North American Journal of Fisheries Management 37:1362–1369, 2017

ISSN: 0275-5947 print / 1548-8675 online
DOI: https://doi.org/10.1080/02755947.2017.1388886

MANAGEMENT BRIEF

Detection Efficiency of a Portable PIT Antenna for Two Small-Bodied Fishes in a Piedmont Stream

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Abstract
Passive integrated transponder (PIT) tags have been used to infer demography and behavior of lotic fishes, but their application has mostly been limited to salmonids. We studied the efficiency of a portable PIT antenna in a small Piedmont stream (mean width = 2.4 m) in South Carolina by comparing two tag sizes (8- and 12-mm full-duplex tags) applied to two nongame species (Mottled Sculpin *Cottus bairdii* and Creek Chub *Semotilus atromaculatus*). A 285-m stream reach was blocked off under base flow conditions in September 2016, and 8- or 12-mm PIT tags were implanted in 67 Creek Chub (62–138 mm TL) and 65 Mottled Sculpin (60–88 mm TL). Starting at 1 d after tagging, the study reach was sampled with the portable PIT antenna twice daily for five consecutive days, during which apparent survival of tagged fish was assumed. Generalized linear mixed-effects models with a logistic link identified that detection efficiency depended on species, tag size, body length, and the species × body length interaction. Mottled Sculpin had detection rates of 56% (8-mm tags) and 79% (12-mm tags), with 67% of detections occurring in riffle-dominated sections, whereas Creek Chub had 3% (8-mm tags) and 16% (12-mm tags) detection rates, with 62% of detections occurring in pool-dominated sections. Detection efficiency decreased with body size in Creek Chub but not in Mottled Sculpin; the observed decrease for Creek Chub was most likely attributable to an ontogenetic habitat shift. The reasonably high detection efficiency of Mottled Sculpin, even with 8-mm tags, suggested that the portable PIT antenna can be a viable option for some species in small streams, allowing individual-based approaches to studying small-bodied species or earlier life stages without the need for repeated physical capture and handling.

Data collected on uniquely marked individuals are useful for obtaining information on life history and biology (Ruetz et al. 2006). Among marking techniques, PIT tags are commonly used in fisheries research because they are small in size and are relatively inexpensive (Cooke et al. 2013; Banish et al. 2016; Cary et al. 2017; O'Donnell and Letcher 2017). Passive integrated transponder technology has multiple applications in mark–redetection studies. One application is portable PIT antennas, which allow for the redetection of aquatic organisms without physical collection and handling (Burnett et al. 2013; Banish et al. 2016). Portable PIT antennas can offer a more time-efficient and effective alternative to other sampling methods (Cucherousset et al. 2005). For instance, a portable PIT antenna detected freshwater mussels more effectively than visual surveys (Kurth et al. 2007).

Portable PIT antennas also offer certain advantages over fixed PIT antenna arrays. Portable PIT antennas are lightweight and mobile, enabling a single operator to detect tagged individuals with relative ease and effort. Moreover, active searching by portable antennas allows for the detection of fish at finer spatial resolutions than fixed PIT antenna arrays. A portable PIT antenna allowed Linnansaari and Cunjak (2013) to study the behavior of Atlantic Salmon *Salmo salar* during the winter period, when their study reach was covered in surface ice. Zydlewski et al. (2001) used a portable PIT antenna to investigate movement of Atlantic Salmon, while other studies have utilized the same technology for obtaining apparent survival estimates (Keeler et al. 2007) and evaluating habitat selection of morphologically and behaviorally different species (Cucherousset et al. 2010).

Although potentially useful in many instances, a limitation of the portable PIT antenna is its short detection range. For example, Cucherousset et al. (2005) reported a maximum detection range of 17–36 cm for 12-mm tags. Detection efficiency of portable PIT antennas depends on various factors. Efficiency can vary

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Received May 13, 2017; accepted October 2, 2017

depending on user proficiency, species behavior (Cucherousset et al. 2010), and PIT tag size (Burnett et al. 2013). Detection is less efficient in complex habitats that may contain boulder substrate, deep holes or pools, and undercut banks (Hill et al. 2006; Cucherousset et al. 2010). Increases in velocity, stream temperature, and width also negatively affect efficiency (Keeler et al. 2007; O'Donnell et al. 2010). The majority of previous studies of portable PIT antenna efficiency focused on game species, particularly salmonids (O'Donnell et al. 2010; Sloat et al. 2011; Banish et al. 2016). Such data are scarce for small-bodied, nongame stream fishes (Keeler et al. 2007; Mitsuo et al. 2013). Marked data on small individuals are difficult to collect because their body size limits suitable marking methods and tag size (Brown et al. 2006; Cooke et al. 2013). However, gaining information on life history, status, and biology of nongame species is critical because many imperiled freshwater fishes are small-bodied, nongame species (Moyle and Leidy 1992; Ricciardi and Rasmussen 1999; Dudgeon et al. 2006).

To investigate the potential application of this technology to small-bodied individuals, we compared the detection efficiency of a portable PIT tag antenna between two nongame stream species with contrasting habitat selection (the riffle-dwelling Mottled Sculpin *Cottus bairdii* and the pool-dwelling Creek Chub *Semotilus atromaculatus*) and between two tag sizes (8- and 12-mm full-duplex [FDX] tags). To our knowledge, 8-mm tags have not been tested for stream fish detection efficiency with a portable PIT antenna, presumably due to their small detection range. Efficient detection using 8-mm tags would lower the minimum body size threshold, providing increased opportunities to collect marked data on small-bodied species or juveniles of other species. Additionally, 8-mm tags are less invasive to fish due to their smaller volume, and it is important to assess whether this advantage is potentially offset by decreased detection efficiency of the smaller tag size. We hypothesized that (1) detection efficiency of Mottled Sculpin would be higher than that of Creek Chub because the former occupy shallower habitats and tend to seek refugia under and around rocks instead of fleeing when wary of danger (e.g., approached by the portable PIT antenna); (2) detection efficiency would be higher for 12-mm tags than for 8-mm tags; and (3) detection efficiency would depend on the body length of tagged individuals due to microhabitat changes through ontogeny (Cucherousset et al. 2005), but this relationship could be more evident in Creek Chub than in Mottled Sculpin (i.e., body length × species interaction) because Creek Chub had a wider range of body sizes in this study, associated with ontogenetic habitat changes from shallower to deeper stream sections (Magnan and FitzGerald 1984).

METHODS

Study area and species.—This study was conducted in Indian Creek (34°26′35.484″N, –82°30′21.6″W), a second-order perennial stream (2.4 m wide) located in the Piedmont region of South Carolina. Indian Creek was situated within the Clemson University Experimental Forest; its surrounding land cover was predominantly mixed hardwood forest, and riparian area consisted of dense herbaceous cover. The study stream was characterized by a series of riffle–pool sequences. Riffles were dominated by pebble (32–64-mm) and cobble (64–128-mm) substrates, whereas pools were characterized by sand substrate. Common species found in the stream included the Mottled Sculpin, Creek Chub, Bluehead Chub *Nocomis leptocephalus*, Yellowfin Shiner *Notropis lutipinnis*, and Striped Jumprock *Moxostoma rupiscartes*.

We tested the efficiency of the portable PIT antenna at detecting two species: the Creek Chub and Mottled Sculpin. These species differ in morphology, habitat preferences, and behavior, which may affect their ease of detection. The Creek Chub is a water column cyprinid with a fusiform body shape, and adults prefer pool habitats (Magnan and FitzGerald 1984). The Mottled Sculpin is a riffle-dwelling species with a cryptically colored, dorsoventrally flattened body that enables it to hide around or under rocks (Grossman and Ratajczak 1998).

Data collection.—Prior to field sampling, the detection range of the 8- and 12-mm PIT tags was measured out of water. An FDX tag of each size was placed on bare soil and was approached with a Biomark BP Plus Portable antenna (Biomark, Boise, Idaho). This process was repeated 10 times. The mean detection distance was 11.5 cm (SD = 2.8) for 8-mm tags and 21.2 cm (SD = 0.9) for 12-mm tags.

We selected a 285-m representative reach of Indian Creek for our field experiment, which was conducted under base flow conditions on September 4–9, 2016. The study reach was isolated for the entire duration of the experiment by setting a 0.318-cm-mesh block net across the stream bed at the upstream and downstream ends of the reach to prevent the emigration of tagged fish. Nets were installed in shallow riffles in a V-shape with the point facing downstream. The top frame of each net was secured to two t-posts on each side of the stream and a third t-post in the middle of the stream. The bottom of the net was anchored by using sandbags and cobbles to prevent fish from passing under the net. The study reach was divided into fifty-seven 5-m sections. Each section was visually classified as a riffle or pool based on the dominant habitat characteristics. Stream width, depth, and velocity measurements were obtained from every other section at three transects per section.

Mottled Sculpin and Creek Chub were collected in Indian Creek by using a two-pass electrofishing method (400 V, 60 Hz on a 25% duty cycle) with a Smith-Root LR-24 pulsed-DC backpack electrofisher (Smith-Root, Inc., Vancouver, Washington). Stunned fish were captured and placed in aerated live wells. Fish were anesthetized in a buffered solution of clove oil and water. Weight and TL (nearest mm) were recorded for each individual on an Allegro^2 field computer (Juniper Systems, Inc., Logan, Utah) by using Dataplus software (Dataplus, Inc., North Chelmsford, Massachusetts). Only fish larger than 60 mm were tagged with Biomark FDX tags. This length is commonly associated with the minimum size for 12-mm tags (Bangs et al. 2013). Individuals were divided between 8- and 12-mm treatments while ensuring similar size distributions between the two treatments. Of the 67 Creek Chub, 31 individuals (mean = 88 mm TL; range = 62–129 mm) were implanted with 12-mm tags, and 36 individuals (mean = 87 mm TL; range = 64–138 mm) received 8-mm tags. Of the 65 Mottled Sculpin, 32 individuals (mean = 72 mm TL; range = 60–87 mm) received 12-mm tags, and 33 individuals (mean = 71 mm TL; range = 60–88 mm) were implanted with 8-mm tags. Body size did not significantly differ between the two tag size treatments for Creek Chub (t = 0.33, df = 62.80, P = 0.74) or Mottled Sculpin (t = 0.36, df = 60.31, P = 0.72). However, Creek Chub were significantly larger in body size than Mottled Sculpin (t = 6.98, df = 84.51, P < 0.001), and the body size range of Creek Chub was wider than that of Mottled Sculpin. The size ranges of Creek Chub and Mottled Sculpin observed were representative of their populations in the study stream.

Creek Chub were tagged by inserting a PIT tag through a ventral incision lateral to the midline (Wagner and Stevens 2000) posterior of the pectoral fins. Incisions were kept minimal, approximately equal to the diameter of the tag. Tags were inserted posteriorly to limit disturbance to internal organs. For Mottled Sculpin, PIT tags were implanted via a Biomark N165 needle inserted anterior to the anal vent and into the abdominal cavity. This method was utilized because of the Mottled Sculpin's soft ventral surface (Ruetz et al. 2006). A pilot study using the same tagging methods indicated that survival and tag retention of Mottled Sculpin and Creek Chub (>40 mm TL) with 8-mm tags were greater than 98% over 1 week (Cary et al. 2017). After handling, fish were allowed to recover in an aerated live well until normal swimming behavior was observed. Tagged fish were distributed throughout the study reach and were given 18 h to recover before sampling with the portable PIT antenna began. The person who distributed tagged fish never participated in antenna detection sampling to avoid the "memory" effect, which could influence detection efficiency; fish were carried in buckets sorted by tag size to ensure spatial mixing between fish with 8-mm tags and those with 12-mm tags.

The stream reach was sampled using a Biomark BP Plus Portable antenna for five consecutive days after the tagging event. Sampling was conducted under stable thermal and flow conditions. The mean daily stream temperature ranged from 20.9°C to 21.4°C during the 5-d period (HOBO Water Temp Pro v2 data logger; Onset Computer Corp., Bourne, Massachusetts), and there was no precipitation. Sampling took place twice daily: once in the morning (between 0800 and 1000 hours) and once in the afternoon (between 1400 and 1600 hours), for a total of 10 sampling occasions. Two individuals, a wander and a recorder, sampled all fifty-seven 5-m sections by using a single pass with the portable PIT antenna on each occasion. The operator waded in the stream upstream while submerging the antenna and scanning all available habitats. To avoid any potential user bias, a different individual operated the portable PIT antenna on each sampling occasion. The recorder, while following alongside on the bank, noted the start and end times for each section so that this information could be used to determine the section of tag detection based on the Biomark BP Plus recorder's time stamps. A section was typically sampled within 1–2 min. Finally, in addition to our experimental reach, the 100-m reaches above and below the block nets were sampled with the portable PIT antenna twice daily on the third, fourth, and fifth sampling day to check for fish that might have escaped.

Statistical analysis.—Generalized linear mixed-effects models (GLMMs) with logistic link were employed to examine factors affecting the detection efficiency of tagged individuals by using the portable PIT antenna. The response variable was binary such that an individual was given a value of 1 if detected on a sampling occasion and 0 otherwise. Predictor variables were species (Creek Chub or Mottled Sculpin), PIT tag size (8 or 12 mm), and body length (standardized by the mean) as main fixed effects and sampling occasion as a random effect to account for potential variation in detection efficiency among the 10 different individuals (twice daily for 5 d) who operated the portable PIT antenna. The models were specified by an effects parameterization method (Kéry 2010), with Creek Chub and 12-mm tags as references. Thus, the intercept of the model represented the mean detection probability of Creek Chub that received 12-mm tags, and differences (i.e., effects) for Mottled Sculpin and 8-mm tags were inferred in the models. In addition, we assumed that the effects of body length could differ by species because the range of body lengths differed between Mottled Sculpin (60–88 mm TL) and Creek Chub (62–138 mm TL), and the latter species is known to change habitat from shallower to deeper areas during ontogeny (Magnan and FitzGerald 1984). Accordingly, the interaction between species and body length was included in the GLMM.

A set of candidate models was constructed, wherein each model represented a hypothesis affecting the detection efficiency of PIT tags. We considered that species and tag size should have strong effects on detection efficiency, whereas body length has had mixed results in previous studies (Cucherousset et al. 2005; Keeler et al. 2007; Weber et al. 2016). Thus, all models contained a species effect, a tag size effect, or both. In total, eight candidate models were constructed (Table 1), including a global model with three main effects and the interaction term. Models were compared using Akaike's information criterion corrected for small sample size (AIC_c). Models for which AIC_c values were within 2 units of the most supported model (i.e., AIC_c difference [ΔAIC_c] ≤ 2) were considered competing models (Burnham and Anderson 2002); however, no competing models were identified. Goodness of fit of the top-ranked model was assessed by using the area under the receiver operating characteristic curve (AUC). The values of AUC range from 0.5 and 1.0, with values closer to 1.0 indicating better predictive performance. Detection probabilities of tags were predicted using the top-ranked model. We simulated 1,000 sets of regression

TABLE 1. List of generalized linear mixed-effects models for PIT tag detection probability, ordered by ascending values of Akaike's information criterion corrected for small sample size (AIC_c). Models differed in their combinations of fixed effects; all models used sampling occasion as a random effect (Species = Mottled Sculpin or Creek Chub; Tag size = 8 or 12 mm; Length = fish TL; K = number of parameters; ΔAIC_c = difference in AIC_c value between the given model and the best-performing model; weight = Akaike weight).

Fixed effects	K	Log likelihood	AIC_c	ΔAIC_c	Weight
Species + Tag size + Length + (Length × Species)	6	−568.0	1,148.99	0.00	0.98
Species + Tag size + Length	5	−572.9	1,155.83	7.84	0.02
Species + Tag size	4	−578.0	1,164.07	16.08	0.00
Species + Length + (Length × Species)	5	−603.2	1,216.38	68.39	0.00
Species + Length	4	−608.3	1,224.70	76.71	0.00
Species	3	−612.0	1,230.02	82.03	0.00
Tag size + Length	4	−846.8	1,701.59	553.60	0.00
Tag size	3	−849.9	1,705.81	557.82	0.00

coefficients to account for correlation among predictors and uncertainties of predictions.

Finally, to assess whether the operation of the portable PIT antenna in an upstream direction affected fish movement (i.e., pushing fish upstream) and whether emigration of tagged individuals from the study reach was likely, the direction and distance moved by tagged individuals were assessed between successive redetection events. A frequency histogram of movement distances and directions (upstream or downstream) was constructed at the 5-m section scale. Proportions of upstream versus downstream movement were compared using a chi-square test of independence to evaluate the null hypothesis that tagged individuals moved equally upstream and downstream when movement occurred. The chi-square test was conducted only for Mottled Sculpin due to the small sample size of redetections for Creek Chub. All analyses in this study were performed using R software (R Core Team 2016), and statistical significance α was set at 0.05.

RESULTS

Overall, 132 individuals (67 Creek Chub and 65 Mottled Sculpin) were PIT-tagged and subsequently released into our study reach. On each of the 10 sampling occasions, we detected from 65% to 90% (mean = 79%) of the Mottled Sculpin that were released with 12-mm PIT tags and from 32% to 77% (mean = 56%) of those released with 8-mm tags. For Creek Chub, we detected from 7% to 42% (mean = 16%) of those released with 12-mm PIT tags and from 0% to 11% (mean = 3%) of those released with 8-mm tags. Habitat occupancy differed between the two species; 67% of the Mottled Sculpin detections occurred in sections characterized as riffles, whereas 62% of the Creek Chub detections occurred in pool sections. Twenty-eight of the 57 sections were designated as pools, where the mean width was 2.7 m (SD = 0.8), depth was 19.0 cm (SD = 5.0), and velocity was 0.04 m/s (SD = 0.02). Across the remaining 29 riffle sections, the mean width was 2.2 m (SD = 0.6), depth was 7.5 cm (SD = 1.9), and velocity was 0.14 m/s (SD = 0.04).

The top-ranked model was the global model, with significant effects of species, tag size, body length, and the species × body length interaction (Table 1). The global model outperformed the second-ranked model (which had a ΔAIC_c value of 7.84) and held an Akaike weight of 0.98. The top-ranked model exhibited high goodness of fit, with an AUC value of 0.88. As hypothesized, tag detection rates differed significantly between species: Mottled Sculpin were more likely to be detected than Creek Chub (coefficient = 3.43, $P < 0.001$). Odds ratios indicated that Mottled Sculpin were 31.02 times more likely to be detected than Creek Chub, and species had the greatest effect of all factors examined based on odds ratios (Table 2). As hypothesized, 8-mm PIT tags were less detectable than 12-mm tags (coefficient = –1.26, $P < 0.001$), and odds ratios indicated that 8-mm tags were 3.03 times less likely to be detected than 12-mm tags. There was a significant species × length interaction (Table 1; Figure 1). Length had a negative effect on detection efficiency in Creek Chub (coefficient = –0.69, $P < 0.001$), indicating that smaller individuals were more likely to be detected than larger individuals of this

TABLE 2. Mean parameter estimates, SEs, P-values, and odds ratios for the top-ranked model of PIT tag detection probability (see Table 1). "Intercept" represents the mean detection probability of Creek Chub that received 12-mm PIT tags; "Mottled Sculpin" and "8-mm tag" represent differences relative to the reference condition (i.e., effects parameterization).

Parameter	Estimate	SE	P-value	Odds ratio
Intercept	−1.98	0.20	<0.001	NA
Mottled Sculpin	3.43	0.19	<0.001	31.02
8-mm tag	−1.26	0.16	<0.001	0.33
Length	−0.69	0.18	<0.001	0.50
Mottled Sculpin × Length	0.59	0.20	0.002	1.80

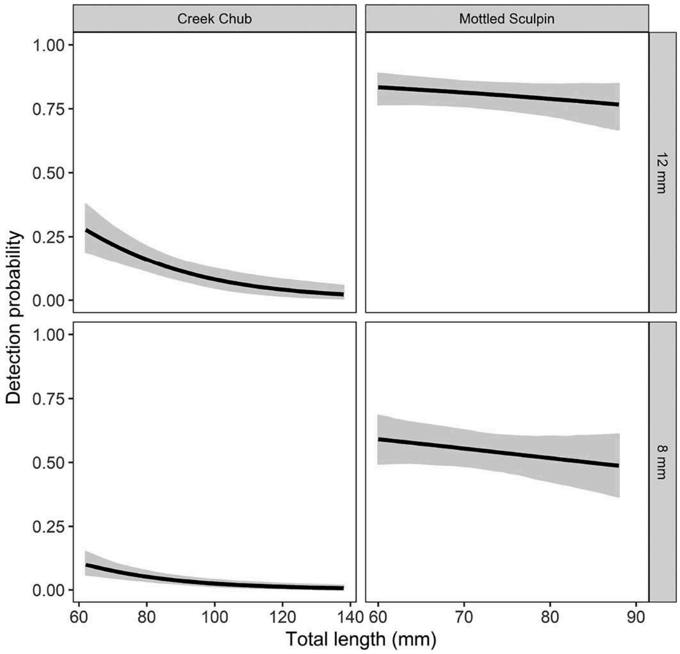

FIGURE 1. Model-predicted effects of fish TL (mm) on detection probability with a portable PIT tag antenna for Creek Chub and Mottled Sculpin that received 8- or 12-mm PIT tags (black lines = mean response; gray shading = 95% confidence interval).

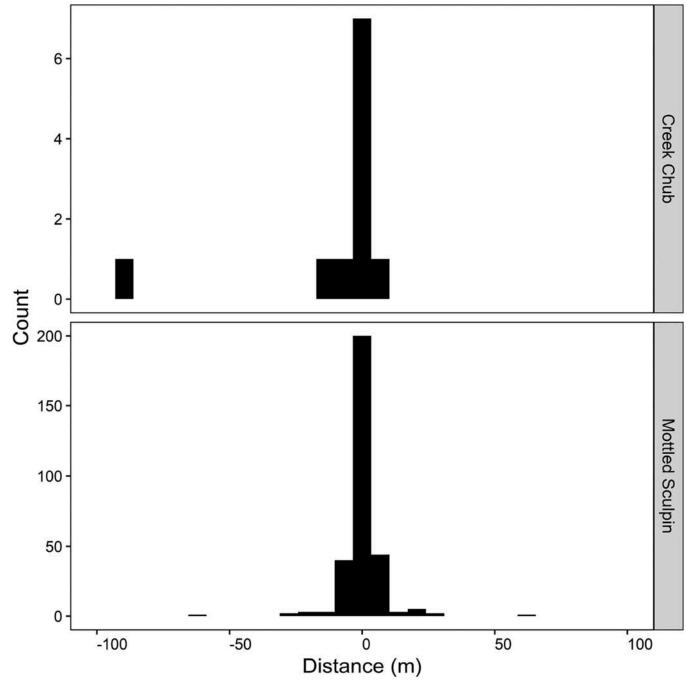

FIGURE 2. Frequency distributions of movement distances (m) between consecutive redetection occasions for Creek Chub and Mottled Sculpin in the Indian Creek study reach. Positive distances indicate upstream movement; negative distances indicate downstream movement. Data from fish that received 8- and 12-mm PIT tags are pooled.

species. However, length did not significantly affect the detection efficiency of Mottled Sculpin (coefficient = –0.10, P = 0.27).

Movement of Mottled Sculpin and Creek Chub was generally limited during the 5-d study period. Sixty-two Mottled Sculpin and seven Creek Chub were detected on at least two sampling occasions, resulting in 304 movements for Mottled Sculpin and 11 movements for Creek Chub (Figure 2). For Mottled Sculpin, 66% of the redetections were recorded in the same 5-m sections, 16% indicated downstream movement, and 18% indicated upstream movement. Proportions of upstream versus downstream movements did not significantly differ (χ^2 = 0.08, df = 1, P = 0.78), thus providing no evidence that operating the portable PIT antenna in an upstream direction pushed tagged individuals upstream. The maximum movement for Mottled Sculpin was 65 m. For Creek Chub, 64% of the redetections were in the same sections, 9% reflected upstream movement, and 27% reflected downstream movement. The maximum movement observed for Creek Chub was 90 m. Finally, no individuals were detected 100 m above or below the study reach by use of the portable PIT antenna on any of the six occasions (twice daily on the third, fourth, and fifth sampling days).

DISCUSSION

Detection efficiencies of PIT-tagged Mottled Sculpin in this study were comparable to those observed in previous studies. Breen et al. (2009) reported that the mean detection efficiency of a portable PIT antenna for Mottled Sculpin with 12.45-mm FDX tags was 76% (versus the 79% found in this study with 12-mm FDX tags), and studies of salmonids that received 12-mm FDX tags reported detection probabilities ranging from 30% to 87% (Cucherousset et al. 2005, 2010; Sloat et al. 2011; Banish et al. 2016). In our study, Mottled Sculpin with 8-mm tags were detected reasonably well (56%), but detection efficiency was low (16%) for Creek Chub that received 12-mm tags and was even lower (3%) for Creek Chub with 8-mm tags. Low detection efficiency (0.7%) was similarly reported for another small-bodied cyprinid, the Eurasian Dace *Leuciscus leuciscus* (with 12-mm FDX tags; Cucherousset et al. 2010).

We attribute the Mottled Sculpin's higher detection rates to their habitat preferences, sedentary behavior, and hiding tendencies. Mottled Sculpin were predominantly detected in riffles, where low habitat complexity and shallow depths allowed for efficient detection by the range-limited portable PIT antenna. When approached by the wander, Mottled Sculpin tended to hide under or around rocks in riffles, and we were able to visually confirm the locations of tagged Mottled Sculpin by slowly lifting rocks in many instances. In contrast, Creek Chub—particularly the larger individuals—preferred pool habitats in which depth and volume allowed this water column species to flee from the approaching antenna more easily. In fact, Creek Chub were often collected via electrofishing in pools containing woody debris or undercut banks. Given the diameter (31 cm) of the portable PIT antenna's circular head, these complex physical characteristics affected the antenna's ability to detect Creek Chub effectively. The differences between the two study species affirm the findings of previous studies in which species tending to hide or use shallow and physically less-complex habitats were more easily detected by portable PIT antenna technology (Cucherousset et al. 2005, 2010).

Body length negatively affected the detection efficiency of Creek Chub but not Mottled Sculpin. The effect of body length has been shown to differ among species in previous studies. Larger individuals of Brown Trout *Salmo trutta* were similarly less detectable in a second-order stream (mean channel width = 1–4 m; Cucherousset et al. 2005), but length did not affect the detection of Slimy Sculpin *Cottus cognatus* (Keeler et al. 2007) or European Bullheads *Cottus gobio* (Weber et al. 2016). Juvenile Creek Chub typically occupy shallower areas, and adults are found in deeper pools with cover (Magnan and FitzGerald 1984), a pattern similarly observed when collecting fish via electrofishing in this study. This ontogenetic habitat shift by Creek Chub likely accounted for the negative effect of body length on detection efficiency. In contrast, Mottled Sculpin prefer riffles (Petty and Grossman 2004), and during our study, they were predominantly collected from this habitat type regardless of their body size. We also note that the size range of individuals used in this study was larger for Creek Chub (62–138 mm TL) than for Mottled Sculpin (60–88 mm TL), which may have further contributed to the difference in body length effects between the two species.

Although the 12-mm PIT tags have a higher detection rate, the minimum fish size for application of these tags is 60 mm TL (Zydlewski et al. 2006; Archdeacon et al. 2009), and 12-mm tags are 241% larger by volume than 8-mm tags. The 56% detection rate of Mottled Sculpin with 8-mm PIT tags was higher than we had anticipated and was comparable to the capture probability of individual fish in single-pass backpack electrofishing, as reported for the Brook Trout *Salvelinus fontinalis* (57%; Letcher et al. 2015), Mottled Sculpin (54%), Central Stoneroller *Campostoma anomalum* (54%), Creek Chub (55%), Brown Trout (59%), and Longnose Dace *Rhinichthys cataractae* (56%; Hense et al. 2010). Use of 8-mm tags allows for the tagging of fish as small as 35–40 mm TL (Bangs et al. 2013; Cary et al. 2017; O'Donnell and Letcher 2017. Thus, the researcher is faced with a trade-off between higher detection efficiency but larger minimum fish size when using 12-mm tags versus lower detection efficiency but smaller minimum fish size when using 8-mm tags. This choice would be largely dictated by the research questions and species of interest. Nonetheless, our study demonstrates that 8-mm PIT tags could be utilized with portable PIT antennas for species with relatively sedentary behavior and shallow habitat preferences in small streams.

We postulate that the operation of the portable PIT antenna did not affect fish movement and, more importantly, that tag loss due to emigration of individuals from the study reach was absent or at best negligible for several reasons. First, block nets were placed at shallow riffles under base flow conditions by using sandbags and pebbles, which effectively sealed space under the nets and along the edge of the wetted width of the stream. Second, movement of tagged fish was limited, with a majority (66% for Mottled Sculpin; 64% for Creek Chub) of tagged fish redetections by the portable PIT antenna recorded in the same 5-m sections where those individuals had been last detected. Our sample size for Creek Chub was admittedly low (N = 11 movements), but Belica and Rahel (2008) similarly observed limited movement of Creek Chub over a 2-week period, during which 54% of 209 tagged individuals moved less than 50 m. Third, when movement occurred, it was equally upstream and downstream despite the consistent upstream tracking with the portable PIT antenna, suggesting that the tracking did not push fish upstream (Hill et al. 2006). Lastly, we did not detect any tagged fish above or below the study reach with the portable PIT antenna despite the high detection efficiency of that antenna, at least for Mottled Sculpin. The mean capture probability of individuals with two-pass electrofishing in the study stream was 0.40 for Mottled Sculpin (Cary et al. 2017) and 0.39 for Creek Chub (Y. Kanno, unpublished data) in comparison with 0.79 (12-mm tags) and 0.56 (8-mm tags) for Mottled Sculpin and 0.16 (12-mm tags) and 0.03 (8-mm tags) for Creek Chub by using the single-pass portable PIT antenna. Along with high survival rates (>98%) of tagged fish over the 5-d study period (Cary et al. 2017), it was highly likely that tagged fish were alive and stayed in the study reach, thus maintaining their availability for detection by the portable PIT antenna. However, if undocumented emigration of tagged fish from the study reach occurred, then our estimates of detection efficiency would be conservative, and true detection efficiency could be higher than the efficiencies reported here.

The application of small PIT tags and antennas to nongame fishes should help to fill knowledge gaps on life history, movement, and demography. Such information is indeed necessary as more small-bodied, nongame freshwater fishes become imperiled (Moyle and Leidy 1992; Ricciardi and Rasmussen 1999; Dudgeon et al. 2006). The portable PIT antenna also enables the detection of unique individuals without physical recaptures and thus diminishes handling stress compared to other sampling techniques. For instance, backpack electrofishing has been shown to negatively influence survival for young-of-the-year cyprinids (Janáč and Jurajda 2011). Moreover, portable PIT antennas can be operated by one user. Our results indicate the viability of individual-based approaches to studying small-bodied stream fishes by using portable PIT antenna technology. The reasonably high detection efficiency of 8-mm tags in Mottled Sculpin is particularly noteworthy and suggests that this technology could be usable for individuals smaller than those tested here (<60 mm TL; Cary et al. 2017).

ACKNOWLEDGMENTS

This study was financially supported by the Creative Inquiry Program for undergraduate research and the College of Agriculture, Forestry, and Life Sciences at Clemson University. Field assistance was provided by Marxie Antonov, Parker Johnson, Daniel Jones, Jae Eui Lee, Ryan Martin, Wesley Moore, Edward Stello, and Alexus Watford. An earlier version of the manuscript was greatly improved by the constructive comments of three anonymous reviewers.

REFERENCES

Archdeacon, T. P., W. J. Resmhardt, and R. L. Knecht. 2009. Comparison of two methods for implanting passive integrated transponders in Rio Grande Silvery Minnow. North American Journal of Fisheries Management 29:346–351.

Bangs, B. L., M. R. Flacy, P. D. Scheerer, and S. Clements. 2013. Comparison of three methods for marking a small floodplain minnow. Animal Biotelemetry [online serial] 1:18.

Banish, N. P., S. M. Burdick, and K. R. Moyer. 2016. Efficiency of portable antennae for detecting passive integrated transponder tags in stream-dwelling salmonids. PLOS (Public Library of Science) ONE [online serial] 11: e0149898.

Belica, L. A. T., and F. J. Rahel. 2008. Movements of Creek Chubs, *Semotilus atromaculatus*, among habitat patches in a plains stream. Ecology of Freshwater Fish 17:258–272.

Breen, M. J., C. R. Ruetz III, K. J. Thompson, and S. L. Kohler. 2009. Movements of Mottled Sculpins (*Cottus bairdii*) in a Michigan stream: how restricted are they? Canadian Journal of Fisheries and Aquatic Sciences 66:31–41.

Brown, R. S., D. R. Geist, K. A. Deters, and A. Grassell. 2006. Effects of surgically implanted acoustic transmitters >2% of body mass on the swimming performance, survival and growth of juvenile Sockeye and Chinook salmon. Journal of Fish Biology 69:1626–1638.

Burnett, N. J., K. M. Stamplecoskie, J. D. Thiem, and S. J. Cooke. 2013. Comparison of detection efficiency among three sizes of half-duplex passive integrated transponders using manual tracking and fixed antenna arrays. North American Journal of Fisheries Management 33:7–13.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer-Verlag, New York.

Cary, J. B., J. L. Holbrook, M. E. Reed, T. B. Austin, M. S. Steffensen, S. Kim, K. C. Pregler, and Y. Kanno. 2017. Survival of upper Piedmont stream fishes implanted with 8-mm passive integrated transponder tags. Transactions of the American Fisheries Society 146:1223–1232.

Cooke, S. J., J. D. Midwood, J. D. Thiem, P. Kimley, M. C. Lucas, E. B. Thorstad, J. Eiler, C. Holbrook, and B. C. Ebner. 2013. Tracking animals in freshwater with electronic tags: past, present and future. Animal Biotelemetry [online serial] 1:5.

Cucherousset, J., J. R. Britton, W. R. C. Beaumont, M. Nyqvist, K. Sievers, and R. E. Gozlan. 2010. Determining the effects of species, environmental conditions and tracking method on the detection efficiency of portable PIT telemetry. Journal of Fish Biology 76:1039–1045.

Cucherousset, J., J. Roussel, R. Keeler, R. A. Cunjak, and R. Stump. 2005. The use of two new portable 12-mm PIT tag detectors to track small fish in shallow streams. North American Journal of Fisheries Management 25:270–274.

Dudgeon, D., A. H. Arthington, M. O. Gessner, Z. Kawabata, D. J. Knowler, C. Lévêque, R. J. Naiman, A. Prieur-Richard, D. Soto, M. L. J. Stiassny, and C. A. Sullivan. 2006. Freshwater biodiversity: importance, threats, status, and conservation challenges. Biological Reviews 81:163–182.

Grossman, G. D., and R. E. Ratajczak Jr. 1998. Long-term patterns of microhabitat use by fish in a southern Appalachian stream from 1983 to 1992: effects of hydrologic period, season and fish length. Ecology of Freshwater Fish 7:108–131.

Hense, Z., R. W. Martin, and J. T. Petty. 2010. Electrofishing capture efficiencies for common stream fish species to support watershed-scale studies in the central Appalachians. North American Journal of Fisheries Management 30:1041–1050.

Hill, M. S., G. B. Zydlewski, J. D. Zydlewski, and J. M. Gasvoda. 2006. Development and evaluation of portable PIT tag detection units: PITpacks. Fisheries Research 77:102–109.

Janáč, M., and P. Jurajda. 2011. Mortality induced by electrofishing and handling in five young-of-the-year cyprinids: effect of the fish size, species and anode size. Journal of Applied Ichthyology 27:990–994.

Keeler, R. A., A. R. Breton, D. P. Peterson, and R. A. Cunjak. 2007. Apparent survival and detection estimates for PIT-tagged Slimy Sculpin in five small New Brunswick streams. Transactions of the American Fisheries Society 136:281–292.

Kéry, M. 2010. Introduction to WinBUGS for ecologists: a Bayesian approach to regression, ANOVA, mixed models and related analyses. Academic Press, Cambridge, Massachusetts.

Kurth, J., C. Loftin, J. Zydlewski, and J. Rhymer. 2007. PIT tags increase effectiveness of freshwater mussel recaptures. Journal of the North American Benthological Society 26:253–260.

Letcher, B. H., P. Schueller, R. D. Bassar, K. H. Nislow, J. A. Coombs, K. Sakrejda, M. Morrissey, D. B. Sigourney, A. R. Whiteley, M. J. O'Donnell, and T. L. Dubreuil. 2015. Robust estimates of environmental effects on population vital rates: an integrated capture–recapture model of seasonal Brook Trout growth, survival and movement in a stream network. Journal of Animal Ecology 84:337–352.

Linnansaari, T. P., and R. A. Cunjak. 2013. Effects of ice on behaviour of juvenile Atlantic Salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences 70:1488–1497.

Magnan, P., and G. J. FitzGerald. 1984. Ontogenetic changes in diel activity, food habits and spatial distribution of juvenile and adult Creek Chub, *Semotilus atromaculatus*. Environmental Biology of Fishes 11:301–307.

Mitsuo, Y., M. Ohira, H. Tsunoda, and M. Yuma. 2013. Movement patterns of small benthic fish in lowland headwater streams. Freshwater Biology 58:2345–2354.

Moyle, P. B., and R. A. Leidy. 1992. Loss of biodiversity in aquatic ecosystems: evidence from fish faunas. Pages 127–169 *in* P. L. Fiedler and S. K. Jain, editors. Conservation biology. Springer, New York.

O'Donnell, M. J., G. E. Horton, and B. H. Letcher. 2010. Use of portable antennas to estimate abundance of PIT-tagged fish in small streams: factors affecting detection probability. North American Journal of Fisheries Management 30:323–336.

O'Donnell, M. J., and B. H. Letcher. 2017. Implanting 8-mm passive integrated transponder tags into small Brook Trout: effects on growth and survival in the laboratory. North American Journal of Fisheries Management 37:605–611.

Petty, J. T., and G. D. Grossman. 2004. Restricted movement by Mottled Sculpin (Pisces: Cottidae) in a southern Appalachian stream. Freshwater Biology 49:631–645.

R Core Team. 2016. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Ricciardi, A., and J. B. Rasmussen. 1999. Extinction rates of North American freshwater fauna. Conservation Biology 13:1220–1222.

Ruetz, C. R., B. M. Earl, and S. L. Kohler. 2006. Evaluating passive integrated transponder tags for marking Mottled Sculpins: effects on growth and mortality. Transactions of the American Fisheries Society 135:1456–1461.

Sloat, M. R., P. F. Baker, and F. K. Ligon. 2011. Estimating habitat-specific abundances of PIT-tagged juvenile salmonids using mobile antennas: a comparison with standard electrofishing techniques in a small stream. North American Journal of Fisheries Management 31:986–993.

Wagner, G. N., and E. D. Stevens. 2000. Effects of different surgical techniques: suture material and location of incision site on the behavior of Rainbow Trout *(Oncorhynchus mykiss)*. Marine and Freshwater Behaviour and Physiology 33:103–114.

Weber, C., H. Scheuber, C. Nilsson, and K. T. Alfredsen. 2016. Detection and apparent survival of PIT-tagged stream fish in winter. Ecology and Evolution 6:2536–2547.

Zydlewski, G. B., A. Haro, K. G. Whalen, and S. D. McCormick. 2001. Performance of stationary and portable passive transponder detection systems for monitoring of fish movements. Journal of Fish Biology 58:1471–1475.

Zydlewski, G. B., G. Horton, T. Dubreuil, B. Letcher, S. Casey, and J. Zydlewski. 2006. Remote monitoring of fish in small streams: a unified approach using PIT tags. Fisheries 31:492–502.