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Juvenile Drift of Round Goby as a Means of Range Expansion in the French Creek Watershed, Pennsylvania

Grace L. Hemmelgarn[1,*], Casey Bradshaw-Wilson[1], and Lee M. Demi[1]

Abstract - An ongoing invasion of *Neogobius melanostomus* (Round Goby) is threatening the unique biodiversity of the French Creek watershed (FCW), a tributary to the Allegheny River located primarily in northwestern Pennsylvania. Management strategies depend on knowledge of dispersal mechanisms. Juvenile drift is an important mechanism of Round Goby dispersal in other populations that is currently unexamined in this system. Our objective was to document the presence of juvenile Round Goby drift, describe temporal drift patterns, and describe the community of drifting fish families in the presence and absence of Round Goby within the FCW. We collected drifting larval fishes with drift nets twice a month from June to August 2021 at 3 sites in the FCW: 1 with an established Round Goby population in LeBoeuf Creek (LC), 1 at the invasion front in the French Creek main stem (FCI), and 1 not currently known to be colonized by Round Goby in the French Creek main stem (FCII). Across all sampling dates and sites, we collected 2689 fishes from 9 families, with 71.5% of drift occurring in June. We captured a total of 172 Round Goby, representing 17.5% of drift (163 individuals) at LC and 1.7% of drift (9 individuals) at FCI. No drifting Round Goby were captured at the currently uninvaded FCII site. All Round Goby drift occurred entirely after sunset. Goby total length was consistent from June to early August with a mean of 7.8 mm. This study presents the first documented evidence of Round Goby juvenile drift in the FCW, which may inform management strategies to limit the spread of this invasive species to larger waterways downstream.

Introduction

Neogobius melanostomus (Pallas) (Round Goby) is a dominant invasive fish species throughout the Laurentian Great Lakes, and its continued spread through North America is of considerable concern (Kornis et al. 2012). Round Goby is expanding its range in the French Creek watershed (FCW), where it was first reported by the Pennsylvania Fish and Boat Commission in 2014 (C. Bradshaw-Wilson, unpubl. data; Bradshaw-Wilson et al. 2019; Mueller et al. 2017). The FCW is adjacent to the Lake Erie basin and spans 319,000 ha of the Upper Allegheny River basin, originating in southwestern New York and joining the Allegheny River in Franklin, PA, then flowing to the Ohio River (Bradshaw-Wilson et al. 2019). Round Goby is currently established and breeding in LeBoeuf Lake, LeBoeuf Creek, and a section of the main stem of French Creek (Bradshaw-Wilson et al. 2019, Mueller et al. 2017). French Creek is the most species-rich stream in Pennsylvania, providing habitat for more than 80 native species of fishes and 29 native species of unionid mussels, 4 of which are listed as endangered under the US Endangered Species

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Act and 1 of which is listed as endangered in the state of Pennsylvania (Bradshaw-Wilson et al. 2019, Endangered Species 2019, Smith and Crabtree 2010, US Fish and Wildlife Service 2023).

The invasion of Round Goby has had predominantly negative impacts on native fauna of aquatic ecosystems. However, the exact effects of Round Goby invasion on native fauna are difficult to predict because they vary widely and are case-specific (Janáč et al. 2016, 2019; Kornis et al. 2013; Poos et al. 2010; Šlapanský et al. 2017). Resource overlap among Round Goby and native benthic fishes, including *Etheostoma* spp. (darters), *Percina caprodes* (Rafinesque) (Common Logperch), and *Cottus* spp. (sculpins), have resulted in dietary and habitat shifts, reduced abundance, or local extirpation of native fishes (Abbett et al. 2013, Bergstrom and Mensinger 2009, Firth et al. 2021, French and Jude 2001, Krakowiak and Pennuto 2008, Poos et al. 2010, Stauffer et al. 2016b, Volkel et al. 2021). In addition, research suggests negative impacts to native unionid mussels in North America by Round Goby predation and/or loss of native fish hosts needed to complete life cycles (Bradshaw-Wilson et al. 2019, Poos et al. 2010).

Round Goby is known to colonize rivers by stratified dispersal, where the majority of individuals diffuse over short distances and a few pioneer individuals migrate long distances to colonize new areas (Baer et al. 2017, Bronnenhuber et al. 2011, Kornis et al. 2012, Šlapanský et al. 2017). Estimates of Round Goby dispersal rates in lotic systems vary from 500 m $year^{-1}$ to 9.14 km $year^{-1}$ upstream and 5.2 km $year^{-1}$ to 16 km $year^{-1}$ downstream (Bronnenhuber et al. 2011, Brownscombe and Fox 2012, Janáč et al. 2019, Šlapanský et al. 2017).

Juvenile drift is a dispersal mechanism that occurs when early life stages of fishes are transported by currents through a water body. Drifting behavior is species-specific and varies by ontogenetic stage and body size and across time, but nearly all fishes exhibit peak drift densities at night (Borcherding et al. 2016, Brown and Armstrong 1985, Gale and Mohr 1978, Janáč et al. 2013, Johnston 1997, Lechner et al. 2016, Oesmann 2003, Ramler et al. 2016, Zitek et al. 2004). Additionally, drift varies by locality and can be influenced by location in the water column, water velocity, temperature, turbidity, turbulence, light intensity, or river topography (Iguchi and Mizuno 1990, Janáč et al. 2013, Johnston 1997, Lechner et al. 2016, Oesmann 2003, Pavlov et al. 2008, Zitek et al. 2004).

Although Round Goby is a benthic species that lacks an air bladder, pelagic and drifting juvenile Round Goby have been reported in the Great Lakes and European rivers (Borcherding et al. 2016, Hayden and Miner 2009, Hensler and Jude 2007, Janáč et al. 2013, Ramler et al. 2016). Within Pennsylvania, drifting Round Goby were documented in Elk Creek, a tributary of Lake Erie, in 2012 (C. Bradshaw-Wilson, unpubl. data). These invasive fish spawn every 3–4 weeks from April to September, cued by water temperatures of 9–26 °C (Kornis et al. 2012). Adult Round Goby migrate more frequently upstream than downstream, so juvenile drift could play an important role in downstream dispersal to fill the gaps between upstream pioneers and established populations during stratified dispersal (Janáč et al. 2013, Šlapanský et al. 2019).

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Thus far, Round Goby have not invaded a stream as biodiverse as French Creek in North America, so dispersal mechanisms may be different from invasions in other lotic systems. While some suggest high biodiversity slows or limits the spread of Round Goby (Carman et al. 2006, Stauffer et al. 2016b, Wisor 2019), others propose invasion success is more related to abiotic environmental variables (Kornis et al. 2013, Poos et al. 2010). It is possible Round Goby juvenile drift may occur in the FCW during the summer spawning season but has not observed by sampling techniques targeted towards the collection of adults.

The objectives of this study were to (1) document whether the range expansion of juvenile Round Goby may be facilitated by drift, (2) analyze temporal patterns of Round Goby juvenile drift across the summer breeding season and within each sampling event, and (3) describe at the family taxonomic level the community of fish drifting downstream in sites with known Round Goby invasion and in presently uninvaded sites within the FCW. French Creek provides a unique opportunity to examine Round Goby-dispersal mechanisms in an ongoing invasion as they move downstream because they are not yet established throughout the entire watershed (Mueller et al. 2017). Given that this is the first documented case of a Round Goby invasion in a highly biodiverse North American stream, the analysis of drifting communities provides baseline information on other drifting fishes that may experience future impacts of the Round Goby invasion. Accurate information about natural dispersal is necessary to inform management strategies for Round Goby in lotic systems such as the Upper Allegheny basin, including French Creek, as the spread of this invasive fish continues.

Field-Site Description

The field study took place at 3 sites in the FCW including 2 in the main stem of French Creek and 1 in LeBoeuf Creek, a fourth-order tributary that flows into French Creek in LeBoeuf Township, Erie County, PA (Fig. 1). Round Goby has an established population in LeBoeuf Creek, LeBoeuf Lake, and a small section of the French Creek main stem. Among our 3 study sites, LeBoeuf Creek (LC) had an established Round Goby population and French Creek main stem I (FCI) was located at the known invasion front as of 2019 (Bradshaw-Wilson et al. 2019), while French Creek main stem II (FCII) was not currently known to be colonized by Round Goby. The mean wetted width and the maximum recorded depth at a net, respectively, across all sampling events was 9 m and 0.62 m. at the LC site, the 27 m and 0.58 m at FCI, and 63 m and 0.54 m at FCII.

Methods

Sampling of fish larvae

Based on the procedure used by Oesmann (2003), we placed 3–5 drift nets across a stream transect. At sites LC and FCI, net A was ¼ of the wetted width from the right bank, net B was in the center, and net C was ¼ of the wetted width from the left bank. At FCII, 5 nets were placed evenly spaced across the transect due

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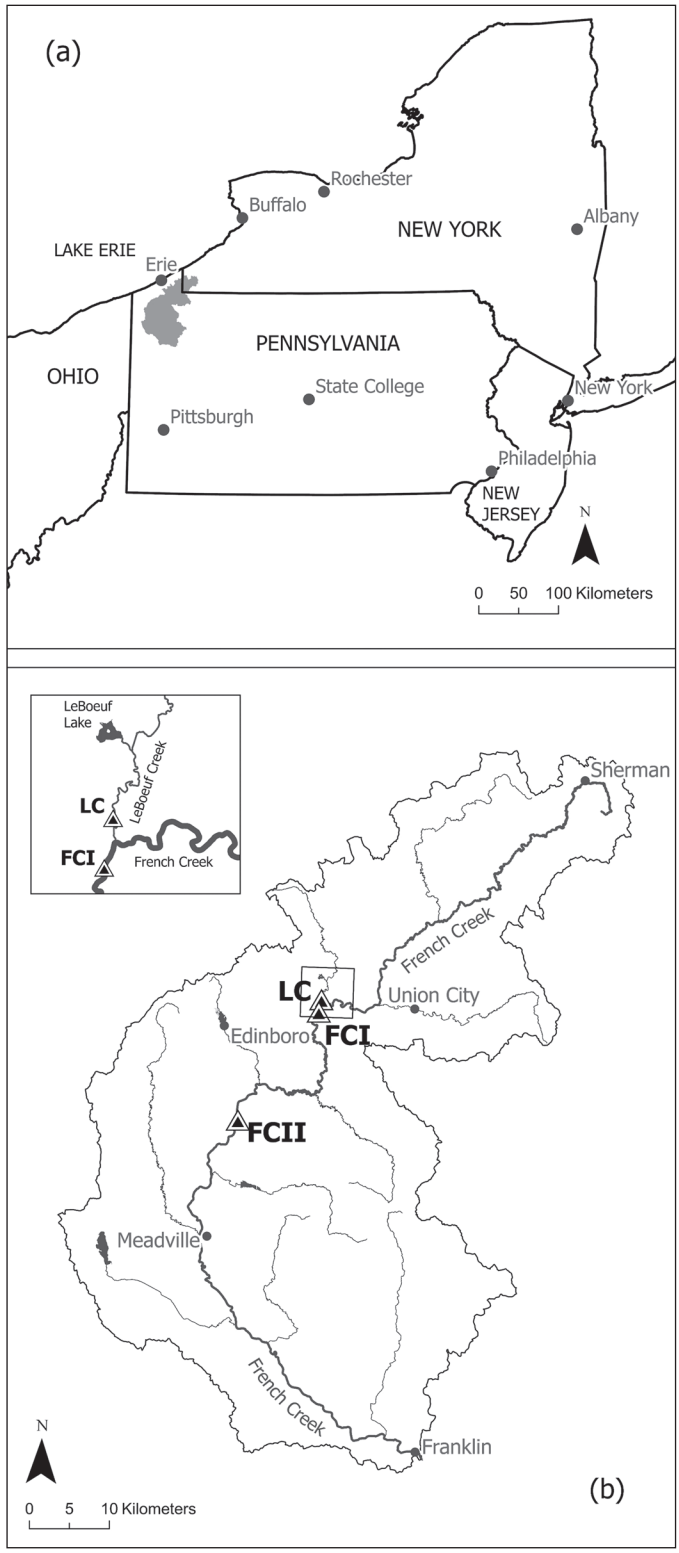

Figure 1. (a) Location of the French Creek watershed in Pennsylvania and New York. (b) Study site locations in the French Creek watershed. Maps created with ArcGIS Pro v. 2.8.1 (Esri, Redlands, CA).

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to the large wetted width at this site. We secured 500-µm–mesh drift nets with a 25.4 cm x 45.7 cm (10 in x 18 in) mouth just below the water surface using rebar hammered into the substrate; if a drift net could not be completely submerged, we measured the distance from the surface of the water to the top of the net to adjust sample volume calculations (Janáč et al. 2013, Lechner et al. 2016, Oesmann 2003). When the water depth was greater than the height of the net, there was a gap between the riverbed and the bottom of the net. We used stakes to mark the transect location on both banks for the entire sampling season.

We placed drift nets in the stream an hour before sunset and collected samples every hour for 5 hours. We recorded the exact start and end times of each of the 5 hourly sampling periods and preserved samples from each net and sampling period separately. Immediately after removal from the net, we placed each sample in a container of creek water with clove oil to anesthetize the fish and subsequently preserved them in 70% ethanol (Allegheny College Animal Research Committee Approval 2021-001; Borcherding et al. 2016). Sampling events occurred roughly twice a month from 1 June 2021 to 27 August 2021 to provide samples throughout the Round Goby spawning season (Table 1). In July, only 1 sampling event occurred at LC and no sampling events occurred at FCI and FCII due to high-flow conditions.

In the lab, we identified larval fishes to family under a Leica S9 D Stereomicroscope using a larval fish identification guide (Auer 1982). We measured the total length of each Round Goby with a ruler under the microscope.

Sampling of abiotic factors

At the beginning of each sampling event, we measured the following: water temperature (YSI ProSolo Handheld ODO Meter; Yellow Springs, OH), water depth at each net (meter stick), water velocity in the center of each net (Hach FH950 Portable Flow Meter; Loveland, CO), wetted width (measuring tape), turbidity (Secchi disk in 95-cm turbidity tube), pH (Oakton EcoTestr pH2+ Meter; Vernon Hills, IL), dissolved oxygen (YSI ProSolo Handheld ODO Meter), and conductivity and total dissolved solids (Traceable Conductivity/TDS Pen; Webster, TX). At the beginning of each hourly sampling period, we measured light intensity with a Plexon LX1010B Digital Lux Meter (Dallas, TX). We visually estimated % cloud cover at the beginning and end of each sampling event and recorded moon phase and % moon illumination with data from The Old Farmer's Almanac for the zip

Table 1. Sampling dates at each site in the French Creek watershed from June to August 2021.

Period	FCII	LC	FCI
Early June	1 June 2021	7 June 2021	8 June 2021
Late June	29 June 2021	24 June 2021	24 June 2021
Early July	–*	–*	–*
Late July	–*	26 July 2021	–*
Early August	11 August 2021	9 August 2021	9 August 2021
Late August	27 August 2021	25 August 2021	25 August 2021

*No sampling events occurred due to high flow conditions.

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code 16335 (The Old Farmer's Almanac 2024). We calculated filtered volume as the submerged area of each net mouth multiplied by water velocity and time (Borcherding et al. 2016, Brown and Armstrong 1985).

Data analysis

We calculated catch-per-unit-effort (CPUE) for all fish combined and for each fish family as the number of fish captured divided by the filtered volume and averaged between the 3–5 simultaneous net samples for each sampling period at each site. We described the community structure of drifting fish families by sampling date based on the sum of abundance and the average of CPUE across sampling periods. We visualized the effect of date on community-composition CPUE with a non-metric multidimensional scaling (NMDS) ordination and tested it with a permutational multivariate ANOVA (PERMANOVA) for each site. We examined differences between the community composition of drifting fishes at each site with an analysis of similarities (ANOSIM) with a Bray–Curtis distance type and 9999 permutations.

We analyzed total fish CPUE at sites LC and FCI based on time of year with a repeated-measure ANOVA and unplanned post hoc comparisons with Bonferroni-corrected paired *t*-tests when ANOVA results were significant. We analyzed total fish CPUE based on time of year at site FCII and time-of-day at all sites, and Round Goby CPUE based on time-of-day and time of year at all sites, with a non-parametric Skillings–Mack test with Monte Carlo estimated *P*-values based on 10,000 replications to account for ties in the data (Chatfield and Mander 2009, Skillings and Mack 1981). We performed unplanned non-parametric post hoc comparisons following each significant Skillings–Mack test result with Nemenyi tests based on the chi-square distribution to correct for ties (Midway et al. 2020). We categorized time-of-day into the 5 hour-long sampling periods for the Skillings–Mack analysis. The nonindependence of samples from the same date in the time-of-day analysis and the same sampling period in the time of year analysis were accounted for in the statistical tests. The late-June sampling event at FCII was interrupted by a thunderstorm, and the first of 4 total sampling periods from that day was 2 hours. We analyzed the CPUE from this long sample as sampling period 2, and there was no data for sampling period 1. We described the total length (TL) of drifting Round Goby. All statistical analyses were performed with significance level of $\alpha = 0.05$.

Statistics were performed with Microsoft Excel version 2201 (Redmond, WA) and R version 4.1.2 in R Studio version 2022.02.0+443 (R Core Team 2021) with the packages 'dplyr' v. 1.1.1 (Wickham et al. 2023), 'ggplot2' v. 3.3.5 (Wickham 2016), 'ggpubr' v. 0.5.0 (Kassambara 2022a), 'lme4' v, 1.1-28 (Bates et al. 2015), 'lmerTest' v. 3.1-3 (Kuznetsova et al. 2017), 'MuMIn' v. 1.47.1 (Bartoń 2022), 'plyr' v. 1.8.7 (Wickham 2011), 'PMCMRplus' v. 1.9.6 (Pohlert 2022), 'rstatix' v. 0.7.1 (Kassambara 2022b), 'Skillings.Mack' v. 1.10 (Srisuradetchai 2015), 'tidyverse' v. 1.3.1 (Wickham et al. 2019), and 'vegan' v. 2.6-4 (Oksanen et al. 2022).

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Results

Community composition

A total of 2689 drifting fish from 9 families, including 172 Round Goby, were captured throughout the summer (Table 2), across all sites. At the LC site across 5 sampling dates from June to August, 929 drifting fish were captured from 6 families. Gobiidae (Round Goby) was the third most abundant family with 163 individuals, behind Centrarchidae (sunfishes) and Cyprinidae (minnows), with 319 and 186 individuals, respectively. At the FCI and FCII sites across 4 sampling dates

Table 2. Larval fish abundance by family and sampling date captured in drift nets at 3 sites in the French Creek watershed from June to August 2021. Abundance was calculated as the cumulative number of fish across all nets and sampling periods collected on each date.

Site	Family	Early June	Late June	Late July	Early August	Late August	Total
LC	Atherinidae	14	57	0	0	0	71
	Catostomidae	0	0	0	0	0	0
	Centrarchidae	122	152	44	0	1	319
	Cyprinidae	14	15	35	77	45	186
	Gobiidae	85	11	19	47	1	163
	Ictaluridae	0	103	8	1	0	112
	Percidae	36	2	0	8	0	46
	Percopsidae	0	0	0	0	0	0
	Petromyzontidae	0	0	0	0	0	0
	Unknown	3	4	14	6	5	32
	LC subtotal	274	344	120	139	52	929
FCI	Atherinidae	0	1	–*	0	0	1
	Catostomidae	12	2	–*	0	0	14
	Centrarchidae	7	7	–*	1	0	15
	Cyprinidae	110	55	–*	64	26	255
	Gobiidae	7	1	–*	1	0	9
	Ictaluridae	0	57	–*	5	2	64
	Percidae	42	26	–*	18	3	89
	Percopsidae	0	1	–*	0	0	1
	Petromyzontidae	2	0	–*	0	0	2
	Unknown	23	16	–*	28	9	76
	FCI subtotal	203	166	–*	117	40	526
FCII	Atherinidae	0	0	–*	0	0	0
	Catostomidae	24	0	–*	0	0	24
	Centrarchidae	4	3	–*	5	2	14
	Cyprinidae	494	171	–*	214	30	909
	Gobiidae	0	0	–*	0	0	0
	Ictaluridae	0	57	–*	3	0	60
	Percidae	85	53	–*	10	7	155
	Percopsidae	0	0	–*	0	0	0
	Petromyzontidae	0	2	–*	0	0	2
	Unknown	11	32	–*	25	2	70
	FCII subtotal	618	318	–*	257	41	1234
	Total	1095	828	133*	513	133	2689

*No sampling events occurred in July at FCI or FCII due to high-flow conditions.

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in June and August, 526 drifting fish from 9 families and 1234 drifting fishes from 6 families were captured, respectively. Gobiidae were present at FCI with 9 individuals but were not present in any drift samples at FCII. The most abundant families at both FC sites were Cyprinidae, with 255 fish at FCI and 909 fish at FCII; Percidae (perch), with 89 fish at FCI and 155 fish at FCII; and Ictaluridae (catfish), with 64 fishes at FCI and 60 fish at FCII.

At LC, the community composition of drifting fishes shifted from a spring and early summer dominance of Centrarchidae, representing 44.5% of the catch

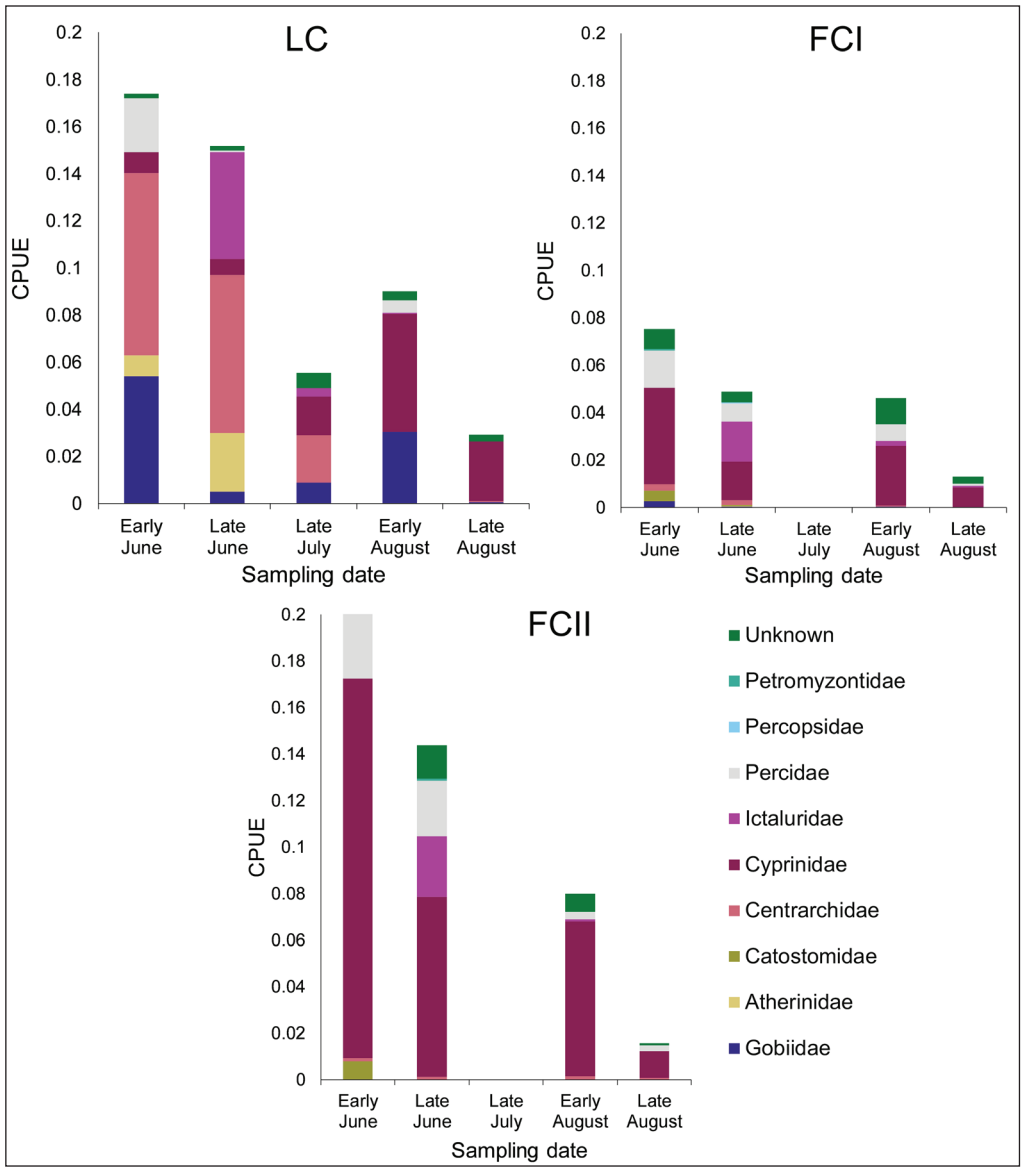

Figure 2. CPUE of larval fish families by sampling date at 3 sites in the French Creek watershed from June to August 2021. CPUE was calculated as fish abundance divided by the sampled water volume (m^3) on each date.

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in early June and 44.1% in late June, to a late-summer dominance of Cyprinidae, representing 86.5% of the catch in late August (Fig. 2). At FCI and FCII, Cyprinidae were dominant throughout the summer. Gobiidae were captured drifting downstream at LC on all 5 sampling dates. At FCI, 7 Gobiidae were captured in early June, 1 Gobiidae was captured in late June, and 1 in early August. Atherinidae were only captured in June, and all but 1 were captured at LC. At all 3 sites, the majority of Percidae were captured in June, and Ictaluridae were almost entirely captured in late June. Catostomidae and Petromyzontidae were only present at FCI and FCII and were only captured in June. The only Percopsidae was captured at FCI in late June. There was a significant effect of date on community composition at LC (PERMANOVA: $F_{4, 18} = 5.261$, $P = 0.001$), FCI (PERMANOVA: $F_{3, 15} = 2.591$, $P = 0.003$), and FCII (PERMANOVA: $F_{3, 15} = 4.558$, $P = 0.001$) (Fig. 3). The community composition of drifting fishes was also significantly different between sites (ANOSIM: $R = 0.2804$, $P < 0.001$).

Temporal patterns of fish drift throughout the summer season

At LC, average total fish CPUE in early June was at least 3 times greater than total fish CPUE in July and late August (repeated-measures ANOVA: $F_{4, 16} = 9.230$, $P < 0.001$; paired *t*-tests with Bonferroni correction: $P < 0.05$; Fig. 4). Round Goby drift at LC showed peaks in early June and early August with a significant effect of

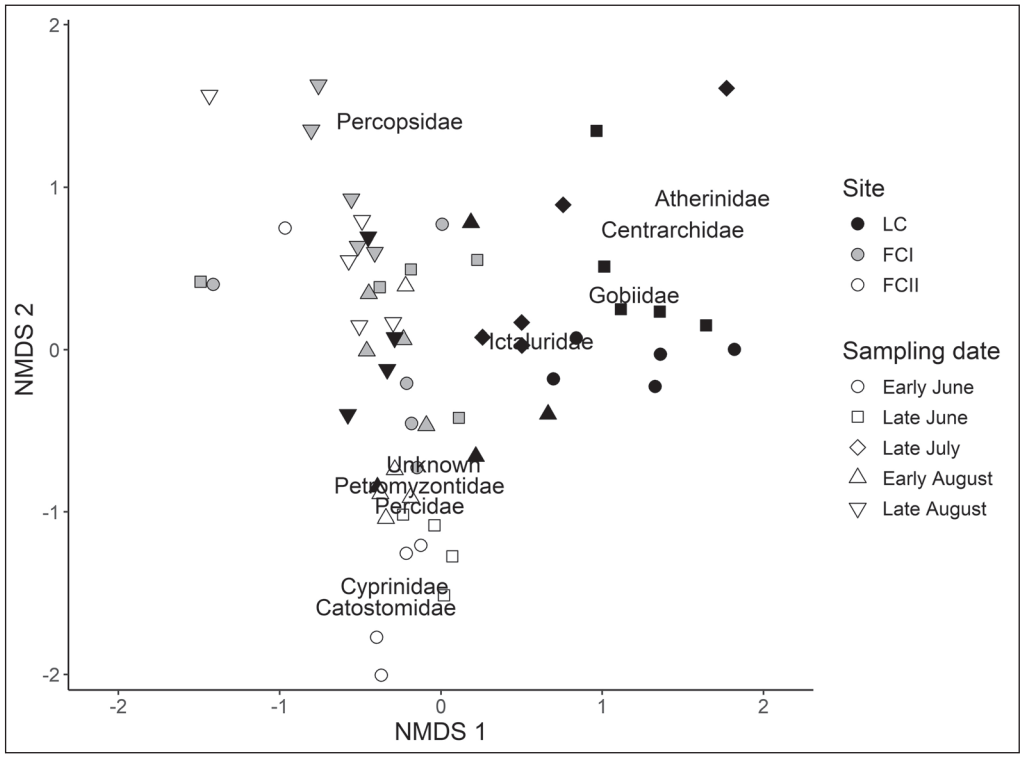

Figure 3. NMDS ordination of larval fish community composition by sampling date at 3 sites in the French Creek watershed from June to August 2021. Each point represents the average of the 3–5 simultaneous net samples in each sampling period.

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sampling date on CPUE (Skillings–Mack: $SM_4 = 6.080$, Monte Carlo estimated $P = 0.049$; Fig. 5), but no significant pairwise differences were detected (Nemenyi test: $P > 0.10$). We only captured a single Round Goby at LC on 25 August 2021 (the final sampling date at that site).

At FCI, both total fish and Round Goby CPUE were greatest in early June and lowest in late August (Fig. 5). There were no significant differences in total fish CPUE between sampling dates (repeated measures ANOVA: $F_{3, 12} = 2.885$, $P = 0.080$) or Round Goby CPUE between sampling dates (Skillings–Mack: $SM_3 = 1.680$, Monte Carlo estimated $P = 0.094$).

At FCII, average total fish CPUE was at least 20 times greater in early and late June than in late August, with a significant effect of sampling date on CPUE (Skillings–Mack: $SM_3 = 11.077$, Monte Carlo estimated $P = 0.002$). Pairwise comparisons were not statistically significant (Nemenyi test: $P > 0.05$).

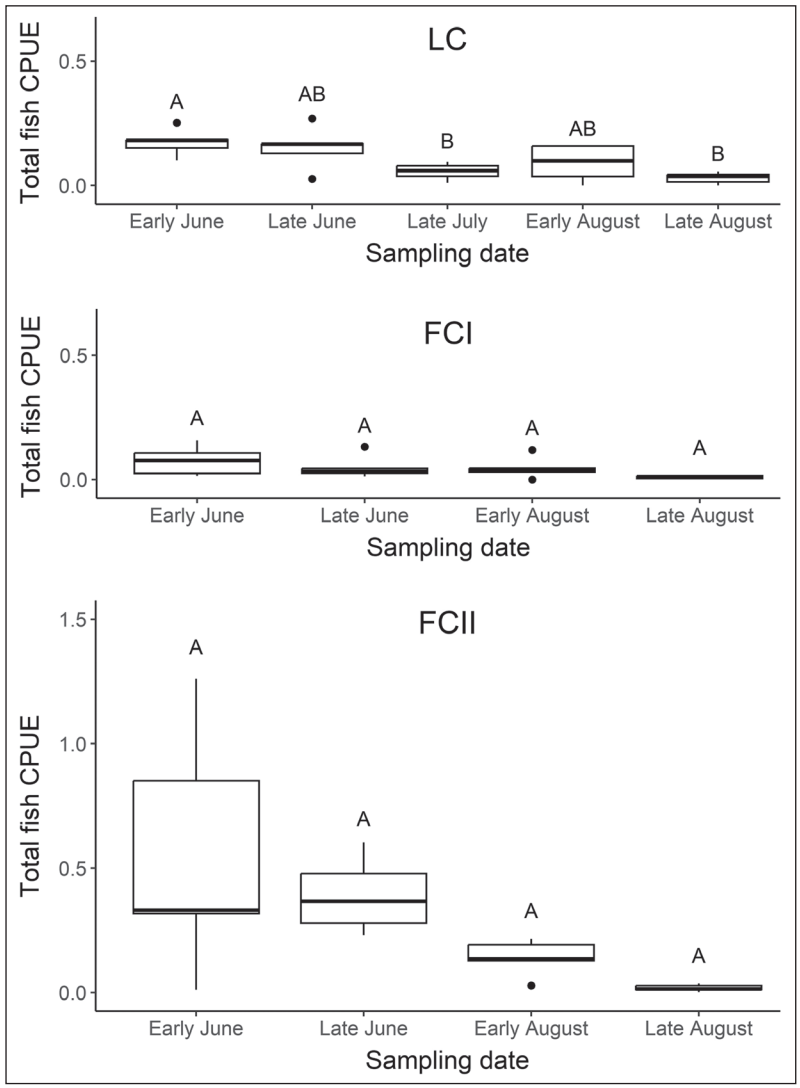

Figure 4. CPUE of total fish by sampling date at 3 sites in the French Creek watershed from June to August 2021. CPUE was calculated as fish abundance divided by the sampled water volume (m^3) and averaged between the 3–5 simultaneous net samples. $n = 5$: the hourly sampling periods on each date. Boxplots show median (center line), interquartile range (box), and maximum and minimum values (whiskers and outlier points). Dates not connected by the same letter within each site are significantly different ($\alpha = 0.05$).

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Diel fish drift

There was a significant sampling-time effect on total fish CPUE at LC (Skillings–Mack: $SM_4 = 12.320$, Monte Carlo estimated $P = 0.005$), FCI (Skillings-Mack: $SM_4 = 10.600$, Monte Carlo estimated $P = 0.015$), and FCII (Skillings-Mack: $SM_4 = 13.254$, Monte Carlo estimated $P < 0.001$) (Fig. 6), and on Round Goby CPUE at LC (Skillings-Mack: $SM_4 = 14.360$, Monte Carlo estimated $P < 0.001$; Fig. 7). There was not a significant sampling-time effect on Round Goby CPUE at FCI (Skillings–Mack: $SM_4 = 3.800$, Monte Carlo estimated $P = 0.057$; Fig. 7). No pairwise comparisons were statistically significant for total fish or Round Goby CPUE

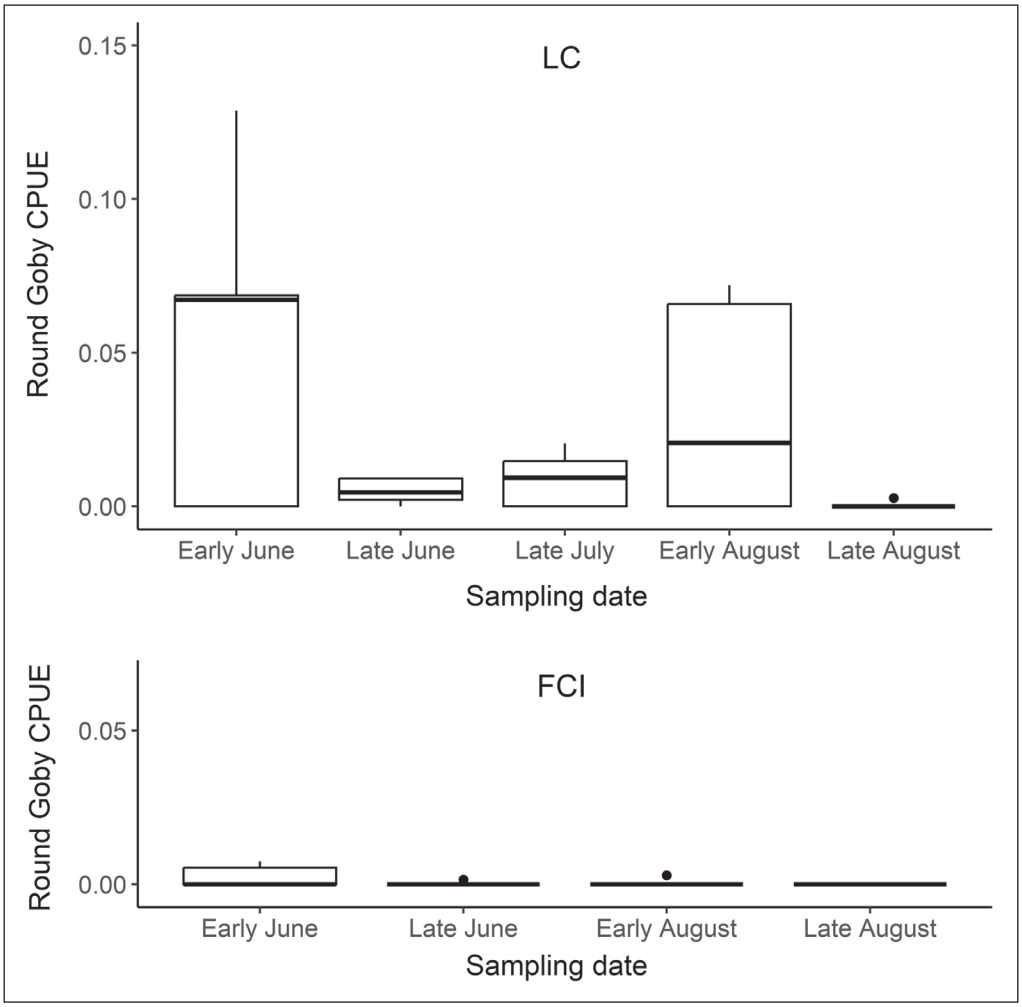

Figure 5. CPUE of Round Goby by sampling date at 3 sites in the French Creek watershed from June to August 2021. CPUE was calculated as fish abundance divided by the sampled water volume (m^3) and averaged between the 3–5 simultaneous net samples. $n = 5$: the hourly sampling periods on each date. Boxplots show median (center line), interquartile range (box), and maximum and minimum values (whiskers and outlier points). No significant pairwise differences were observed ($\alpha = 0.05$).

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at any site (Nemenyi test: $P > 0.05$). Throughout the entire sampling season at both LC and FCI sites, no Round Goby were captured during sampling period 1, which occurred in daylight before sunset. During the second sampling period, 1 Round Goby was captured at LC in late June in the hour after sunset and no Round Goby were captured at FCI during any sampling events. Round Goby CPUE and abundance peaked at both sites during sampling period 3 with a total of 74 Round Goby captured at LC and 5 Round Goby captured at FCI throughout the sampling season. Similarly, at all sites, total fish CPUE and abundance was lowest during sampling period 1 with a total of 48 fishes captured at LC, 20 at FCI, and 120 at FCII throughout the sampling season. Total fish CPUE and abundance peaked during sampling

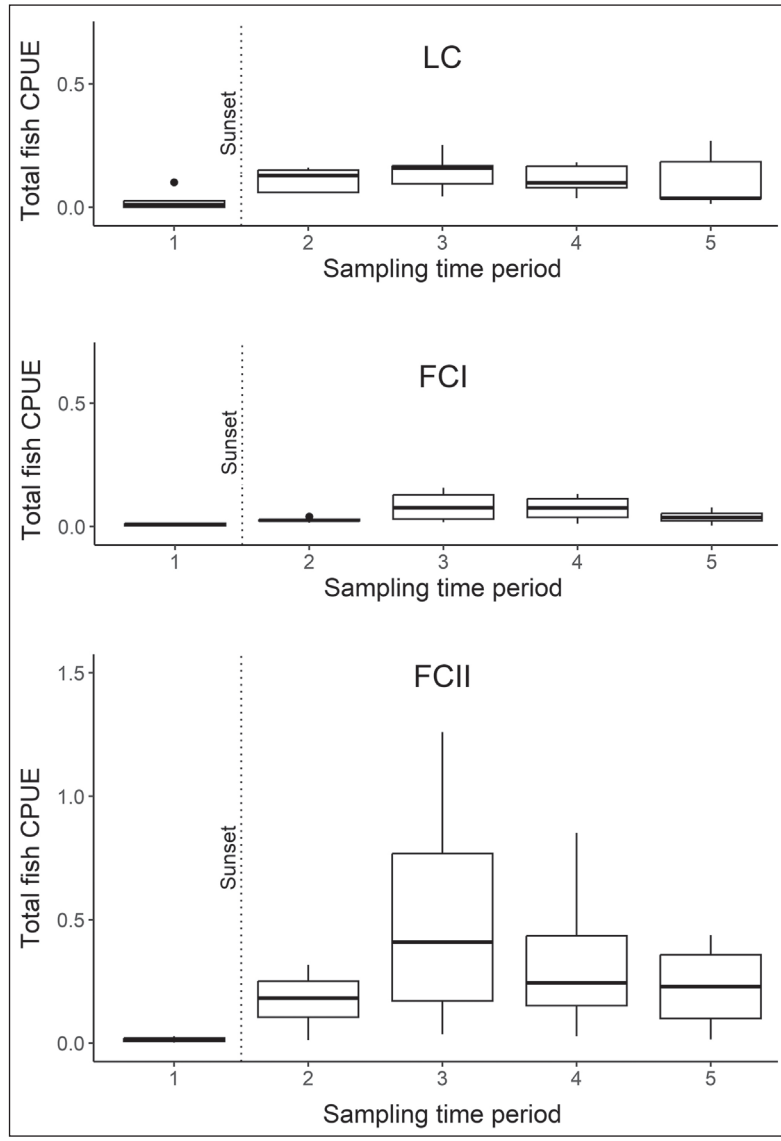

Figure 6. CPUE of total fish by sampling time period at 3 sites in the French Creek watershed from June to August 2021. Time period 1 began an hour before sunset, and each time period had a duration of one hour. CPUE was calculated as fish abundance divided by the sampled water volume (m^3) and averaged between the 3–5 simultaneous net samples. $n = 5$: the sampling events throughout the spawning season. Boxplots show median (center line), interquartile range (box), and maximum and minimum values (whiskers and outlier points). The vertical dotted line represents the time of sunset relative to the sampling periods. No significant pairwise differences were observed ($\alpha = 0.05$).

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period 3 at all sites with a total of 263 fishes captured at LC, 180 at FCI, and 421 at FCII throughout the sampling season (Fig. 6).

Round Goby total length

The TL of drifting Round Goby varied from 5.3 to 21.0 mm with a mean of 7.8 mm. Of the 169 Round Goby that were intact for TL measurement, 166 were within 5.3–9.4 mm (Fig. 8). Two Round Goby of a later ontogenetic stage were captured in July with lengths of 13.6 and 21.0 mm, and the only Round Goby captured in late August was also more developed at a length of 14.2 mm. Two Round Goby in July and 1 in early August could not be measured due to physical deterioration.

Abiotic conditions

Abiotic conditions recorded at each sampling event are reported in Table 3. At all sampling events, light intensity decreased during the first sampling period, which occurred in the hour before sunset. Light intensity at the beginning of the first sampling period varied from 410 to 3730 lux, and light intensity at the end of the first and beginning of the second sampling period varied from 0 to 300 lux across

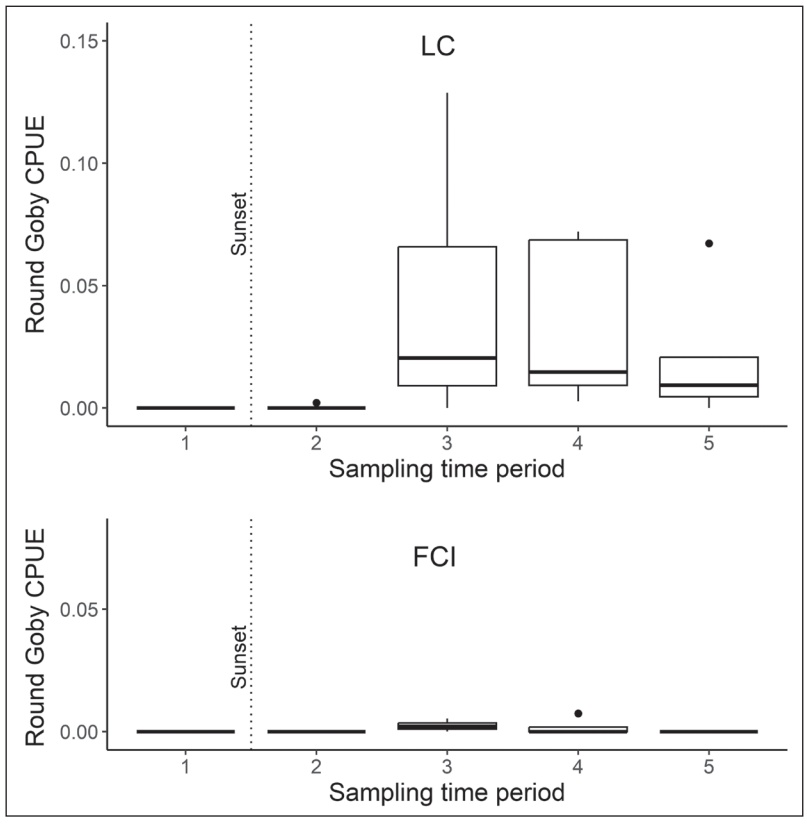

Figure 7. CPUE of Round Goby by sampling time period at 3 sites in the French Creek watershed from June to August 2021. Time period 1 began an hour before sunset and each time period had a duration of one hour. CPUE was calculated as fish abundance divided by the sampled water volume (m^3) and averaged between the 3–5 simultaneous net samples. n = 5: the sampling events throughout the spawning season. Boxplots show median (center line), interquartile range (box), and maximum and minimum values (whiskers and outlier points). The vertical dotted line represents the time of sunset relative to the sampling periods. No significant pairwise differences were observed ($\alpha = 0.05$).

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all sampling events. At all sampling events, the lux meter reported a light intensity of 0 lux by the end of the second sampling period and for the remaining duration of the sampling event regardless of moon phase and cloud cover.

Discussion

The presence of drifting behavior in juvenile Round Goby in the FCW supports other research findings for drift of this species in both lentic and lotic systems in Europe and North America (Borcherding et al. 2016; C. Bradshaw-Wilson, 2021 unpubl. data; Hayden and Miner 2009; Hensler and Jude 2007; Janáč et al. 2013; Ramler et al. 2016). Nonetheless, the unique biodiversity of the FCW may alter Round Goby behavior, so documentation confirming Round Goby juvenile drift in the FCW is important for understanding the natural history of Round Goby in a highly speciose lotic system and for management purposes.

The majority of Round Goby drift occurred at the LC site, where Round Goby has an established population. The low abundance of drifting Round Goby at FCI (invasion front) and absence of drifting Round Goby at FCII (believed to be currently uncolonized) are consistent with the current understanding of the invasion status of Round Goby in the FCW (Mueller et al. 2017).

LeBoeuf Creek is known to contain 12 fish families, 6 of which were captured as drifting larvae at the LC site (J. Stauffer Jr., Pennsylvania State University, State

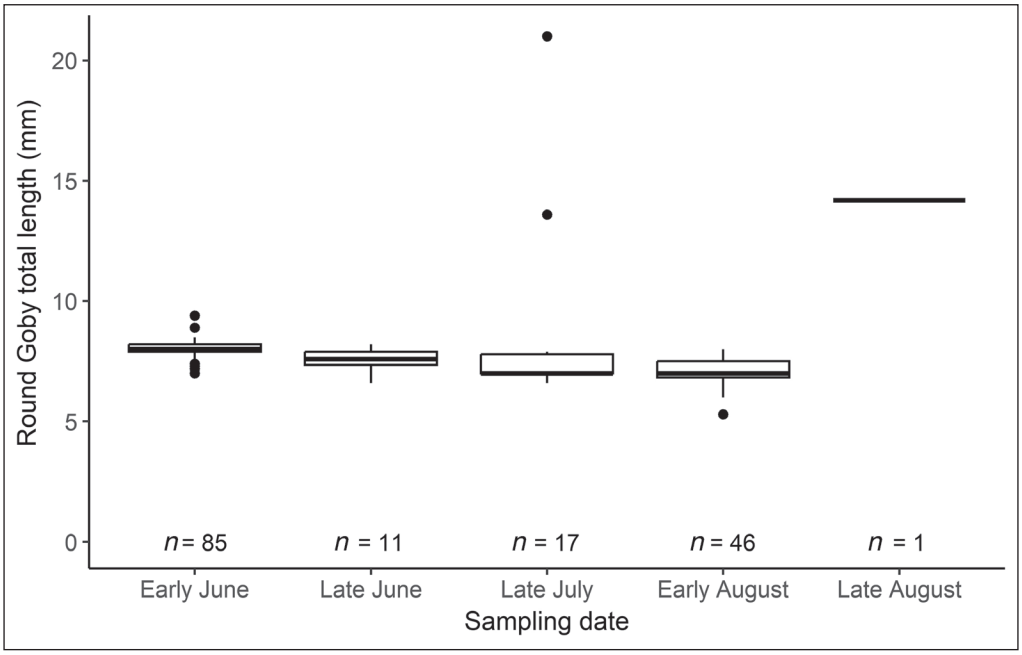

Figure 8. Total length by sampling date of Round Goby captured in drift nets in the French Creek watershed from June to August 2021. Boxplot shows median (center line), interquartile range (box), and maximum and minimum values (whiskers and outlier points). The number of Round Goby captured on each sampling date that were sufficiently intact for length measurement is represented by *n*. Two Round Goby in late July and 1 in early August were not able to be measured. No statistical analysis was performed.

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College, PA, 2021 unpubl. data). Correlations have been observed between peak seasonal drift of fish species and their spawning seasons, and 10 of the 12 LeBoeuf

Table 3. Abiotic conditions by site and sampling date recorded in the French Creek watershed from June to August 2021. Water depth and water velocity are the average of measurements taken at each of 3 (LC and FCI sites) or 5 (FCII site) nets at the beginning of each sampling event. Cloud cover is the average of measurements taken at the beginning and end of each sampling event. Moon phases: WnC = waning crescent, WxC = waxing crescent, FM = full mon, and WG = waning gibbous.

Site	Abiotic factor	June	Early June	Late July	Late August	Early Late August
LC						
	Water temperature (°C)	25.1	22.7	25.6	27.3	27.6
	Water depth (m)	0.39	0.49	0.46	0.39	0.39
	Water velocity (m/s)	0.25	0.36	0.35	0.25	0.29
	Wetted width (m)	8.8	9.4	9.2	8.7	8.9
	Moon phase	WnC	FM	WG	WxC	WG
	Moon illumination (%)	5.3	99.6	91.8	1.4	89.1
	Cloud cover (%)	90	93	5	85	90
	Turbidity (m)	0.90	0.71	>0.95[A]	>0.95[A]	>0.95[A]
	pH	7.8	7.8	7.1	7.2	7.7
	Dissolved oxygen (ppm)	7.58	8.03	7.90	7.49	7.09
	Conductivity (ppm)	197	179	154	178	178
	Total dissolved solids (mg/L)	295	267	232	266	266
FCI						
	Water temperature (°C)	25.5	22.9	–[B]	26.3	26.7
	Water depth (m)	0.47	0.55	–[B]	0.48	0.52
	Water velocity (m/s)	0.43	0.54	–[B]	0.41	0.51
	Wetted width (m)	27.4	28.6	–[B]	25.1	26.6
	Moon phase	WnC	FM	–[B]	WxC	WG
	Moon illumination (%)	1.8	99.6	–[B]	1.4	89.1
	Cloud cover (%)	100	95	–[B]	75	90
	Turbidity (m)	>0.95[A]	>0.95[A]	–[B]	>0.95[A]	>0.95[A]
	pH	8.7	8.3	–[B]	8.0	8.2
	Dissolved oxygen (ppm)	9.07	8.67	–[B]	8.54	8.25
	Conductivity (ppm)	196	230	–[B]	207	199
	Total dissolved solids (mg/L)	292	274	–[B]	309	297
FCII						
	Water temperature (°C)	17.5	27.9	–[B]	25.3	27.6
	Water depth (m)	0.34	0.31	–[B]	0.37	0.32
	Water velocity (m/s)	0.31	0.23	–[B]	0.34	0.28
	Wetted width (m)	63	63	–[B]	63	63
	Moon phase	WG	WG	–[B]	WxC	WWG
	Moon illumination (%)	56.7	71.8	–[B]	10.8	74.1
	Cloud cover (%)	35	100	–[B]	50	50
	Turbidity (m)	>0.95[A]	>0.95[A]	–[B]	>0.95[A]	>0.95[A]
	pH	8.1	7.9	–[B]	7.8	8.3
	Dissolved oxygen (ppm)	9.59	8.90	–[B]	8.18	8.79
	Conductivity (ppm)	179	190	–[B]	198	195
	Total dissolved solids (mg/L)	268	281	–[B]	297	291

[A]Turbidity was greater than the maximum detectable value of the turbidity tube (0.95 m).
[B]No sampling events occurred in July at FCI or FCII due to high-flow conditions.

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Creek families have spawning seasons that include June, July, and/or August (Brown and Armstrong 1985, Johnston 1997, Stauffer et al. 2016a). The 4 families with spawning seasons that include the sampling dates that were not captured in the drift nets at LC were Petromyzontidae, Catostomidae, Umbridae, and Percopsidae. These fishes may not have been caught because June represents the very end of a spring spawning season for Petromyzontidae, Catostomidae, and Umbridae; and Percopsidae and Umbridae are only represented by a single species each in LeBoeuf Creek (J. Stauffer Jr., 2021 unpubl. data; Stauffer et al. 2016a). Some species present in a stream reach have been absent in drift collections in the Illinois River, indicating not all fishes engage in drifting behavior (Brown and Armstrong 1985). The shift in drifting-community dominance from Centrarchidae to Cyprinidae in LeBoeuf Creek as the summer progressed correlates with their spawning seasons in the study region (Stauffer et al. 2016a). At all 3 sites, the lack of Atherinidae and decline of Percidae in August samples also align with the spawning seasons of those families in the study region (Stauffer et al. 2016a). Similarly, Ictaluridae are expected to spawn at the greatest densities in June, which is supported by the data shown here (Stauffer et al. 2016a). The observed differences in community composition between sampling dates are likely a result of differences in spawning seasons among fish families, and the observed difference in community composition between sites is likely a result of differences in overall community composition. Due to previously observed differences between sites, community-composition differences cannot be attributed to impacts of Round Goby.

Juvenile Round Goby were present in drift samples from LeBoeuf Creek on all sampling dates, but only 1 was captured in late August on our last sampling date at that site. This individual had a total length of 14.2 mm, longer than the average length of other drifting Round Goby collected in this study. At FCI, the majority of Round Goby were captured in June, with 1 captured in early August. These findings correspond to an additional study in LeBoeuf Lake, which found no adult female Round Goby captured in LeBoeuf Lake in late August 2021 were gravid (Byington 2022). Therefore, the Round Goby spawning season may have finished by the end of August in LeBoeuf Creek and LeBoeuf Lake, suggesting an earlier end to the spawning season in the FCW than observed in other Round Goby populations. Round Gobies are known to recruit until September in their native range in the Black and Caspian Sea area and until early October in invasive populations in Lake Erie tributaries and the Rhine River (Borcherding et al. 2016, Kornis et al. 2012, Pennuto et al. 2010). Similarly, juveniles from a non-native population of Round Goby in the Dyje River were caught drifting up to the end of sampling in September (Janáč et al. 2013). All of these Round Goby populations exist within the northern temperate zone, and the FCW experiences very similar climatic conditions to Lake Erie tributaries due to geographic proximity. Therefore, climatic differences are not likely to explain the observed differences in spawning-season termination. Alternatively, an additional September spawning may have occurred in the FCW after our sampling concluded, and further investigation is needed to examine spawning-season length in the watershed.

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It is likely that Round Goby drift began before the beginning of June sampling in the FCW, since a high abundance of Round Goby was captured on the first sampling date in early June. Pelagic juvenile Round Goby have been captured in April and May in the Lower Rhine, the Dyje River, and the Danube (Borcherding et al. 2016, Janáč et al. 2013, Ramler et al. 2016). Multiple peaks of Round Goby drift density were observed throughout the summer in the Danube and the Dyje, which supports the early June and early August peaks seen in LeBoeuf Creek (Janáč et al. 2013, Ramler et al. 2016). Round Goby drift density at FCI showed a similar peak in June, but the low total abundance of drifting Round Goby at this site only exhibited marginal statistical support for differences in Round Goby CPUE between sampling dates. The June peak in total drifting larval fishes seen at the LC and FCII sites is supported by similar peaks in June in the Illinois River, the Susquehanna River, and a tributary of the Danube (Brown and Armstrong 1985, Gale and Mohr 1978, Zitek et al. 2004). A similar June peak was also observed at the FCI site, but only had marginal statistical support for differences in total fish CPUE between sampling dates. In the Illinois River, the drift of all larval fishes occurred from late April to late August, so the June to August data presented here likely represents only the later portion of the drifting season (Brown and Armstrong 1985).

Time, represented as a categorical variable of each sampling hour, had a significant effect on total fish CPUE at all 3 sites and on Round Goby CPUE at LC. At FCI, there was moderate statistical support for an effect of sampling time on Round Goby CPUE. Both total fish and Round Goby CPUE exhibited an increase in drift after sunset occurred and light decreased at all sites, with the greatest CPUE and abundance of drift occurring 2 hours after sunset during sampling period 3. A longer duration of sampling throughout the entire night may reveal one or multiple peaks in drift, but the early termination of sampling after 5 hours in this study is not sufficient to make any conclusions about the timing of peak drift. In the Illinois River, total fish drift showed a distinct diel pattern with 2 peaks each night, at 2300 and 0300 hours (Brown and Armstrong 1985). Comparison to their study would be possible in a future investigation with a longer duration of sampling each night.

Round Goby drift exhibited a distinct diel pattern, with individuals exclusively drifting in darkness after sunset at both LC and FCI. The absence of Round Goby drift during daylight is supported by studies in the Lower Rhine, the Dyje, and the Danube (Borcherding et al. 2016, Janáč et al. 2013, Ramler et al. 2016). Diel vertical migration of Round Goby to the surface of the Great Lakes also only occurs at night (Hayden and Miner 2009, Hensler and Jude 2007). Round Goby drift may have a short duration each night due to their negative buoyancy created by the lack of an air bladder, but a longer sampling duration is needed to examine this pattern in the FCW (Janáč et al. 2013). While it is not known how far Round Goby drift downstream, an estimate based on the duration of darkness and water velocity in the Dyje River suggests Round Goby have the potential to drift 5.2–10.4 km in a single night (Janáč et al. 2013). However, this distance is likely to vary widely between systems (Janáč et al. 2013).

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The narrow range and consistent mean of total length of drifting Round Goby in the FCW throughout the sampling season was similar to that observed in the Great Lakes, Lower Rhine, Dyje, and Danube (Borcherding et al. 2016, Hensler and Jude 2007, Janáč et al. 2013, Lechner et al. 2016, Ramler et al. 2016). The average drifting Round Goby total length of ~8 mm is estimated to be reached at ~2.5–5.5 days old (Borcherding et al. 2016). The consistency of total length of drifting Round Goby throughout the sampling season indicates repeated spawning and drift at a consistent ontogenetic stage from June to early August. The limitation of Round Goby drift to a specific ontogenetic stage and size range may be due to the high energetic costs for larger goby to remain in the water column in the absence of an air bladder (Hensler and Jude 2007). In the Dyje River, Round Goby with a larger size appeared randomly in the drift, especially at the end of the sampling season (Janáč et al. 2013). This finding is consistent with the 3 larger Round Goby collected on 26 July 2021 and 25 August 2021 in LeBoeuf Creek.

Round Goby are likely drifting for dispersal or predator avoidance (Hensler and Jude 2007, Ramler et al. 2016, Šlapanský et al. 2017). Downstream drift may fill gaps between long-distance upstream migrators and the established population in stratified dispersal, but it may also limit the success of population establishment in upstream regions as juveniles drift downstream (Janáč et al. 2013). In the Round Goby invasion in the Czech Upper Elbe, newly established downstream populations were first detected as juvenile populations that became older with time, indicating downstream juvenile movements were used by the species to facilitate invasion (Janáč et al. 2019). However, low Round Goby drift abundance at the FCI invasion front site indicates that juvenile drift may not be a primary method of downstream range expansion in this study region. The low drift abundance at this site may also be a result of the smaller Round Goby population observed in the French Creek main stem than LeBoeuf Creek by Mueller et al. (2017). It is unknown if downstream drift is directly related to juvenile density, or if intraspecific competition may create a threshold that affects downstream drift rates.

Whether entrance into the drift by Round Goby is active or passive remains unknown, and, more generally, the active versus passive nature of larval drift in fishes is not well understood. While some suggest most larval fish drift is passive (Brown and Armstrong 1985, Iguchi and Mizuno 1990, Pavlov et al. 2008), others assert most larvae exhibit an intermediate "actipassive drift" with limited control of direction within the current (Lechner et al. 2016, Oesmann 2003). A low correlation of drift with light intensity and velocity may indicate more active entry into the water column (Lechner et al. 2016). Given the high correlation of Round Goby drift with light intensity in LeBoeuf Creek, Round Goby may be entering the water column passively, potentially by disorientation in low-light conditions. Alternatively, Round Goby may actively enter or most successfully remain in the water column under the cover of darkness due to predator avoidance.

In addition to seasonal and temporal variation in drift patterns, fish drift may be influenced by a combination of water temperature, water velocity, turbulence, turbidity, river topography, and spawning success (Borcherding et al. 2016, Brown

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and Armstrong 1985, Iguchi and Mizuno 1990, Johnston 1997, Lechner et al. 2016, Oesmann 2003, Pavlov et al. 2008, Zitek et al. 2004). Future research into correlations of abiotic factors with total fish and Round Goby drift in LeBoeuf Creek and other locations in the FCW may provide additional insight into Round Goby drift patterns in the study region.

This study was limited to only 3 sites in the FCW during part of the Round Goby spawning season but does compare patterns of larval fish drift in sites of contrasting invasion status (established, invasion front, uninvaded). However, a lack of replication precludes any conclusions about fish-community compositions in the presence and absence of Round Goby in the FCW. The presence of drifting Round Goby has altered the species composition of other drifting fishes in the Lower Rhine but did not affect young-of-the-year native fishes in the Dyje River in the Danube basin (Borcherding et al. 2016, Janáč et al. 2016). Therefore, the description of drifting fish families at the study sites included here may aid in future examinations of Round Goby impact on native fish drift in the FCW.

Now that the presence of downstream juvenile Round Goby drift in the FCW is known, future work should examine drift distance, the proportion of juveniles that drift downstream, the relationship between juvenile density and drift rates, the establishment success of juvenile populations downstream of the established population, methods to disrupt Round Goby juvenile drift without harming native fishes, and impacts of Round Goby on other drifting fishes. Future work could begin collecting samples in early April and continue until November to determine the exact length of the Round Goby spawning season and examine the suspected early end of spawning in this watershed. Sampling should also take place from dusk until dawn to further examine diel drift patterns. An addition of sites including LeBoeuf Lake, additional sites in LeBoeuf Creek and the main stem of French Creek, and other French Creek tributaries would also allow for a more complete analysis.

The Round Goby population in the Great Lakes is too established for successful eradication, so Round Goby management in North America is focused on prevention and early detection of new invasions (Kornis et al. 2012, Wisor 2019). The FCW contains a recent invasion that needs to be carefully monitored and potentially managed. Current methods used to control Round Goby throughout the US include bait regulations, electric barriers, ballast-water regulations, baited trapping, commercial exploitation, and piscicides (Kornis et al. 2012). An understanding of dispersal strategies, including juvenile drift, used by Round Goby is important for designing effective methods to slow their spread and control their density. The information presented here about the presence, location, timing, and ontogenetic stage of Round Goby drift in the FCW may help inform invasion-management strategies. In the absence of methods to prevent Round Goby juvenile drift, downstream range expansion may occur even in the presence of management strategies designed to prevent downstream migration of adults. Juvenile drift of Round Goby should be considered as managers prioritize resources for projects to control invasive species.

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