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ARTICLE

Survival of Upper Piedmont Stream Fishes Implanted with 8-mm Passive Integrated Transponder Tags

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Abstract

We studied weekly and bimonthly survival of select nongame fishes that were implanted with 8-mm PIT tags in upper Piedmont streams of South Carolina, USA. Weekly survival in stream enclosures was assessed for a total of 350 tagged individuals and 311 control (untagged) fish (39–101 mm TL; median = 65 mm TL) belonging to six species (Bluehead Chub *Nocomis leptocephalus*, Creek Chub *Semotilus atromaculatus*, Yellowfin Shiner *Notropis lutipinnis*, Mottled Sculpin *Cottus bairdii*, Northern Hog Sucker *Hypentelium nigricans*, and Striped Jumprock *Moxostoma rupiscartes*). Weekly survival rates ranged from 93.3% to 100% among species, with Yellowfin Shiners experiencing the lowest survival rate. Only 2 of the 337 surviving tagged individuals lost their tags (0.6% tag loss). Logistic regression indicated that species and body length were statistically significant predictors of survival and tag retention. Odds ratios indicated that tagged fish were 1.718 times less likely to survive than control fish, but the tagging effect was not statistically significant. Bimonthly survival was estimated by conducting a mark–recapture study from September 2015 to May 2016, which involved tagging 1,413 unique individuals of Bluehead Chub (45–75 mm TL) in a 520-m stream section and 431 individuals of Mottled Sculpin (45–75 mm) in another 740-m section. Bayesian state–space analysis of Cormack–Jolly–Seber models indicated that apparent survival did not differ between newly tagged and previously tagged (i.e., recaptured) individuals in any sampling interval, suggesting that the acute and chronic effects of tagging did not differ. Mean bimonthly apparent survival rate was 0.76 (95% credible interval = 0.64–0.86) for Bluehead Chub and 0.74 (95% credible interval = 0.59–0.88) for Mottled Sculpin. Our results indicate that PIT tags can be successfully applied to study the ecology and life history of small-bodied, nongame fish species, although caution should be exercised when selecting the species and body sizes to be tagged.

Physical tagging of individuals is a common technique in fisheries research. Identifying and tracking unique individuals over space and time provide key ecological and demographic information, including data on survival (Muir et al. 2001), growth (Hayes et al. 2008), movement (Texeira and Cortes 2007), and habitat use (McEwan and Joy 2011). Due to their low cost and relative ease of use, PIT tags have frequently been utilized when many individuals need to be tagged for ecological inferences (Skov et al. 2005; Ruetz et al. 2006; Archdeacon et al. 2009).

Application of PIT tags has been limited mostly to commercially and recreationally important species, particularly salmonids (Gries and Letcher 2002; Bateman and Gresswell 2006; Acolas et al. 2007). Few studies have used PIT tags to study the ecology of small-bodied nongame species. The paucity of PIT tag applications to nongame species may be partly attributable to their body size (Knaepkens et al. 2007). Larger PIT tags (i.e., 23- and 12-mm tags) were initially used in fisheries research (Ruetz et al. 2006; Knaepkens et al. 2007; Compton et al. 2008; Archdeacon et al. 2009). Minimum total body lengths within the 50–60-mm TL range have been recommended for the 12-mm tags (Ruetz et al. 2006; Acolas et al. 2007; Archdeacon et al. 2009).

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Currently, 8-mm tags are the smallest PIT tags commercially available, but only a few studies have tested their applications to small-bodied species, and those studies have reported mixed results. For example, Dixon and Mesa (2011) reported a high survival rate (95.6%) and retention rate (100%) over 41 d in Moapa White River Springfish *Crenichthys baileyi moapae* ranging in size from 40 to 67 mm TL. To the contrary, Bangs et al. (2013) found that Oregon Chub *Oregonichthys crameri* had lower survival at lengths less than 61 mm TL, and Ward et al. (2015) reported similar findings with Humpback Chub *Gila cypha* (40–49 mm TL), which experienced a high tag loss rate (up to 30%) and high mortality (up to 20%) over 60 d. These few studies and their conflicting results suggest that the minimum body size for 8-mm tags is still poorly known compared to larger PIT tags. Smaller tags could be applied to smaller species or earlier life stages, and successful applications would lead to a better understanding of life history and population dynamics for a greater number of species; however, such data are reliable only if tag loss and mortality associated with tagging are minimum.

Testing the feasibility of 8-mm tags in application to small, nongame species is much needed for fish conservation. Approximately 50% of freshwater fish species in North America belong to two families (Cyprinidae and Percidae), and a majority of those species are small-bodied, nongame fishes (Warren and Burr 1994). The southeastern USA harbors a disproportionate amount of freshwater fish diversity, but ecological knowledge of many small, nongame species is lacking (Warren et al. 2000). We contend that the knowledge gap is partly due to an inability to identify unique individuals of small-bodied species. Many analytical tools for estimating population vital rates rely on individually marked data (e.g., Cormack–Jolly–Seber [CJS] models for survival), whereas “unmarked” data, such as presence/absence and abundance, are less powerful for analysis of vital rates and life histories (Zipkin et al. 2014).

In this study, we assessed the survival of stream fishes that were subject to implantation with 8-mm PIT tags in the upper Piedmont region of South Carolina. The objectives of our study were twofold. First, we assessed weekly survival and tag retention of six morphologically diverse species by using stream enclosures for tagged and control (i.e., untagged) groups of fish. Second, we conducted a bimonthly mark–recapture study of Bluehead Chub *Nocomis leptocephalus* and Mottled Sculpin *Cottus bairdii* from September 2015 to May 2016 to examine whether survival differed between newly tagged and recaptured individuals. We considered that survival of newly tagged individuals would represent the short-term (acute) effects of tagging, whereas survival of recaptured (previously tagged) individuals would represent the long-term (chronic) effects of tagging.

METHODS

Study Area and Species

This study was conducted at nine sites in six streams located in the upper Piedmont region of South Carolina (Table 1). Study sites were chosen to be representative of wadeable streams in the region. Three streams were located in the Clemson Experimental Forest (Indian, Sixmile, and Todd creeks), and the remaining three streams were located on private land (Reedy Cove, Middle Fork Twelvemile, and Cove creeks). Streamside soils were predominantly fine sandy loam and sandy loam. Riparian land uses included shrubland (Todd Creek), pasture (Reedy Cove Creek), low-intensity residential (Cove and Middle Fork Twelvemile creeks), and mixed forest (Indian and Sixmile creeks). Riparian communities consisted primarily of deciduous mixed hardwoods and shrubs, such as American beech *Fagus grandifolia*, tulip-poplar *Liriodendron tulipifera*, mountain-laurel *Kalmia latifolia*, and American holly *Ilex opaca*.

Six morphologically and ecologically diverse species were examined in this study. They included three water-column cyprinids (Bluehead Chub, Creek Chub *Semotilus atromaculatus*, and Yellowfin Shiner *Notropis lutipinnis*)

TABLE 1. List of study stream sites in South Carolina and a description of the locations, species composition, and environmental characteristics (BHC = Bluehead Chub; CRC = Creek Chub; MTS = Mottled Sculpin; NHS = Northern Hog Sucker; STJ = Striped Jumprock; YFS = Yellowfin Shiner).

Stream site	Latitude	Longitude	Species tagged	Mean water temperature (°C)	Mean wetted width (m)
Cove Creek	34.957381°N	82.747781°W	BHC, CRC, NHS, YFS	7.93	3.88
Indian Creek, downstream	34.741731°N	82.849872°W	MTS	17.32	2.46
Indian Creek, upstream	34.742019°N	82.852064°W	MTS	12.03	3.10
Middle Fork Twelvemile Creek	34.920319°N	82.759719°W	BHC, CRC, NHS, YFS	NA	8.14
Reedy Cove Creek	35.001728°N	82.825922°W	BHC, CRC, NHS, YFS	6.74	5.21
Sixmile Creek, downstream	34.758756°N	82.859547°W	BHC, CRC, YFS	14.53	6.85
Sixmile Creek, upstream	34.762939°N	82.855981°W	BHC, CRC, YFS	16.16	8.45
Todd Creek, downstream	34.749214°N	82.813911°W	BHC, CRC, STJ, YFS	17.30	6.78
Todd Creek, upstream	34.761242°N	82.810650°W	BHC, CRC, STJ, YFS	12.69	3.84

characterized by a fusiform body shape; two benthic catostomids (Striped Jumprock *Moxostoma rupiscartes* and Northern Hog Sucker *Hypentelium nigricans*) with elongate and cylindrical bodies; and a single cottid (Mottled Sculpin), representing a benthic species characterized by a dorsoventrally flattened body. These morphological differences may affect the shape and volume of the abdominal cavity, where the PIT tag is typically inserted. These six species were used for analyses of weekly survival and tag retention, whereas the bimonthly survival study was conducted with Bluehead Chub in Todd Creek and with Mottled Sculpin in Indian Creek. Weekly and bimonthly studies took place in different stream sections of Todd and Indian creeks, and different sets of individuals were used in the two types of study (i.e., no individual was used in both weekly and bimonthly studies).

Field Collection

Weekly survival.—Weekly survival was examined for six species by conducting 10 trials at nine sites in six Piedmont streams (Table 1) by using instream enclosures. Fish were collected from October 2015 through March 2016 by crews of three to five individuals who conducted single-pass, pulsed-DC electrofishing using a Smith-Root LR-24 backpack unit (Smith-Root, Inc., Vancouver, Washington) and a Halltech HT-2000 backpack unit (Halltech Aquatic Research, Inc., Guelph, Ontario). Sampling proceeded in an upstream direction by surveying all available habitat types. Stunned fish were captured and placed in aerated live wells for processing.

Fish within the range of 39–101 mm TL were targeted to assess the impact of tagging on small-bodied individuals. Collected fish were sorted into two treatment groups: a tagged group and an untagged (“control”) group. Individuals of both groups were measured for TL and weight, and those in the tagged group additionally were anesthetized in a buffered solution of clove oil prior to tagging.

We used two tagging techniques to accommodate morphological differences among the six study species. Mottled Sculpin were tagged by using an N165 needle (Biomark, Boise, Idaho) inserted anteriorly above the anal vent into the abdominal cavity. This method was chosen due to the soft ventral surface of Mottled Sculpin (Ruetz et al. 2006). All other species were tagged by using a ventral incision that was made lateral to the midline (Wagner and Stevens 2000) and posterior of the pectoral fins. Incisions were kept minimal, approximately equal to the diameter of the tag, so that some resistance was felt when the tag was inserted (Oregon RFID, Portland, Oregon; or Biomark). Length (mm) and weight (g) were measured for each individual, and the fish’s PIT tag identification number was recorded on an Allegro^2 field computer (Juniper Systems, Inc., Logan, Utah) by using DataPlus software (Data Plus, Inc., Chelmsford, Massachusetts). Tagged fish were allowed to recover in an aerated live well until normal swimming behavior was observed; the fish were then placed into an instream enclosure.

At each stream site, two instream enclosures were set up to house tagged fish in one enclosure and control fish in the other. Enclosures were constructed from 0.635-cm (0.25-in) polyvinyl chloride pipes and 0.47625-cm (0.1875-in) fabric-mesh screen; enclosure dimensions were 90 × 120 × 70 cm. The enclosures were placed in areas with moderate flow and depth (e.g., glide habitat). Rocks and woody debris were placed inside the enclosures to anchor them and to provide cover for the fish. A HOBO Water Temperature Pro v2 data logger (Onset, Bourne, Massachusetts) was attached to one of the enclosures, and stream temperatures were recorded hourly for the week. Approximately equal numbers of fish were placed in tagged and control enclosures, with a maximum of 40 fish/enclosure. After 7 ± 2 d of placement, the fish were retrieved, checked for survival, and measured for weight and TL, and the tagged fish were scanned to assess tag retention.

Bimonthly survival.—A bimonthly mark–recapture study was conducted at Indian Creek (Mottled Sculpin) and Todd Creek (Bluehead Chub) between September 2015 and May 2016 to assess acute versus chronic tagging effects on survival. The streambank was marked every 20 m to establish permanent sections: 27 sections in Todd Creek and 37 sections in Indian Creek. A crew of three to five people sampled each section with two-pass electrofishing in an upstream direction by using backpack units on each sampling occasion (September and November 2015; January, March, and May 2016). Captured fish were checked for the presence of a PIT tag. If an individual belonging to the target species was over 45 mm TL but did not bear a PIT tag, it was tagged by using the procedure described above. However, survival was estimated based on individuals between 45 and 75 mm TL to assess tagging effects on small-bodied individuals. Mortality from electrofishing and tagging was recorded so that individuals with known mortalities would not contribute to estimates of survival from that occasion forward. Fish were allowed to recover in aerated live wells and were returned to the section of capture.

Each sampling occasion was completed as quickly as possible to conform to the assumption of instantaneous sampling on each occasion (Kéry and Schaub 2012). Each occasion was completed within 1–6 d (mean = 3 d) in Indian Creek and within 3–12 d (mean = 6 d) in Todd Creek. The mean interval between sampling occasions (from the median sampling day on a given occasion to the median sampling day on the next occasion) was 61 d (range = 55–68 d) in Indian Creek and 62 d (range = 54–65 d) in Todd Creek. To account for varying numbers of days between sampling intervals, we report bimonthly survival estimates on the 60-d standardized scale for all occasions. Stream temperature was collected hourly by using a HOBO Water Temperature Pro v2 data logger in each creek.

Statistical Analysis

Weekly survival.—Logistic regression analysis was used to examine the factors affecting weekly survival. Data were binary, such that a tagged individual was represented with a value of 1 if it survived the weekly experiment and retained the PIT tag; otherwise, the individual was represented with a 0. A control fish received a value of 1 if it survived the week and a 0 otherwise. Striped Jumprocks and Northern Hog Suckers were removed from logistic regression analysis due to their small sample sizes. Predictors of survival included species, tagging (tagged or not), TL, and weekly mean stream temperature. Species and tagging were factors. The TL and stream temperature were continuous covariates and were standardized by the mean prior to analysis. Covariates were checked for collinearity by using the variance inflation factor at a threshold of 5, and all covariates were included in analyses. A set of candidate logistic regression models was constructed using all possible combinations of four predictors as main effects. Models with an Akaike weight equal to or greater than 10% of the most supported model were considered competing models and were retained for interpretation (Burnham and Anderson 2002). The regression coefficient (i.e., effect size) was model-averaged among competing models based on Akaike weights using the package "AICcmodavg" (Mazerolle 2016) in R (R Core Team 2016). Effect size was considered statistically significant if its 95% confidence interval (CI) did not overlap zero. Odds ratios were calculated for all coefficients except the intercept term by exponentiating them.

Bimonthly survival.—We assessed whether bimonthly survival rates differed between previously and newly tagged individuals by using CJS models (Kéry and Schaub 2012). The survival rates should not differ between the two groups of individuals if there are no differences between chronic and acute effects. The CJS models use capture–recapture histories of individuals over sampling occasions to estimate apparent survival rates (Φ) while accounting for the detection probability of individuals (p). Incorporating imperfect detection is particularly important for small-bodied aquatic species. Cormack–Jolly–Seber models were fitted based on 75-mm TL and smaller individuals of the Mottled Sculpin and Bluehead Chub because our study goal was to assess tagging effects on small-bodied individuals.

We fitted CJS models for Mottled Sculpin and Bluehead Chub individually. Capture histories of individuals were formatted in a two-dimensional array ($y_{i,t}$), where rows indicate individuals (i) and columns indicate sampling occasions (t). Capture histories were coded as 1 for capture events and 0 for noncapture events. The primary interest in applying CJS models is to infer the latent state of fish survival ($z_{i,t}$), where $z_{i,t}$ is equal to 1 if an individual i is alive on occasion t and $z_{i,t}$ equals 0 if individual i is dead on occasion t. This latent state is imperfectly observed because survival is confidently known when an individual is captured, but a noncapture event could indicate either that an individual was dead or that the individual was alive but not captured. Following Kéry and Schaub (2012), we fitted CJS models representing an ecological process (equations 1–3) and observation process (equation 4) for each species:

$$z_{i,t+1}|z_{i,t} \sim \text{Bernoulli}\left[z_{i,t}\Phi_{g(i),t}\right], \tag{1}$$

$$\text{logit}\left[\Phi_{g(i),t}\right] = \mu + \varepsilon_{g(i),t}, \tag{2}$$

$$\varepsilon_{g(i),t} \sim \text{Normal}\left(0,\ \sigma^2\right), \tag{3}$$

$$y_{i,t}|z_{i,t} \sim \text{Bernoulli}\left(z_{i,t}p\right), \tag{4}$$

where μ represents the overall mean bimonthly survival rate; $\varepsilon_{g(i),t}$ is the variation around the mean for group g (i.e., previously or newly tagged) to which an individual i belongs on occasion t; and $\Phi_{g(i),t}$ refers to the bimonthly survival rate of group g on occasion t. The survival variation among sampling intervals was modeled as a random effect with a mean of zero and a variance of σ^2.

Survival was modeled conditional on the latent state of each individual on the immediately previous occasion (equation 1). This ensured that a dead individual ($z_{i,t}$ = 0) remained dead and a live individual ($z_{i,t}$ = 1) would survive to the next occasion with a probability of $\Phi_{g(i),t}$. We assumed that survival could depend on the sampling occasion (i.e., season) and whether an individual was newly tagged or previously tagged. Therefore, survival was modeled as an interactive effect of occasion and timing of tagging (equations 2, 3). The logit transformation was used so that survival probability ($\Phi_{g[i],t}$) would vary between 0 and 1 and is a canonical choice in CJS models (Kéry and Schaub 2012). Finally, detection probability of individuals was modeled as constant across sampling occasions (equation 4). There was no biologically plausible reason to suggest that detection probability would differ between previously tagged and newly tagged individuals. We did posit that detection probability (p) could differ among sampling occasions due to seasonal environmental variation, such as streamflow. To test this assumption, we had initially fit a CJS model by considering that both survival and detection (fixed effects) would vary among sampling occasions. Detection probability of either Mottled Sculpin or Bluehead Chub did not significantly differ among sampling occasions based on the overlap of 95% credible intervals (CRIs; results not shown). Accordingly, we used a constant detection probability across occasions. A constant detection probability also allowed an estimate of survival rate during the last sampling interval because survival and detection cannot be separately estimated when the last interval is assessed independently of other occasions in CJS models (Kéry and Schaub 2012).

Cormack–Jolly–Seber models use capture histories after the initial capture, and the sampling occasion of initial capture must be identified for each individual. Thus, we created a vector indicating the occasion of initial capture for all individuals. For some individuals, the "exit" sampling occasion was also known. An individual exited the study either when it experienced a known mortality (i.e., electrofishing or handling mortality) or when it reached 75 mm TL. We created another vector that included the known exit occasions for those individuals and the final sampling occasion (May 2016) for the remaining individuals. The two vectors were used to constrain the study period for each individual when individuals were looped in CJS models (Kéry and Schaub 2012). Because previously tagged individuals were not available on the first sampling occasion (September 2015), we report survival of previously and newly tagged individuals from the next occasion (November 2015) until the last bimonthly interval (March–May 2016). For comparisons of survival rates among sampling occasions, we estimated a 60-d survival rate of previously tagged and newly tagged individuals on each occasion as ${\Phi_{i,t}}^{60/n.\text{days}}$, where *n*.days refers to the number of days between the median sampling day of one occasion and that of the following occasion.

We analyzed CJS models in the Bayesian framework using Markov-chain Monte Carlo methods in Program JAGS (Plummer 2003) called from R (R Core Team 2016) with the rjags package (Plummer 2011). Uninformative priors were used throughout the Bayesian models: μ = logit(mean.μ) and mean.μ ~ Uniform(0, 1) in equation (2); σ ~ Uniform(0, 1) in equation (3); and p ~ Uniform(0, 1) in equation (4). Posterior distributions of model parameters were estimated by taking every 10th sample from 10,000 iterations of three chains after discarding 10,000 burn-in iterations. Model convergence was checked by visually examining plots of the Markov chains for good mixture and ensuring that the potential scale reduction factor value was less than 1.1 for all model parameters to assume model convergence (Gelman and Hill 2007). To test for differences in survival probability between previously tagged and newly tagged individuals for each sampling interval, we compared posterior samples between the two groups and recorded the proportion of posterior samples in which the survival probability of previously tagged individuals (i.e., chronic effects) was higher than that of newly tagged individuals (i.e., acute effects). This one-tailed posterior test was used to assess whether newly tagged individuals experienced lower survival rates than previously tagged individuals; statistical significance was inferred when the proportion of posterior samples was equal to or larger than 95%, corresponding to the $\alpha = 0.05$ level.

RESULTS

Weekly Survival

Overall, 350 tagged and 311 control individuals were collected across six study species in 10 weekly trials. Fish ranged from 39 to 101 mm TL (median = 65 mm TL). The Bluehead Chub (249 individuals) and Yellowfin Shiner (239 individuals) were the two most common species found in the study streams, comprising 73.8% of total individuals. Body size was comparable between tagged and control groups of Creek Chub and Yellowfin Shiners, but tagged individuals were statistically smaller than control fish for Bluehead Chub (*t*-test: $t = 2.578$, df = 224, $P = 0.011$) and Mottled Sculpin ($t = 6.131$, df = 52, $P < 0.001$), partly due to their large sample sizes (Table 2). Among tagged fish, 30.3% of individuals were smaller than 60 mm TL, the minimum threshold body size typically reported with a 12-mm tag (Ruetz et al. 2006; Acolas et al. 2007; Archdeacon et al. 2009). We tagged proportionately more Bluehead Chub individuals than Yellowfin Shiner individuals because the former species was used in the bimonthly mark–recapture study, and the tag retention of Bluehead Chub was of greater interest (Tables 3, 4). Mean stream temperature during weekly survival trials ranged from 6.74°C to 17.32°C (mean = 13.09°C). These values corresponded with fall–spring stream temperatures (October 2015–March 2016).

TABLE 2. Mean TLs (mm; range in parentheses) for control and PIT-tagged individuals of each species used in weekly survival trials; and results of *t*-tests comparing body lengths between the control and tagged groups.

	Control fish		Tagged fish				
Species	*N*	Mean TL	*N*	Mean TL	*t*	df	*P*
Bluehead Chub	105	72 (40–100)	144	66 (40–100)	2.578	224	0.011
Creek Chub	23	69 (41–100)	51	72 (39–101)	–0.505	39	0.616
Mottled Sculpin	32	75 (55–90)	43	63 (50–80)	6.131	52	<0.001
Northern Hog Sucker	1	47 (47–47)	19	75 (47–97)	NA	NA	NA
Striped Jumprock	0	NA	4	71 (59–81)	NA	NA	NA
Yellowfin Shiner	150	63 (45–91)	89	64 (51–87)	–1.488	162	0.139

TABLE 3. Counts of control and PIT-tagged individuals by species that survived for a week in stream enclosures.

	Control fish		Tagged fish		
Species	Total number	Number that survived	Number tagged	Number that survived	Number that survived and retained their tags
Bluehead Chub	105	105	144	139	138
Creek Chub	23	23	51	50	50
Mottled Sculpin	32	32	43	42	42
Northern Hog Sucker	1	1	19	19	19
Striped Jumprock	0	0	4	4	4
Yellowfin Shiner	150	140	89	83	82

TABLE 4. Counts of individuals smaller than 60 mm TL that were used in the weeklong survival and PIT tag retention study. Individuals ranged from 39 to 59 mm TL (median = 54 mm).

	Control fish < 60 mm TL		Tagged fish < 60 mm TL		
Species	Total number	Number that survived	Number tagged	Number that survived	Number that survived and retained their tags
Bluehead Chub	23	23	47	44	44
Creek Chub	8	8	15	15	15
Mottled Sculpin	4	4	17	17	17
Northern Hog Sucker	1	1	3	3	3
Striped Jumprock	0	0	1	1	1
Yellowfin Shiner	43	38	23	19	19

Weekly survival was 96.9% for tagged fish and 96.3% for the control when pooled across all individuals. When Yellowfin Shiners were excluded, weekly survival rates were 97.3% and 100% for tagged and control fish, respectively (Table 3). The lowest survival rate for a weekly trial was 90.0% for the tagged group and 92.1% for the control group. There were three trials in which tagged fish experienced no mortality and six trials in which control fish had a 100% survival rate. Yellowfin Shiners experienced the lowest survival rates in both the control (93.3%; n = 150) and tagged (93.3%; n = 89) groups (Table 3). Survival of tagged fish was 100% for both catostomids (Northern Hog Sucker: n = 19; Striped Jumprock: n = 4; Table 3). Only two individuals lost their tags (one Bluehead Chub [70 mm TL] and one Yellowfin Shiner [63 mm TL]; tag retention rate = 99.4%) among the 337 tagged fish that survived (Table 3). The smallest tagged individual of each species survived the weekly experiment (Table 2). Seven of the 13 tagged fish mortalities were individuals less than 60 mm (three Bluehead Chub [43, 46, and 49 mm TL] and four Yellowfin Shiners [51, 51, 55, and 57 mm TL]; Table 4).

Logistic regression analyses identified 8 competing models for weekly survival (Table 5). The top-ranked model included a species effect and a positive effect of body length on survival and had an Akaike weight of 0.243 (Tables 5, 6). The sum of Akaike weights across competing models indicated that body length was the strongest predictor of weekly survival (0.85), followed closely by species (0.82) and then mean stream temperature and tagging (0.36 each). Yellowfin Shiners had the lowest weekly survival rate, although the model-averaged 95% CI indicated that only Bluehead Chub were statistically more likely to survive than Yellowfin Shiners (95% CI = 0.235, 2.373; Table 6). The 95% CIs of effect sizes for Creek Chub (95% CI = –0.377, 3.769) and Mottled Sculpin (–0.520, 3.611) overlapped with a value of zero. Odds ratios indicated that fish were 2.035 times more likely to survive with a 1-SD increase (13.3 mm) in TL, and the model-averaged effect of body length was statistically significant (95% CI = 0.097, 1.324). Odds ratios also indicated that tagged fish were 1.754 times less likely to survive relative to control fish, but this effect was not statistically significant (95% CI = –1.450, 0.325).

Bimonthly Survival

Over five sampling occasions spanning from September 2015 to May 2016, we tagged 431 unique individuals of

TABLE 5. List of candidate models describing weekly survival (models for which Akaike weight [w_i] ≥ 10% of the top-ranked model), with predictors, number of predictors (K), Akaike's information criterion corrected for small sample size (AIC$_c$), difference in AIC$_c$ between the given model and the best-performing model (ΔAIC$_c$), and w_i.

Model	K	AIC$_c$	ΔAIC$_c$	w_i
Species + TL	5	191.89	0.00	0.243
Species + Tagging + TL	6	192.43	0.54	0.185
Species + TL + Temperature	6	192.48	0.60	0.180
Species + Tagging + TL + Temperature	7	192.89	1.00	0.147
TL	2	194.74	2.85	0.059
Species	4	195.69	3.80	0.036
TL + Temperature	3	195.85	3.96	0.034
Species + Tagging	5	196.11	4.22	0.029

TABLE 6. Model-averaged parameter estimates, SEs, 95% confidence limits (CLs), and odds ratios (ORs). The Yellowfin Shiner was used as the reference level (intercept) in the logistic regression models of weekly survival rate.

Parameter	Estimate	SE	95% CLs Lower	95% CLs Upper	OR
Intercept	3.046	0.377	2.307	3.785	NA
Bluehead Chub	1.304	0.545	0.235	2.373	3.685
Creek Chub	1.696	1.058	–0.377	3.769	5.453
Mottled Sculpin	1.546	1.054	–0.520	3.611	4.691
Tagging	–0.563	0.453	–1.450	0.325	0.570
Length	0.710	0.313	0.097	1.324	2.035
Temperature	0.275	0.227	–0.170	0.721	1.317

Mottled Sculpin in Indian Creek and 1,413 individual Bluehead Chub in Todd Creek that were 75 mm TL or smaller at the time of first capture (Mottled Sculpin: mean = 60 mm; range = 45–75 mm) and Bluehead Chub (mean = 65 mm; range = 45–75 mm). Mean stream temperature between the first day and last day of each sampling occasion varied from 11.1°C (January) to 20.1°C (September) in Indian Creek (mean = 15.5°C) and from 8.0°C (January) to 19.6°C (May) in Todd Creek (mean = 14.5°C).

Survival rates of Bluehead Chub and Mottled Sculpin varied among bimonthly intervals (Figure 1), but the mean bimonthly survival averaged across sampling intervals (i.e., μ in equation 2 on the probability scale) was 0.74 (95% CRI = 0.56–0.87) for Mottled Sculpin and was 0.76 (95% CRI = 0.63–0.85) for Bluehead Chub. In both species on all sampling occasions, survival probability did not significantly differ between previously tagged and newly tagged individuals (Figure 1), suggesting that acute and chronic effects of PIT-tagging on survival did not differ. For Bluehead Chub, the proportion of posterior samples in which the survival probability of previously tagged individuals was higher than that of newly tagged individuals was 0.49 in the November–January interval, 0.19 in the January–March interval, and 0.77 in the March–May interval (Figure 1). For Mottled Sculpin, the proportion was 0.70 in the November–January interval, 0.94 in the January–March interval, and 0.47 in the March–May interval (Figure 1). Posterior mean detection probability (p) after two electrofishing passes was 0.40 (95% CRI = 0.33–0.49) for Mottled Sculpin and 0.33 (95% CRI = 0.29–0.37) for Bluehead Chub.

DISCUSSION

Our results show that in general, 8-mm PIT tags can be successfully applied to a suite of morphologically and ecologically diverse small-bodied fish species (≥40 mm TL). Weekly survival of tagged fish was high (96.9%) and comparable to that of control fish (96.3%), and tag loss was negligible (0.6%). The Yellowfin Shiner was the only species to experience any mortality in the control group. When this species was excluded, the control and tagged fish survival rates were higher (100% and 97.3%, respectively). Tagging had a negative effect on survival, but the effect was not statistically significant. In addition, bimonthly survival rates

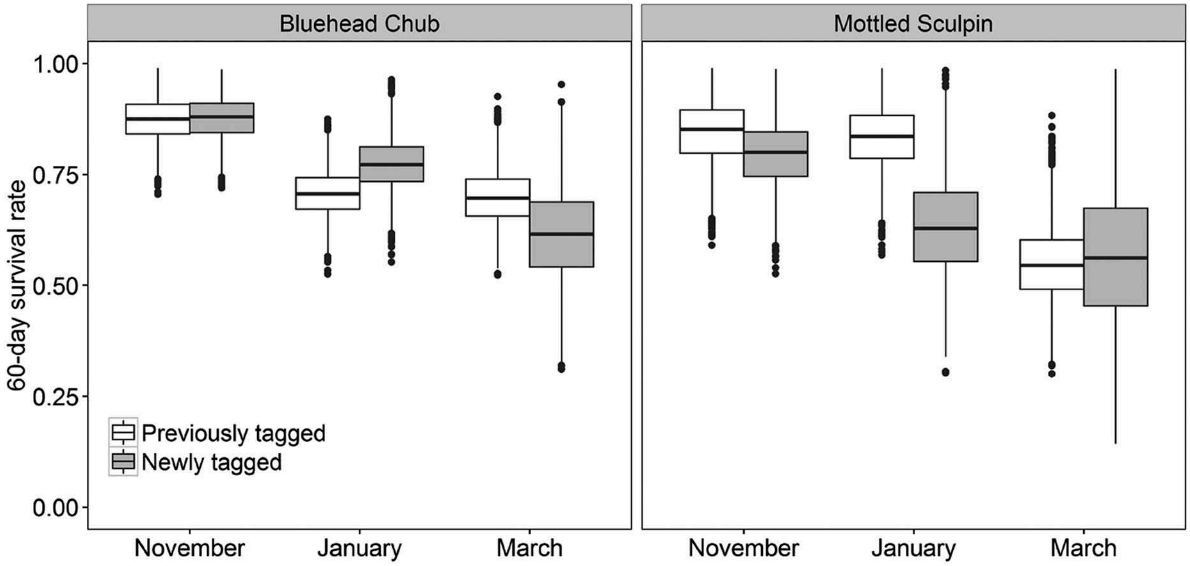

FIGURE 1. Posterior estimates of 60-d survival rates of previously tagged and newly tagged Bluehead Chub and Mottled Sculpin. November survival refers to the 60-d period from November to January, and so on. Each box shows the interquartile range (IQR = 25th and 75th percentiles), with median values represented by the center line. Whiskers extend 1.5 times the IQR from the upper and lower limits of the IQR; dots are outliers.

did not differ between previously tagged and newly tagged individuals, indicating that chronic and acute effects of tagging did not differ. These results represent among the most successful applications of 8-mm PIT tags to small-bodied, nongame fishes (Dixon and Mesa 2011).

We believe that the successful tagging of small fishes in this study was partly due to our tagging procedures, which were intended to minimize both stress and wound size. Fish were tagged for weekly survival trials under cooler water temperatures (October–March), thus reducing physiological stress that could cause mortality or tag expulsion. Tags were injected into Mottled Sculpin with a hypodermic needle, as it was shown to be the most effective technique (Ruetz et al. 2006). The benthic nature and dorsoventrally flattened bodies of Mottled Sculpin provided enough surface area to perform injections. Performing surgical incision rather than the use of hypodermic needles for all other species most likely contributed to higher survival rates (Baras et al. 1999; Dixon and Mesa 2011). Incisions proved to be more precise and less internally damaging for the other, more fusiform and cylindrical-bodied species. However, during our preliminary trials, we also observed that large individuals (approximately >120 mm) of catostomids, such as Striped Jumprocks and Northern Hog Suckers, were tagged more easily with hypodermic needles than with scalpel incisions. Thus, flexible methods in tagging would enhance the success of PIT tag studies. Finally, inserting the PIT tag into an area lateral to the midline may have contributed to increased survival and reduction of internal injury to the fish (Wagner and Stevens 2000).

Despite our overall success, some signs of negative impacts of tagging were also documented in the weekly study, although typically they were not statistically significant despite the large sample size (total $n = 661$ individuals). The most obvious among them was the lower weekly survival rate of Yellowfin Shiners relative to other species. The weekly tagged survival rate of Yellowfin Shiners was 93.3% (96.5–100% for the other five species), and this species also experienced a 93.3% survival rate in control cages. Thus, we attribute the lower survival rate of Yellowfin Shiners to their inherent vulnerability to electrofishing and handling procedures. During our preliminary trials, we also tagged Rosyface Chub *Hybopsis rubrifrons* and noticed their vulnerability to handling and tagging, as they shed scales easily. Thus, effects of PIT-tagging will depend upon species-specific vulnerability to handling. Morphology of species can also influence tagging effects. For example, we did not study the Turquoise Darter *Etheostoma inscriptum* and Blackbanded Darter *Percina nigrofasciata*, two percids found in our study streams, due to their very slender bodies and small abdominal cavity volume. Body size was equally important in affecting weekly survival. Larger fish were significantly more likely to survive. Nearly half (7 of 13) of the tagged fish that did not survive in the weeklong experiment were smaller than 60 mm TL, although they comprised 30.3% of tagged individuals (Tables 3, 4). Finally, mortalities of control fish were observed only among Yellowfin Shiners, but mortalities of tagged fish were recorded in Bluehead Chub, Creek Chub, Mottled Sculpin, and Yellowfin Shiners (Table 3). These observations further highlight that care should be taken in designing tagging studies of small-bodied species.

Weekly and bimonthly survival rates are not directly comparable because the former are true survival rates and the latter are apparent survival rates in this study. In other words, weekly survival was documented in confined enclosures, whereas bimonthly survival was estimated in a stream section from which fish could emigrate. Weekly survival rate of Mottled Sculpin (42/43 = 0.977) would translate to $(0.977)^8 = 0.830$ (for 8 weeks or 2 months), and that of Bluehead Chub (139/144 = 0.965) would translate to $(0.965)^8 = 0.752$ (Table 3). In comparison, estimates of the mean bimonthly apparent survival rate were 0.74 for Mottled Sculpin and 0.76 for Bluehead Chub. The lower bimonthly survival rate in Mottled Sculpin is at least partly attributable to the emigration of fish from study sections based on the spatial extent of our investigation (740 m in Indian Creek; 520 m in Todd Creek).

Successful applications of PIT tag technology to small-bodied fishes allow for an improved understanding of their ecology and conservation. These applications should help to fill knowledge gaps in biology and life history of small-bodied, nongame species, which would be particularly useful for regions like the southeastern United States, where diversity is high and many endemic species are small bodied (Warren and Burr 1994; Warren et al. 2000). Tagging affected weekly survival only minimally, and the level of mortality we observed is unlikely to impact population dynamics and persistence. However, caution should be exercised when even a small number of mortalities must be avoided (e.g., for endangered and threatened species). In these cases, the minimum body size for tagging should be carefully examined, and other tagging techniques (e.g., visible implant elastomer) may need to be considered (Bangs et al. 2013). The surrogate-species approach can also be considered when morphologically and ecologically similar species exist (Wenger 2008). Judicious applications of PIT tag technology should expand the knowledge base for many lesser-known nongame species through individual-based approaches.

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