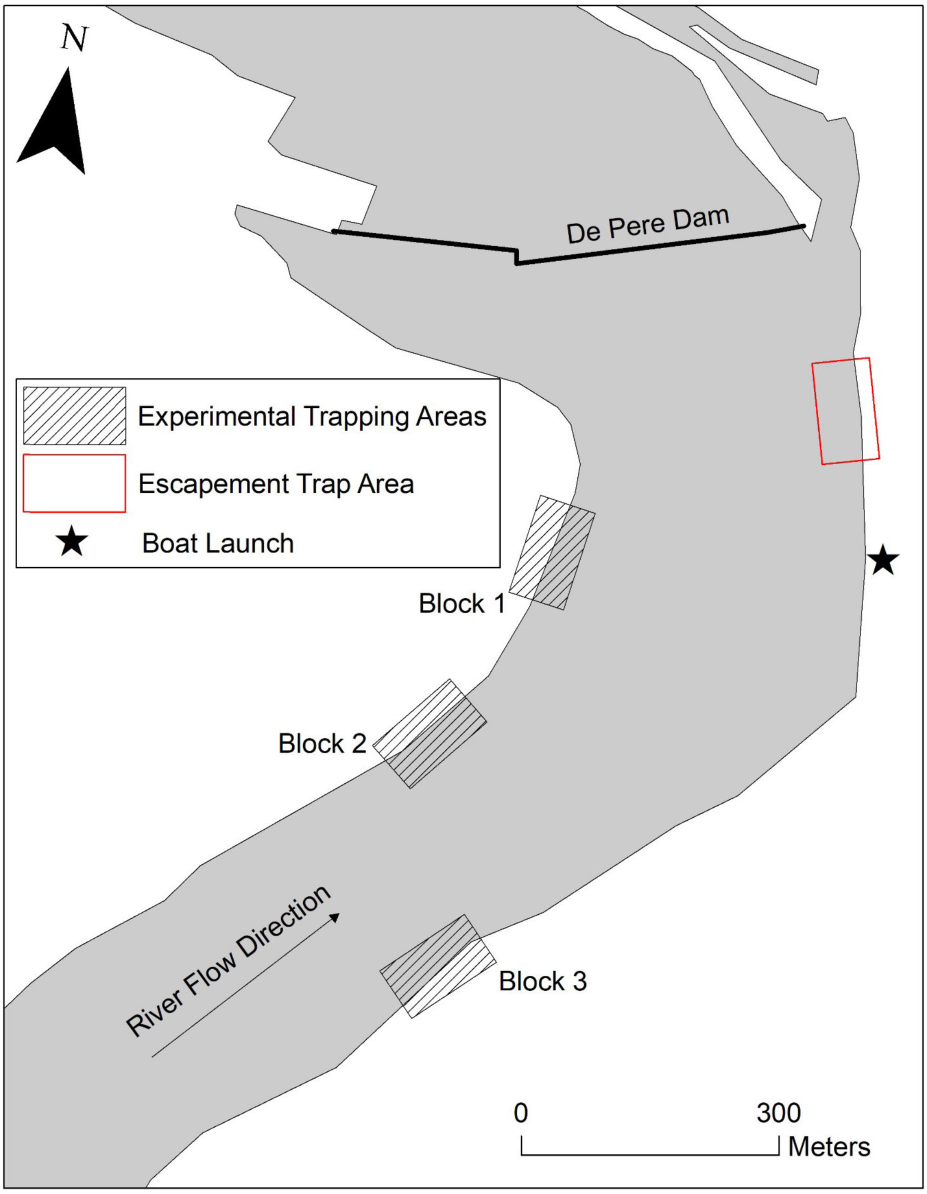

Figure 2. Round goby experimental trapping areas (blocks) and escapement trap area located in river reach site DP-A within the Lower Fox River, Wisconsin, USA

2 m from shore and fished overnight for 24 hours. In attempt to account for variations in round goby abundance and microhabitat features, each food treatment (paired box-style and round-style traps) was systematically rotated within each block to act as a replicate for each standardized location over the course of the study. Round goby catch was recorded according to our experimental design and individuals were measured for total length (± 1 mm).

In 2021, only round-style traps were used (see 2020 results) and baited with either, no bait (control), 200 g dog food, a single hotdog, or a live male round goby (Figure 3B). Traps were deployed biweekly July–August. Live male round goby used in this study were captured via angling off the boat launch prior to each sampling event. Male round goby were identified, measured for total length (± 1 mm), and marked with an anal fin clip prior to placement into traps. Selection of the largest males was attempted to be

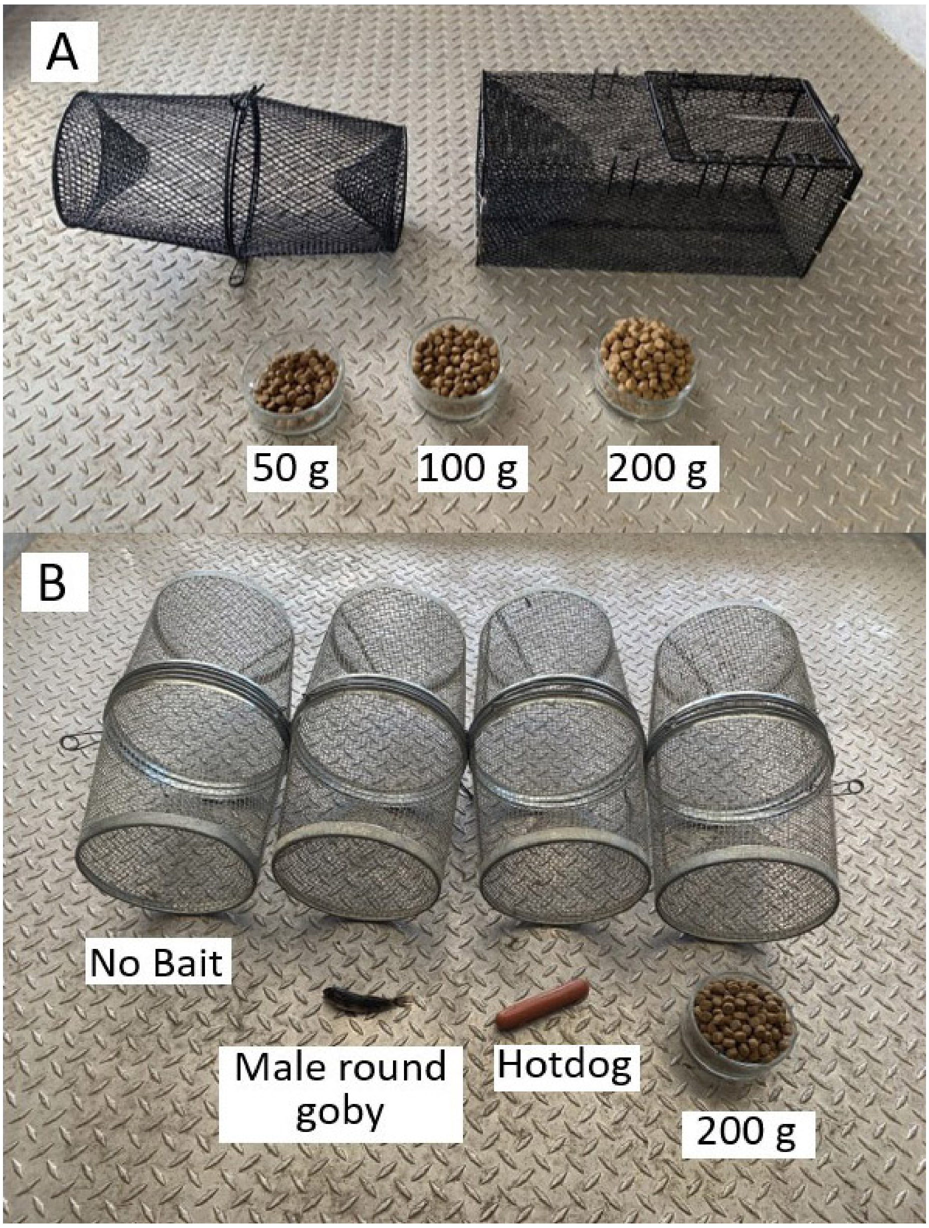

Figure 3. Experimental traps and bait types used for collections of round goby in 2020 (A) and 2021 (B). Round-style traps are 419.1 mm long x 228.6 mm diameter, with two 25.4 mm cylindrical-funnel entry points, and 6.35 mm square wire mesh. Box-style traps are 457.2 mm long × 203.2 mm wide and 203.2 mm tall, with a single 50.8 mm pyramidal-funnel entry point, and 6.35 mm × 12.7 mm diamond wire mesh.

used in this portion of the study (mean = 106 mm, range = 88–130 mm), under the assumption that largest individuals would showcase pronounced behavioral qualities (e.g., attraction or aggression). Trap treatments were deployed at the three standardized locations within each block and fished for 24 hours.

Additionally, it was suspected that escapement was a factor in round goby capture and retention rates among round (2–25.4 mm entry points) and box (1–50.8 mm entry point) style traps. To investigate this further, escapement trials were conducted in 2021 where 4 round-style and 4 box-style minnow traps were each populated with five, live, round goby (see Figure S2) and deployed, un-baited, within the study site across the river from the blocks described above (Figure 1). All round goby were measured for total length (nearest mm) and marked via anal fin clip prior to placement into traps. Sex was not recorded during escapement trials. Traps were fished for 24 hours, with no bait, and processed the following day during two events on July 13 and July 23, 2021. Remaining round goby were checked for anal fin clip to enumerate escapement.

Data analysis

Trapping data in 2020 and 2021 was analyzed separately. In both cases, a general linear mixed model was used to evaluate the effects of minnow trap type (e.g., round-style and box-style), bait type and bait quantity (fixed effects) on the number of round goby captured (dependent variable) using a Poisson distribution because of scenarios with 0 catch. Block and time were included in the models as random effects in order to account for spatial differences in catch and the likely reduction in catch over time (round goby were not released). Differences in round goby total length was also evaluated using the same model structure. Models were fit using SPSS software and model effects were considered significant at $p < 0.05$ and post hoc comparisons were evaluated using a Least Significant Difference test. Model results were back transformed to their original form for statistical interpretation.

Results

Round goby abundance and distribution

Round goby were captured at all monitoring sites within the LFR during 2019 (n = 677), 2020 (n = 470), and 2021 (n = 694) and this is the first documentation to confirm distribution within all river reaches above the invasive species barrier at RCB (Table 1). Total length of round goby captured ranged from 33–132 mm throughout the LFR and the largest individuals were captured in river reaches below the invasive species barrier (Table 1). Three hundred ninety-five minnow traps were deployed in Lake Winnebago near its outflows during the three years of this study and no round goby were caught within Lake Winnebago (Table 1). Despite very low sampling effort in LLBM in 2021 round goby were documented in this river reach and only one barrier (Menasha Lock) prevents connectivity of the LFR to Lake Winnebago. Although round goby are now distributed throughout the LFR up to the Menasha Lock, the highest abundances and catch per unit effort (CPUE) are still found below the invasive species barrier at Rapid Croche Dam, site RC-B, (Table 1, Figure 4). Furthermore, sex information collected in 2021, confirms male and females are distributed throughout all river sections in the LFR and sex ratios below the invasive species barrier are male dominated, exceeding 2:1 (male: female); however sex ratios become female dominated increases with progression upriver above the invasive species barrier (Table 1).

Table 1. Round goby abundance, distribution, and demographics throughout the Lower Fox River, Wisconsin, USAduring 2019-2021.

Year	Site	Sampling Events	Traps Deployed	Total Catch	Trap Hours	CPUE (catch/trap/hr)	Total Length Range (mean, SD)	Sex Ratio (M:F:U)
2019	WINN	5	110	0	3168	0.0000	-	-
	FR-A	4	32	4	768	0.0052	-	-
	FR-B	4	40	11	960	0.0115	-	-
	RC-A	4	39	1	936	0.0011	-	-
	RC-B	4	40	247	960	0.2573	-	-
	DP-A	4	40	414	1152	0.3594	-	-
2020	WINN	5	180	0	4320	0.0000	-	-
	FR-A	4	32	1	768	0.0013	90 (NA, NA)	-
	FR-B	4	32	7	768	0.0091	36–90 (63.9, 18.2)	-
	RC-A	4	32	3	768	0.0039	63–112 (88.7, 24.6)	-
	RC-B	4	32	40	768	0.0521	53–127 (81.3, 14.6)	-
	DP-A*	6	108	419	4320	0.0970	33–131 (78.1, 15.0)	-
2021	WINN	4	106	0	2248	0.0000	-	-
	LLBM	2	16	21	384	0.0547	65–112 (85.9, 12.1)	5:16:0
	FR-A	4	32	20	744	0.0269	59–115 (90.6, 15.5)	6:9:5
	FR-B	3	24	35	552	0.0634	56–120 (91.0, 17.8)	8:14:13
	RC-A	3	24	9	576	0.0156	72–119 (97.8, 17.2)	4:5:0
	RC-B	3	24	194	552	0.3514	48–127 (91.5, 18.1)	91:102:1
	DP-A*	3	108	415	2520	0.1647	43–132 (94.3, 16.3)	277:130:8

* denotes expanded effort to facilitate experimental design conducted in 2020 and 2021.

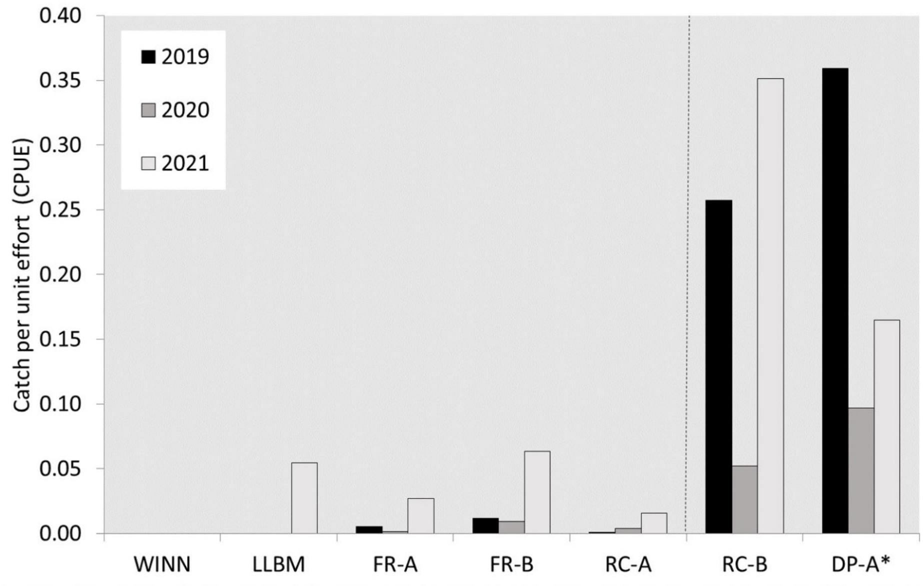

Figure 4. Catch per unit of effort (CPUE) for round goby abundance monitoring throughout the Lower Fox River and Lake Winnebago, Wisconsin, USA. Dotted vertical line represents invasive species barrier at Rapid Croche Dam (site RC-B).

Effect of trap type and bait on catch

2020 Results

A total of 419 round goby were captured during six sampling events ranging in total lengths of 33–131 mm (mean = 78.1, SD = 15.02 [Table 2]). Trap style had a significant effect on round goby catch ($X^2 = 7.18$, $p < 0.05$, df = 1), where round-style traps captured 237 round goby (mean/trap = 4.4,

Table 2. Round goby catch rates and sizes during experimental trapping within river reach DP-A in the Lower Fox River, Wisconsin, USA.

Year	Trap type	Bait	Catch (mean/trap, SD)	Size range (mean, SD)
2020	Round-style	dog food (50 g)	62 (3.4, 4.5)	44–119 (76.0, 15.3)
	Round-style	dog food (100 g)	90 (5.0, 8.2)	35–114 (80.6, 16.1)
	Round-style	dog food (200 g)	85 (4.7, 5.5)	53–130 (79.4, 15.7)
	Box-style	dog food (50 g)	50 (2.8, 3.5)	51–125 (75.4, 13.7)
	Box-style	dog food (100 g)	53 (2.9, 4.5)	51–131 (77.6, 13.5)
	Box-style	dog food (200 g)	79 (4.4, 5.1)	33–110 (76.3, 15.3)
2021	Round-style	dog food (200 g)	186 (6.9, 7.5)	48–132 (93.2, 15.8)
	Round-style	hotdog	155 (5.7, 7.2)	43–131 (96.8, 16.2)
	Round-style	male round goby	46 (1.7, 2.8)	47–121 (95.2, 16.3)
	Round-style	empty trap	28 (1.0, 1.8)	46–129 (93.6, 17.3)

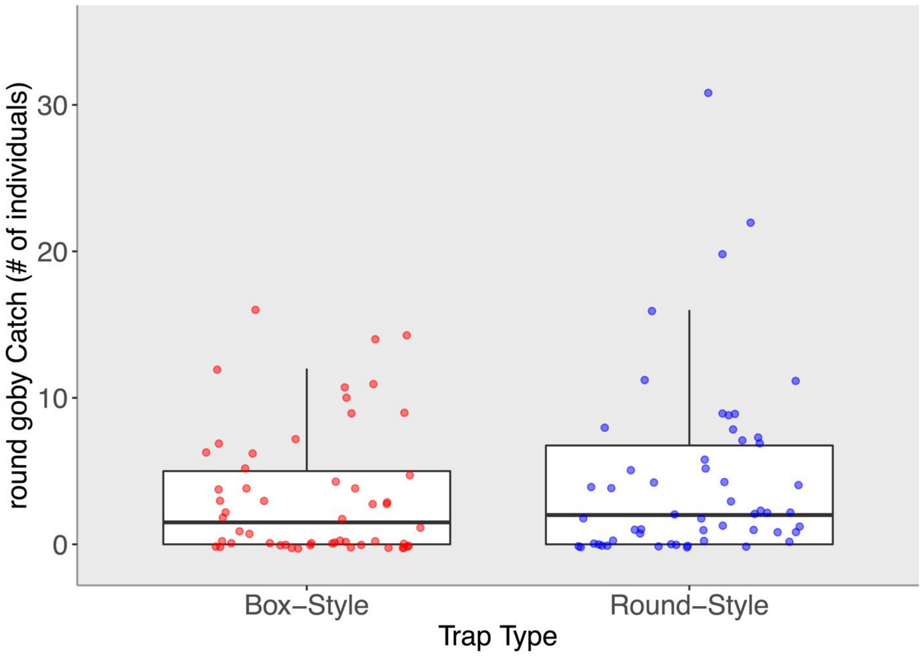

Figure 5. Boxplot of round goby catch by trap type. The extent of the box displays the Interquartile Range. Lower and upper box boundaries are 25th and 75th percentiles, respectively. The horizontal line inside the box represents the median value. The upper error line is the 90th percentile. Jittered points represent raw instances of catch. Round-style traps captured significantly more round goby than box-style traps (p= 0.007). Asterisk indicated significance.

SD = 6.2) and box-style traps captured 182 (mean/trap = 3.4, SD = 4.4 [Table 2, Figure 5]). Food quantity also had a significant effect on round goby catch ($X^2 = 9.7$, $p < 0.05$, df = 2) and catch increased with increasing bait quantity (Table 2, Figure 6). Traps baited with 200 g of dog food captured the most round goby (n = 164, mean/trap = 4.6, SD = 5.2), followed by traps baited with 100 g of dog food (n = 143, mean/trap = 4.0, SD = 6.6) and lastly, traps baited with 50 g of dog food (n = 112, mean/trap = 3.1, SD = 4.0). However, pairwise comparisons show that traps baited with 200 g of dog food and traps baited with 100 g of dog food were not different ($p > 0.05$). Similarly, traps baited with 100 g of dog food were not significantly different than those baited with 50 g ($p = 0.53$), but traps baited with 200 g of dog food were significantly different than those baited with 50 g ($p < 0.05$) resulting in increased round goby catch using 200 g of dog food.

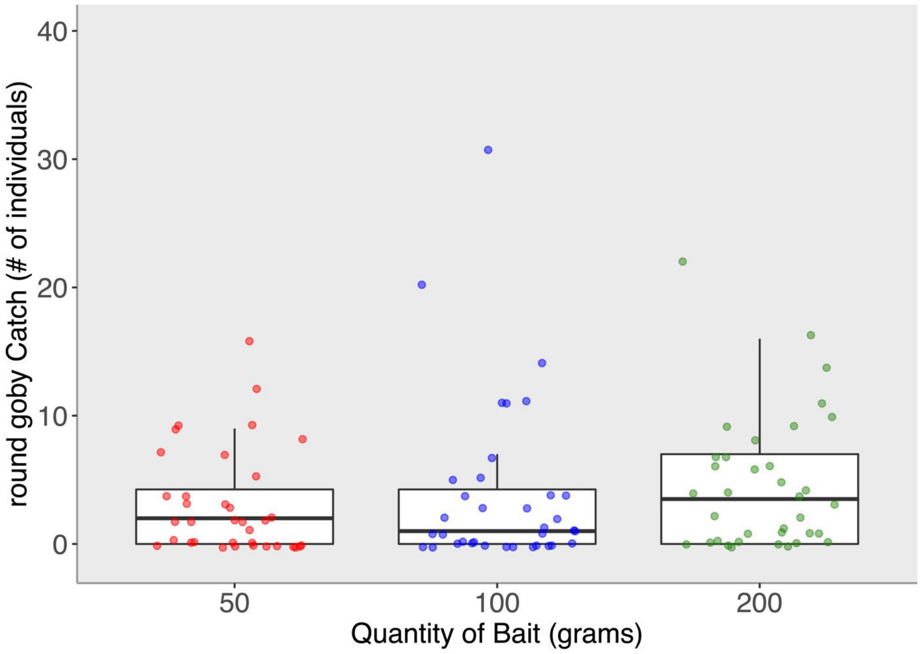

Figure 6. Boxplot of round goby catch by the quantity of bait (dog food) used in 2020. The extent of the box displays the Interquartile Range. Lower and upper box boundaries are 25th and 75th percentiles, respectively. The horizontal line inside the box represents the median value. The upper error line is the 90th percentile. Jittered points represent raw instances of catch. Traps baited with 200 g of dog food captured significantly more round goby than traps baited with 50 g of dog food ($p = 0.002$).

There was evidence to suggest trap type influenced the size of round goby captured ($X^2 = 8.99$, $p < 0.05$, df = 1). Round-style traps captured larger individuals (mean = 79.4 mm, SD = 15.7) compared to box style (mean = 76.3 mm, SD = 13.9). There was no evidence that food amount influenced the size of round goby captured ($X^2 = 0.63$, $p > 0.05$, df = 2). Block had a significant effect on round goby catch rates ($X^2 = 28.3$, $p < 0.001$, df = 2), where Block 1 captured a total of 183 round goby (mean/trap = 5.1, SD = 5.5) followed by Block 2 (n = 143, mean/trap = 4.0, SD = 6.4) and Block 3 (n = 93, mean/trap = 2.60, SD = 3.7). Sampling period (occurring bi-weekly June–September 2020) was also a significant predictor of round goby catch rates ($X^2 = 169.5$, $p < 0.001$, df = 5). Sampling period 1 captured the most round goby (n = 156), followed by 56, 42, 21, 31 and 113 for periods 2–6 respectively.

2021 Results

A total of 415 round goby were captured during 3 sampling events ranging in total lengths of 43–132 mm (mean = 94.3 mm, SD = 16.3 [Table 2]). Model outputs indicated a significant difference in round goby catch rates among bait types ($X^2 = 9.73$, $p < 0.001$, df = 3). Traps baited with dog food outperformed all other bait types (Table 2, Figure 7) and mean catch rates were significantly different (e.g., higher) than non-food type baits (i.e., control and male round goby). Specifically, during 2021, traps baited with 200 g of dog food captured the most round goby followed by hotdog, control,

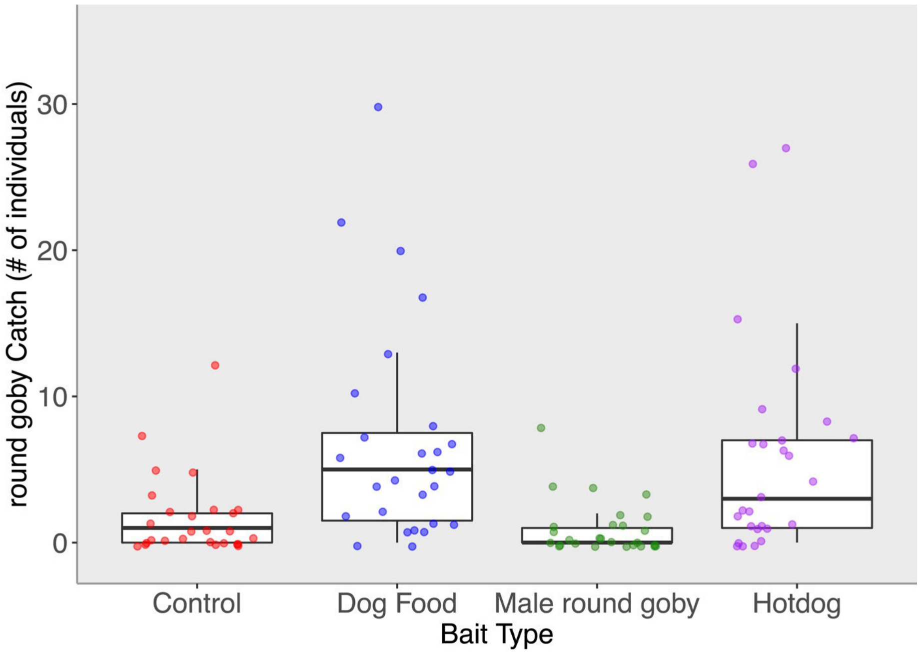

Figure 7. Boxplot of round goby catch by bait type used in 2021. The extent of the box displays the Interquartile Range. Lower and upper box boundaries are 25th and 75th percentiles, respectively. The horizontal line inside the box represents the median value. The upper error line is the 90th percentile. Jittered points represent raw instances of catch. Traps baited with dog food captured significantly more round goby than different than non-food type baits (i.e., control p=0.00; male round goby p=0.00). Mean catch rates were not significantly different between 200g dog and hotdog bait type treatments (p=0.810), or control and male round goby treatments (p=0.412).

and lastly male round goby (Table 2). However, mean catch rates were not significantly different between bait types consisting of food (200 g dog food and hotdog bait types $p > 0.05$), or between non-food type baits (control and male round goby treatments, $p > 0.05$). Total length of captured round goby did not differ among bait types ($X^2 = 3.48$, $p > 0.05$, df = 3). Sampling period (bi-weekly July–August 2021) was a significant predictor of round goby catch rates ($X^2 = 15.51$, $p < 0.001$, df = 2), where pairwise comparison showed sampling period 1 captured more round goby (n = 217), followed by event 3 (n = 112), and event 2 (n = 86). There was no significant effect of block ($X^2 = 1.23$, $p > 0.05$, df = 2), indicating no spatial difference in round goby catch rates across the study site during 2021.

A total of 80 round goby were used in escapement trials (n = 40 in round-style and n = 40 box-style minnow traps). Total length of round goby used in escapement trials ranged between 75–109 mm (mean = 95.1 mm, SD = 8.20) for round-style traps and 79–126 mm (94.2 mm, SD = 12.13) for box-style traps. Escapement was 27.5% (11 of 40) and 60.0% (24 of 40) for round-style and box-style respectively. Round goby escapement from within individual traps ranged from 0–4 (mean = 1.4, SD = 1.5) for round-style traps and 2–4 (mean = 3.0, SD = 0.76) for box-style traps. Total length of individuals which escaped traps were 92–109 mm (mean = 99.6 mm, SD = 6.55) for round-style traps and 80–126 mm (mean = 97.0 mm, SD = 14.85) for box-style traps.

Discussion

Round goby were initially thought to be a sedentary species with limited home ranges, with occasional long distance movements (Kornis et al. 2012). Upstream expansion of round goby have been documented to be 1–4 km/year in the LFR system (Kornis and Vander Zanden 2010), and up to 7.5 km/year in European systems (Brandner et al. 2018). Simulated studies suggest round goby exhibit site fidelity, but dispersal may be due to density dependent factors, and generally smaller males are believed to be the pioneers of range expansion (Šlapanský et al. 2020), and the presence of reservoir type habitat in riverine systems may foster range expansion (Raab et al. 2018). Furthermore, round goby within Great Lakes tributaries grow faster and mature earlier than those within open waters of the Great Lakes, promoting invasiveness (Kornis et al. 2017). Our monitoring efforts have confirmed round goby presence within all river reaches of the LFR, extending to the final barrier (Menasha Lock) at the outflow of Lake Winnebago. Round goby were not detected in Lake Winnebago during this study, suggesting that the closure of the Menasha Lock aids in the prevention of range expansion. We detected the highest abundances of round goby below the invasive barrier. Male and female round goby are present in all LFR reaches though female abundance increased with upstream progression (see also Šlapanský et al. 2020). The presence of both male and females at the forefront of invasion would grant immediate reproductive potential if both sexes were able to advance into Lake Winnebago (see Brownscombe and Fox 2012).

Round goby capture rates were influenced by minnow trap style, bait type, and bait quantity in the LFR. Catch was highest in round-style minnow traps baited with a food source (e.g., dog food or hotdog), and positively influenced by bait quantity when dog food was used. Dog food has the ability to dissolve in water and drift out of traps in lotic systems. Increased quantities would be expected to reduce dilution and improve the effectiveness of this bait type. Placing bait in a sealed but vented container would also aid in bait longevity (see also Kornis et al. 2017). Notably, there was no difference in catch rates when 200g of dog food was compared to a hotdog, which does not have the ability to wash away from the traps. Un-baited minnow traps were less successful, but the few instances of round goby capture may suggest that traps functioned as a form of cover (see also Harris et al. 2018), or simply the proximity to baited traps increased capture probability. The use of a male round goby was the least successful bait option. Male round goby make two sounds, one attracts females and the other repels competing males or feeding females (Marsden et al. 1996), suggesting behavior/communication may play a role in capture rates (Marentette et al. 2011). Isabella-Valenzi and Higgs (2016) used acoustic traps to test this response finding that traps playing reproductive calls caught more round goby than traps playing silent or aggressive calls. In our study, traps populated with male round goby often yielded no additional captures, suggesting avoidance (Steingraeber et al. 2006); however, few instances of increased catch rates (up to eight additional individuals) indicate there may be an attraction aspect at play that we cannot fully describe.

Minnow trap design has been shown to play an important role in capture rates of target species (Merilä et al. 2013; Merilä 2015; Budria et al. 2016). Steingraeber et al. (2006) suspected that reduced round goby catch in minnow traps may be due to large mesh size limiting retention to larger individuals (e.g., 110 cm TL). In comparison, Diana et al (2006), suggests minnow traps may bias towards smaller individuals. Our traps captured a range of round goby sizes, similar to other populations (Brownscombe and Fox 2012; Kornis et al. 2017), including small individuals noted to be the pioneers of range expansions (Ray and Corkum 2001; Johnson et al. 2005; Bergstrom et al. 2008; Šlapanský et al. 2020), suggesting mesh size was not limiting. Round-style traps did capture significantly larger individuals on average (~ 4 mm) compared to box-style traps. Notably, the largest round goby populated into each trap style during escapement trails (e.g., 126 mm for box-style and 109 mm for round-style) did escape their respective traps. The number of trap entry points, and size of trap entrance, may play a role in capture and retention rates. Kneib and Craig (2001) found escapement rates of mummichogs (*Fundulus heteroclitus*), a small minnow species in the Killifish family, to be almost two times higher in two-entry round-style traps compared to single-entry box style-traps and further described duration of trap deployment, fish density, and fish behavior to influence escapement. Furthermore, subtle differences in traps of the same manufacturer and style, for example color, can have adverse effects on catch rates (Merilä et al. 2013; Synyshyn et al. 2023). Catch data from minnow traps used to determine relative abundance must be interpreted cautiously taking into consideration the factors that influence trap entry, escapement, and retention.

Steingraeber et al. (2006), suggests inefficiencies of minnow traps for capturing round goby are likely related to trap loss, mesh size, and elevation of trap entrance. While the use of minnow traps in the LFR proves to be effective, we experienced similar gear limitations. For example, some traps would land vertically along the river bottom with trap entrances either blocked or elevated off the river bottom which may limit entry. Similarly, Steingraeber et al. (2006) notes the use of minnow traps with trap entrances 10 cm above its base resulted in low round goby capture. Attempts were made to prevent improper trap position during this study when deploying in shallow/clear water, but sites with deep, turbid water, made confirmation of trap position challenging. Ensuring traps are deployed properly (e.g., use of underwater cameras), and modification to trap design (i.e., benthic trap entry with closure, see Smith 2020), may increase round goby capture rates and retention.

An adaptive approach when conducting distribution/monitoring surveys that focuses on continually identifying suitable habitat, and relocating unsuccessful traps, will improve round goby captures. Our sampling generally occurred within close proximity of boat launches and traps were primarily deployed on visually identified coarse rocky shorelines (e.g., riprap for bank stabilization). Notably, during our evaluations of trap types, bait types/ quantities within river section DP-A, block (e.g., trap deployment location), was a significant factor in round goby capture during 2020, but was not significant during 2021. This may be due to annual variations in abundance, or micro-habitat features that could not be controlled in our field-based study despite site replication during both years of study. Furthermore, upstream river reaches in the LFR (i.e., LLBM, FR-A, FR-B, and RC-A), proved challenging to find suitable habitats. In these instances, traps were deployed in areas of vegetation, bedrock, and/or silt dominated substrates. Regionally, studies describe rocky habitats as preferred, but round goby are also documented in less ideal habitats such as macrophyte edges and sand (Jude et al. 1992, Marsden and Jude 1995; Jude and DeBoe 1996; Clapp et al. 2001; Ray and Corkum 2001; Young et al. 1996). Such differences may reflect local adaptations to specific habitats or density dependent factors (Gutowsky and Fox 2011; Kornis et al. 2012). During our study, when traps were suspected to be deployed in low-quality habitats, and deemed ineffective, traps were relocated. Side-scan imaging (Lowrance HDS 7) onboard the research vessel was used to identify submerged, offshore, rocky habitats for relocation of traps in 2021. Relocation did yield a modest increase in round goby catch and should underscore the importance of adaptive sampling approaches.

This survey is the most recent extensive sampling effort of round goby to occur in the LFR and outflows of Lake Winnebago. We suggest that monitoring using round-style traps baited with a food type (e.g., 200 g of dog food) will continue to successfully describe changes in population dynamics along this invasion front. Although no round goby have been detected within the Lake Winnebago proper to date, the sole use of minnow traps may be challenging to document the first individuals (see also Bergman et al. 2022). Lake Winnebago is over 137,000 acres, with extensive shoreline rip-rap and offshore rocky reefs that may serve as suitable habitat, as well as hosts over 60 boat launches that may have increased potential for first introduction locations. If round goby became present in low abundance or spatially explicit areas the use of minnow traps combined with other gears and techniques (e.g., environmental DNA: Nett et al. 2012; Nevers et al. 2018; Euclide et al. 2021; George et al. 2021) would improve odds for detection. Future research on this system would benefit from exploring topics related to habitat associations or selectivity in the LFR, and habitat availability in Lake Winnebago and upper tributaries, as well as exploring the influences of density and seasonality on movements throughout the system (see also

Blair et al. 2019) and confirming means of distribution. Considerable effort has been placed into invasive species campaigns to educate the public on the threat of aquatic invasive species (AIS) spread, and the combination of public knowledge, DNR recommendation, and coordination with the FRNSA, has facilitated a cooperative prevention of AIS spread for Lake Winnebago and the LFR.

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Authors' contribution

ST – research conceptualization, design, methodology, data collection/interpretation, manuscript writing/editing. TH – data interpretation/presentation, manuscript writing/editing. AC – design, methodology, data collection/interpretation, manuscript writing/editing. RB – design, methodology, data collection, manuscript writing/editing. PF – research conceptualization, data analysis/interpretation, funding/ethics, manuscript writing/editing.

Ethics and permits

Authors have complied with the institutional and/or national policies governing the humane and ethical treatment of the experimental subjects, and that they are willing to share the original data and materials if so requested

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Supplementary material

The following supplementary material is available for this article:

Figure S1: Dimorphic urogenital papilla of round goby collected in the Lower Fox River, Wisconsin, USA.
Figure S2: Box-style (left) and round-style minnow traps used in round goby escapement trails.

This material is available as part of online article from:
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