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MANAGEMENT BRIEF

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Abstract
We compared detection efficiency for three lengths (12, 23 and 32 mm) of half-duplex (HDX) passive integrated transponder (PIT) tags for both manual tracking and fixed array applications. In a stream we used a wand-type manual tracking antenna and determined that detection efficiency was considerably influenced by tag size (i.e., 20% for 12 mm, 43% for 23 mm, and 81% for 32 mm) and water depth. Vertical and horizontal read range also varied among tag sizes (lower for smaller tags) and orientation (12-mm and 23-mm tags oriented perpendicularly failed to read in the horizontal test). Using a fixed PIT array, we also compared the detection efficiency of the same three sizes of PIT tags in Shorthead Redhorse *Moxostoma macrolepidotum* released into a fishway. Again, detection efficiency increased with tag size: 12 mm = 55.8 ± 9.2% (mean ± SE), 23 mm = 91.0 ± 1.8%, and 32 mm = 97.0 ± 1.5%. When using PIT telemetry on smaller fish species and/or life stages, we suggest that researchers consider the tag size, as the diminished detection efficiency of 12-mm tags could introduce a bias and impede the ability to address some research questions.

Since its initial development in the mid-1980s, passive integrated transponder (PIT) technology has been applied across a range of taxa, including fish, invertebrates, reptiles, amphibians, birds, and mammals (reviewed in Gibbons and Andrews 2004). However, PIT tags have perhaps been most embraced by the fisheries science community to mark and track fish in laboratory, aquaculture and natural systems (Prentice et al. 1990; Lucas and Baras 2000; Cooke et al. 2012). Although PIT tags provide a long-term mark often used to identify broodstock (Moore 1992), early studies relied on physically recapturing tagged fish and decoding their unique alpha-numeric tag code with a handheld wand. However, innovations in reader technology have led to the development of systems capable of manually tracking fish using back-pack units (e.g., Roussel et al. 2000; Bubb et al. 2006; Hill et al. 2006) and fixed arrays capable of detecting tagged animals as they pass near antennas (e.g., Castro-Santos et al. 1996; Bond et al. 2007; Aymes and Rives 2009). Upon detection, tagged fish can provide valuable insight into life history traits, such as habitat utilization, migratory processes and patterns, behaviors, and survival (Brännäs et al. 1994). Passive integrated transponder telemetry in fisheries research has developed into a more affordable method of tracking compared with traditional radio and acoustic telemetry methods (Cooke et al. 2012).

Manual tracking and use of fixed antenna arrays have increased in popularity and have been subject to continuous testing and improvement. For example, over the past two decades, fisheries scientists have been experimenting with several portable PIT detector designs (Morhardt et al. 2000; Cucherousset et al. 2005; Linnansaari and Cunjak 2007), aiming to improve the tag-reading performance of the portable unit, with the ultimate goal of increasing the detection range of tags. The general premise of these manual tracking devices is that an antenna on the distal end of a pole is systematically swept over the surface of streams (open water and through ice) interrogating tags and recording tag information. Fixed arrays are deployed at strategic sites to detect and record tagged fish as they pass near (or through) antennas. From an applied perspective in the wild, PIT tags have been used for monitoring small-scale fish movements through

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stationary streamwide antennas and above flatbed antennas (Armstrong et al. 1996; Aarestrup et al. 2003; Bond et al. 2007; Aymes and Rives 2009), for evaluating the passage efficiency of fishways (Castro-Santos et al. 1996; Baumgartner et al. 2010; Thiem et al. 2011; Thiem et al. in press), for estimating the survival of out-migrating salmonid smolts in hydropower-impacted systems (Williams et al. 2001; Hockersmith et al. 2003; Axel et al. 2005; Welch et al. 2008), and for identifying critical habitats of small stream fish (Gresswell et al. 2006; Enders et al. 2007).

Despite advances in manual tracking and fixed-array PIT technology, research has demonstrated that detection efficiency varies with several major biotic and abiotic factors. For example, physical habitat features such as undercut banks, deep pools, and woody debris accumulations negatively affect the detection efficiency of manual tracking systems, allowing fish to take shelter beyond the maximum detection distance of the wand-type antenna and impeding the movement of the operator (Bubb et al. 2002; Keeler et al. 2007; Cucherousset et al. 2008). Subsequently, missed detections can result due to low recapture rates and high habitat complexity, resulting in unrepresentative spatial ecology data. When using fixed arrays, fish traveling at high speeds or in large groups have been associated with decreased reader efficiencies, where code collision results in missed detections (Castro-Santos et al. 1996; Morhardt et al. 2000). Nonetheless, study objectives will dictate whether manual tracking, fixed arrays, or a combination of strategies are most appropriate for addressing research questions.

Passive integrated transponders are available in a variety of sizes, and it is well established that there is a tradeoff between tag size and read range (Cucherousset et al. 2010; Barbour et al. 2011). Larger tags tend to have higher detection efficiencies but smaller tags enable the tagging of smaller species or life stages, thus extending the utility of the technology. In addition to tag size, there are two types of PIT tags used in fisheries science that differ in their ability to transmit and receive data. While half-duplex (HDX) PIT tag systems separate data transmission and receiving periods temporally, full duplex (FDX) communication systems involve simultaneous data transmission and reception. As a result, HDX communication systems are much simpler than FDX systems, ultimately lowering the cost of the equipment required to undertake a PIT telemetry study (Barbour et al. 2011). However, until recently, HDX tags were only available in the 23-mm and 32-mm sizes. Therefore, existing studies that have evaluated the role of tag size (12, 23 and 32 mm) have been limited to FDX technology (e.g., Cookingham and Ruetz 2008; Cucherousset et al. 2009, 2010) or larger sizes of HDX tags (e.g., 23 and 32 mm; Morhardt et al. 2000; Linnansaari and Cunjak 2007). In addition, a number of recent studies have reported that a transponder oriented perpendicular to the antenna plane possesses a higher range of reading (Bubb et al. 2002; Hill et al. 2006; Bond et al. 2007). However, it is unclear how tag orientation influences detection efficiency of the full spectrum of HDX tag sizes.

Comparative analyses that examine the influence of HDX tag size on detection efficiency via both manual tracking and fixed arrays would inform researchers in selecting optimal tag size for a given application. Therefore, we used three sizes of HDX tags (12, 23 and 32 mm) representing the contemporary range of commercially available tags, and two detection strategies (manual tracking and a fixed array) to evaluate detection efficiency. Specifically, the objectives of this study were to (1) compare the detection efficiency of a portable backpack reader and a fixed PIT antenna array and (2) quantify the maximum vertical and horizontal read ranges of the three available tag sizes and determine how this varies with tag orientation.

METHODS

Experiment 1: detection efficiency in stationary PIT tags.— To test whether the detection efficiency of a portable HDX backpack reader varied with tag size and orientation, an experiment was carried out in Watts Creek (Kanata, Ontario, Canada; 45°20′42″N, 75°52′19″W), a small urban tributary of the Ottawa River. Ten PIT tags of each HDX size (12 × 2.12 mm, 23 × 3.65 mm, 32 × 3.65 mm; Texas Instruments Inc., Dallas, Texas) were fastened to the top of flat limestone rocks (mean weight = 168.1 g; SE, 7.2) using nonconductive tape and Plasti Dip (Plasti Dip International, Blaine, Minnesota), and randomly deployed throughout a 100-m study site reach on 4 April 2012. Limestone rocks were used because they contain only trace amounts of iron and, thus, were unlikely to influence tag performance. The study site reach (mean depth = 22.4 cm, SE = 6.1; channel width range = 3.7–8.5 m) was composed of deep pools, shallow and moderately deep riffles, and undercut banks. No artificial structures were present within or in close proximity to the study site. The rocks were placed in order to position the PIT tags either parallel (upstream–downstream) or perpendicular to stream flow. Considerable effort was directed to avoid woody debris accumulations, deep pools, and undercut banks when deploying tags. Additionally, all three tag sizes were spread equally among various potential fish habitats and depths: 12 mm at mean depth of 21.8 cm (SE, 1.4), 23 mm at 23.5 cm (SE, 2.2), and 32 mm at 22.0 cm (SE, 2.3). There was no significant difference in mean deployed water depth among tag sizes (one-way ANOVA: $F = 0.0089$, df = 27, $P = 0.925$). An experienced operator used a portable HDX backpack reader (Oregon RFID, Portland, Oregon) with a watertight polyvinyl chloride (PVC) antenna wand (1.85-m length) and circular antenna (0.5-m diameter). The operator was visually obstructed using semitransparent sunglasses, unaware of tag detections (disconnected piezoelectric buzzer) and naïve with respect to tag location (see Linnansaari and Cunjak 2007). The operator conducted five complete pass-through scans of the reach for each of the two tag orientations (time: 16.1 min; SE, 1.1) in the downstream direction (maximum of 50 detections per tag size), sweeping the antenna along the stream surface at a consistent sampling effort of 6.2 m/min. In deeper sections of the creek, the antenna was submerged to a maximum of 8 cm below the surface in an attempt to interrogate tags on the streambed. Water quality values at the Watts Creek study site (YSI model 85 water quality meter, Yellow Springs, Ohio) were as follows: temperature = 8.3°C, conductivity = 1,404 μS/cm, and dissolved oxygen = 5.55 mg/L.

Experiment 2: PIT tag read range tests.—To evaluate the vertical and horizontal read range of the three PIT tag sizes relative to tag orientation, an experiment was conducted in still, 77-cm-deep water in Watts Creek on 4 April 2012. Similar to past studies, one operator held the wand and circular antenna on the stream surface while another slowly moved a wooden meter stick (PIT transponder secured to bottom) away from the front end of the wand in either a vertical or horizontal direction (Morhardt et al. 2000; Cucherousset et al. 2005). Using this method, the maximum read range was noted when the portable backpack reader failed to detect a tag (piezoelectric buzzer would cease to alarm) for longer than 30 s (portable unit reads 10 times/s). Horizontal read ranges were performed with the tag in parallel and perpendicular orientations. Vertical tests were conducted exclusively with the tag in a parallel orientation, as this was the only possible orientation to mount the tag onto the meter stick. A tag in the parallel orientation was defined as being parallel to stream flow (upstream–downstream), while a perpendicular tag was oriented at a right angle to stream flow. A horizontal read-range test was also conducted with the PIT tag in a perpendicular orientation. During both horizontal read-range tests, the meter stick was moved away from the front of the antenna at a depth equal to half of the mean maximum vertical read range of the 12-mm HDX tag. We believed this to be an adequate depth to assess the horizontal read range because all PIT tags were detected within this vertical distance. All read-range tests were conducted eight times to establish reproducible results.

Experiment 3: detection efficiency of Shorthead Redhorse.—To assess how the tag-reading performance of a fixed PIT antenna array varies with tag size, an experiment was conducted at the Vianney-Legendre Fishway on the Richelieu River (Saint-Ours, Québec; 45°51′48′′N, 75°09′00′′W). The fishway consisted of 15 vertical slots (0.6 m wide), two resting–turning basins, and large entrance and exit basins. The PIT array consisted of 15 pass-through antennas, all of which were attached on the upstream-facing side of each vertical-slot baffle. Antennas were constructed from 12-gauge stranded electrical wire that connected to a remote tuner box (Oregon RFID); groups of four antennas connected to a multiplexor unit (Oregon RFID) via twin-axial cable. All antennas were tuned prior to conducting the experiment to ensure optimal reading range (about 0.5 m) and tag-reading performance. Further details regarding the Vianney-Legendre fishway and antenna array can be found in Thiem et al. (2011).

Sixty Shorthead Redhorse *Moxostoma macrolepidotum* (mean TL = 407 mm, SE = 3.6) were captured (10–15 May 2012, 0900–1400 hours) in a trap near the exit of the fishway, PIT-tagged (20 of each tag size), and released into the second turning basin between antennas 6 and 7. There was no significant difference in TL among released fish (one-way ANOVA, $F = 0.578$, df = 57, $P = 0.450$). Of the 60 fish released, 30 were male, 29 were female, and 1 was a juvenile. Passive integrated transponders were injected into the coelomic cavity (long axis of tag aligned along sagittal plane) of each fish through the use of a 6-gauge hypodermic needle and syringe (see Thiem et al. in press). The entire handling process took less than 2 min, and care was taken to minimize air exposure. Fish were placed ventral side up in a foam-lined v-shaped trough; river water flowed through the trough and was directed towards the mouth of the fish. Shorthead Redhorse were used in this study as they were locally abundant during the study period. By releasing the tagged fish into the second turning basin (i.e., seven antennas upstream and nine antennas downstream), we were able to guarantee the greatest amount of detection data of fish either ascending or descending the fishway. Shorthead Redhorse were released into the fishway in groups of 15 (5 of each tag size) to avoid large group-associated detection errors. Fish were given a total of 5 d to freely ascend (or descend) the fishway. We were able to infer a direction of movement by comparing time-stamped detection data from multiple antennas. Throughout the study period, the fishway passed 1 m^3/s and the predicted maximum velocity through each vertical slot was 1.72 m/s (Thiem et al. 2011). Water quality values in the Vianney-Legendre Fishway (YSI model 556 water quality meter, Yellow Springs, Ohio) throughout the duration of the study were as follows: temperature 14.1°C (SE = 0.7), conductivity 183.8 μS/cm (SE = 3.2), and dissolved oxygen = 11.2 mg/L (SE = 0.1).

Data analysis.—Detection efficiency of each stationary PIT tag size (and orientation) was calculated as the proportion of detected tags compared with the total possible number of detections (experiment 1). As both 12-mm and 23-mm tags failed to read in the perpendicular orientation during the horizontal read range test (Table 1), no statistical analysis was possible (experiment 2). Following release into the second turning basin, 92% (55 of 60) of fish descended the Vianney-Legendre fishway, resulting in the greatest amount of potential detection data from the nine antennas downstream (experiment 3). Some tagged Shorthead Redhorse were detected by the first few antennas and then failed to continue to descend (or ascend) the fishway 5 d

TABLE 1. Mean vertical and horizontal maximum read ranges (cm; ± SE) of half-duplex PIT tags ($n = 8$ for each tag size) in parallel and perpendicular orientations. Numbers with different letters were significantly different based on Tukey post hoc analysis.

Tag size (mm)	Parallel orientation		Perpendicular orientation
	Vertical	Horizontal	Horizontal
12	12.4 ± 0.04 x	6.4 ± 0.02 x	
23	20.2 ± 0.07 y	10.1 ± 0.02 y	
32	29.0 ± 0.13 z	14.8 ± 0.10 z	4.6 ± 0.35

postrelease, which limited the detection data to five antennas. This detection failure may have been due to tag loss, death within the fishway, predation, or simply passing through antennas undetected. Because all fish were known to have passed through antennas 8 through 12, detected or undetected, we used only these antennas to quantify detection efficiency among tag sizes. As one 12-mm-tagged fish was only detected by antennas 8 and 9, this individual was subsequently removed from detection efficiency analyses.

Portable PIT detection efficiency data (experiment 1) were subjected to an analysis of covariance (ANCOVA) to determine if detection efficiency covaried with tag size and depth. Read range (experiment 2) and fishway detection (experiment 3) data for all tag sizes were compared using a one-way ANOVA and Tukey post hoc analysis. All statistical analyses were performed using R version 2.13.0 (R Development Core Team; www.r-project.org) at $\alpha = 0.05$ for all tests.

RESULTS

Experiment 1: Detection Efficiency in Stationary PIT Tags

The detection efficiency of stationary HDX tags in Watts Creek varied considerably among tag sizes, with a higher proportion of larger tags (23 and 32 mm) being detected than smaller tags (Figure 1). After controlling for the effect of tag size, an ANCOVA revealed that water depth also significantly contributed to the detection efficiency results ($F = 13.49$, df = 26, $P = 0.001$).

Experiment 2: PIT Tag Read Range Tests

There were significant differences in the mean maximum vertical (one-way ANOVA: $F = 1989.6$, df = 2, 21, $P < 0.001$) and horizontal (one-way ANOVA: $F = 1074.3$, df = 2, 21, $P < 0.001$) read ranges among all parallel HDX tags (Figure 2). Tukey post hoc analyses revealed that the read range (vertical and horizontal in the parallel plane) of all HDX tags differed significantly from each other, with larger tag sizes yielding larger read ranges (Table 1). While both 12-mm and 23-mm perpendicularly oriented tags failed to read in the

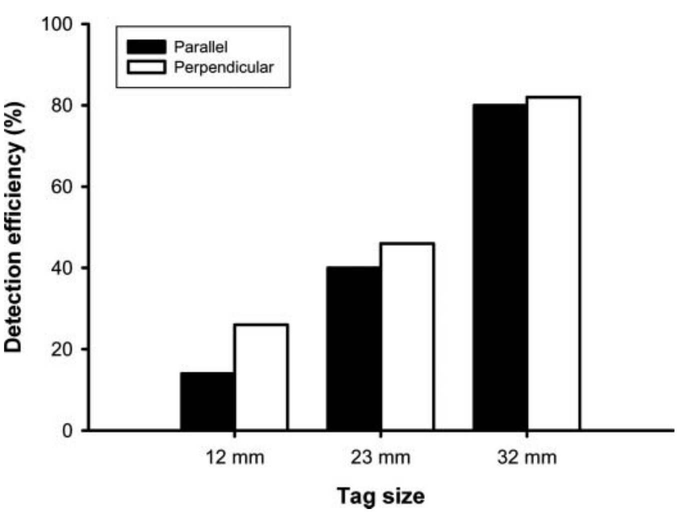

FIGURE 1. Detection efficiency of the three half-duplex (HDX) PIT tag sizes in Watts Creek using a portable HDX backpack reader.

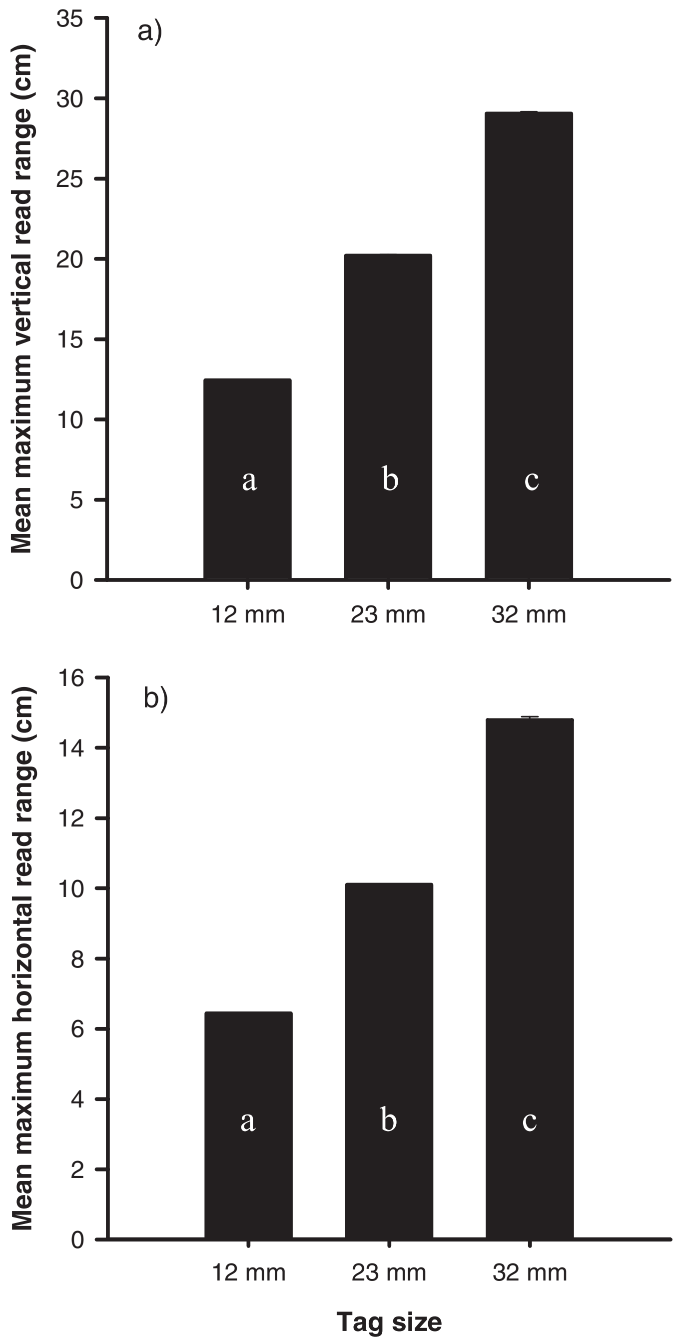

FIGURE 2. Mean maximum (**a**) vertical and (**b**) horizontal read ranges of the three half-duplex PIT tag sizes ($n = 8$ for each tag size and trial). Read ranges correspond to a parallel tag orientation. Error bars = SEs; different lowercase letters represent significant differences ($P < 0.05$) from ANOVA and Tukey post hoc tests. Note that the y-axes possess different scales.

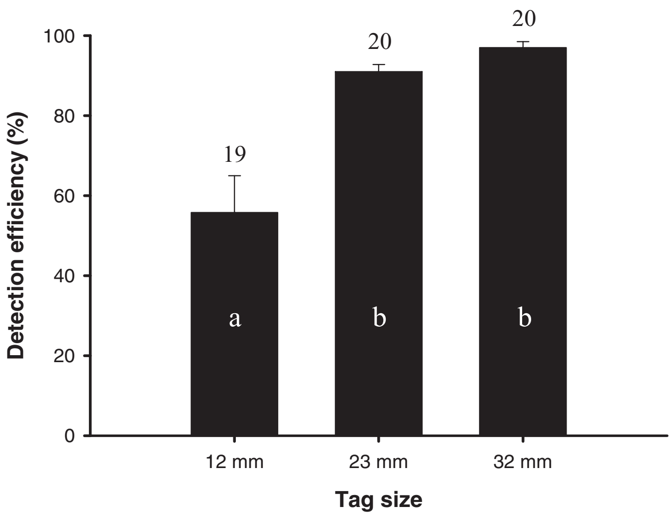

FIGURE 3. Detection efficiency of PIT-tagged Shorthead Redhorse passing through five antennas in the Vianney-Legendre Fishway. The numbers above bars are the sample sizes (*n*). Error bars = SEs; different lowercase letters represent significant differences ($P < 0.05$) from ANOVA and Tukey post hoc tests.

horizontal test, 32-mm tags had a mean maximum horizontal read range of 4.6 cm (SE, 0.35; Table 1).

Experiment 3: Detection Efficiency of Shorthead Redhorse

Detection efficiency among tag sizes (Figure 3) varied significantly in the Vianney-Legendre Fishway (one-way ANOVA: $F = 17.8$, df = 12, $P = 0.001$). Tukey post hoc analyses identified that the detection success of 12-mm tags (55.8%, SE = 9.2%) was significantly lower than for the 23-mm (91.0%, SE = 1.8) and 32-mm (97.0%; SE, 1.5) tags, and there was no significant difference in detection efficiency between 23-mm and 32-mm tags.

DISCUSSION

Using a handheld wand-type antenna, we found a positive relationship between PIT tag size and detection efficiency. As we expected, the smaller HDX tags possessed a reduced read range relative to larger tags, a finding most likely attributable to the size of the internal copper coil within each transponder (Cucherousset et al. 2010; Barbour et al. 2011). Detection efficiency data within the current study (14–82%) corresponded with past manual tracking studies, with differences probably due to the PIT tag type and size, specifics of the portable unit design, and physical habitat characteristics (Morhardt et al. 2000; Roussel et al. 2000; Zydlewski et al. 2001; Cucherousset et al. 2005; Hill et al. 2006). Although the tag-reading performance of a portable PIT detection system can be influenced by highly varying, extreme environmental conditions (Cucherousset et al. 2009), we believe it is unlikely that the surroundings during the study had a direct influence on the Watts Creek detection results, and the findings from this study are largely transferable.

Past research has identified that read range can be reduced by the suboptimal orientation of the tag with respect to the antenna plane (Bond et al. 2007; Linnansaari and Cunjak 2007; Aymes and Rives 2009). Despite the apparent difference in detection between parallel and perpendicular tag orientations, the operator swept consistently throughout the study reach for all trials, moving from one stream bank to the other, effectively approaching tags from all possible angles. Although this sweeping technique is a common antenna-maneuvering method (Bubb et al. 2006; Cucherousset et al. 2008, 2010), it interrogates transponders in the same manner, regardless of orientation. As such, we were unable to describe a precise, unbiased difference in detection efficiency between parallel and perpendicular stationary PIT tags. Although the current study did not use live fish to test the handheld PIT tracking system, the results do indicate that tag size is important to consider when performing an assessment of small-bodied fish behavior and migration in freshwater systems.

Tag-reading performance of the portable reader also varied with tag depth. This finding contrasts previous work by Enders et al. (2007) who found that depth did not affect the detection success of finding 23-mm tagged juvenile Atlantic Salmon *Salmo salar* and Brown Trout *Salmo trutta* in water less than 1 m. However, handheld PIT detection technology may be limited to shallow water streams (<0.3 m) so that the water depth is effectively less than the maximum read range of the portable unit (Cucherousset et al. 2008). Although all tags we deployed were in water less than 0.4 m deep, the results indicate that the water depth at which the stationary PIT tags were deployed exceeded the maximum read range of the tags. Future work using HDX tags on smaller species or life stages of fish should conduct read-range tests prior to undertaking extensive manual tracking to ensure that water depth does not exceed the maximum read range. Additionally, when conducting a portable PIT telemetry study, it is prudent to ensure that a wand-type antenna is effectively watertight so that the wand can be submerged to a depth that falls within the maximum reading range of the PIT tags.

Read range tests yielded results similar to the manual tracking detection efficiency, with larger PIT tags (23 and 32 mm) possessing greater vertical and horizontal mean maximum read ranges when in a parallel orientation. Using portable antennas on Steelhead *Oncorhynchus mykiss* Hill et al. (2006) identified an innate flight response during the sweeping process, causing fish to move deeper into the water column or up to 50 cm upstream from the operator. Although the trout did not move out of the portable unit's detection range, several other studies have commented that fish exhibiting escape behavior could swim by the portable backpack reader undetected, potentially causing spatial ecology assessments on small stream fish to be biased and unrepresentative of the local fish community (Cucherousset et al. 2005, 2008; Cookingham and Ruetz 2008). We believe this warrants a further investigation in order to determine the role fish escape behavior can play on the detection efficiency of portable PIT telemetry tools, particularly for fish tagged with 12-mm HDX tags, for which read range is diminished.

Only 32-mm transponders were successfully read in a perpendicular orientation during the horizontal read-range test. In reality, most fish species would not be tagged with the transponder oriented perpendicular (or nearly perpendicular) to the long-axis of the body, simply because only larger animals (i.e., large-bodied fish, turtles, etc.) would have the body depth to allow the tag to be oriented in a different manner. We believe this finding is irrelevant for small-bodied fish because there would probably not be enough space in the body cavity for a larger transponder, which could, if used, introduce a tag burden to the fish. However, it is possible that a fish tagged with the long axis aligned with the sagittal plane could be oriented perpendicular to stream flow during a flight response or sudden change in direction. Indeed, this may decrease the fish's detectability when using a portable backpack reader.

Using five antennas we were able to quantify the difference in detection efficiency between the three HDX tag sizes in live Shorthead Redhorse in the Vianney-Legendre Fishway. The larger tags (i.e., 23 and 32 mm) provided a significantly greater reader efficiency. Past detection efficiency work using 23-mm PIT tags and stationary detection systems have reported similar efficiency results (Brännäs et al. 1994; Armstrong et al. 1996; Zydlewski et al. 2001; Axel et al. 2005; Aymes and Rives 2009; Thiem et al. 2011). As the fishway used in the current study is designed to attract fish to pass through each vertical slot directly against flow, we are confident that tagged Shorthead Redhorse were interrogated with the transponder in an optimal, perpendicular orientation, similar to previous research (Zydlewski et al. 2001; Bubb et al. 2002; Bond et al. 2007). Furthermore, Aymes and Rives (2009) discovered that the sagittal plane of Brown Trout were oriented parallel to the antenna plane in countless detection-error events. As there was no significant difference in detection efficiency between 23-mm and 32-mm tags, we would expect representative movement and habitat use data through the use of either tag size. Although fixed PIT antenna studies on age-0 fish are limited to 12-mm tags (Prentice et al. 1990; Bond et al. 2007), our results suggest that when sample sizes are small or fish are unlikely to school, larger tags and subsequent larger read ranges are advantageous. Alternatively, smaller read ranges may reduce the chance of code collision in schooling species. Thus, a tradeoff exists when attempting to maximize detection efficiency. Researchers must balance the probability of missing an individual due to code collision versus the probability of missing an individual due to a reduced read range. We acknowledge that this issue is both species and study specific.

To conclude, when performing a PIT telemetry study, we suggest that one should strongly consider the type of communication system (i.e., FDX versus HDX), tag size, and the method of interrogation (i.e., fixed versus manual). All of those factors could individually or collectively influence the ability to address some research questions. Although 12-mm HDX tags open the possibility of tracking smaller species or life stages, it is not without limitations given the reduced read range and detection efficiencies noted using both manual tracking and fixed PIT arrays.

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