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ARTICLE

A Review of Factors Affecting PIT Tag Detection Using Mobile Arrays and Use of Mobile Antennas to Detect PIT-Tagged Suckers in a Wadeable Ozark Stream

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Abstract

Advantages of PIT tags are their small size, longevity, and low cost compared to other tags. They are often used in fisheries to study movement patterns and survival or to estimate population size. However, PIT tags are limited by their short detection distance. Mobile PIT antennas may increase the utility of PIT tags in fisheries. In this study, we synthesized current detection efficiency literature for mobile PIT antennas, determined physical factors that decreased PIT tag detection probabilities for our antenna, determined factors that influenced the proportion of PIT-tagged suckers detected by our mobile antenna, and summarized techniques used to increase detections of PIT-tagged suckers using mobile antennas in a wadable stream. Our literature review indicated that tag size and orientation were the most important factors affecting detection probabilities. However, our manual testing suggested that the detection probability for our antenna was primarily influenced by water depth of the tag and distance from the antenna. Our sucker detection data showed that detection efficiency in our stream was most influenced by discharge, turbidity, and sample date. Tracking methods that include targeting key habitats (e.g., rootwads) and using natural features to congregate tagged fishes (e.g., riffles or pinch points) may increase detection efficiency in wadable streams. This is the first formal review of factors affecting mobile PIT antenna detection efficiency. The published literature, combined with our study results, indicates that several factors need to be considered prior to mobile PIT antenna tracking.

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Passive integrated transponder (PIT) tags are widely used in fisheries. These tags are often selected for fish tagging due to their relatively low cost, comparatively high retention rate among species, range of tag sizes to accommodate even small-bodied fishes, and long tag life (Pine et al. 2012; Ousterhout and Semlitsch, 2014; Musselman et al. 2017). Because PIT tags allow individual identification, they are particularly useful for monitoring fish growth, survival, and movement over time (Banish et al. 2016; Richer et al. 2017). For example, they have been used to determine aging bias from hard structures in White Sturgeon *Acipenser transmontanus* (Paragamian and Beamesderfer 2003), population abundance of Rainbow Trout *Oncorhynchus mykiss* (Meyer et al. 2012), and movement of Atlantic Salmon *Salmo salar* (Cunjack et al. 2005). Consequently, our ability to document ecological patterns over space and time has improved with the development of technological and creative advances in the construction and use of passive PIT tag monitoring systems (hereafter, "passive antennas").

The use of passive antennas has reduced the effort needed to conduct PIT tag studies (Hewitt et al. 2010); however, the short detection range associated with PIT tags requires tagged individuals to pass through, or come close to, an antenna location to be detected (Zydlewski et al. 2001; Aymes and Rives 2009). These findings suggest passive antenna location can influence the study results, especially if passive antennas are placed in locations where individuals are unlikely to be detected (Pearson et al. 2016). For example, Beard et al. (2017) found that passive antennas within 1 km of stocking sites accounted for 88% of detections of juvenile Burbot *Lota lota* and suggested that antenna placement could bias inferences about dispersal. Stream size and site location are also important to consider when determining the applicability of passive antennas (Zydlewski et al. 2006). Passive antennas are commonly deployed at shallow and narrow locations within stream systems in an attempt to increase the chance that tagged fish moving through that location are detected; however, these locations occur infrequently in medium to large rivers and are relatively rare in lentic environments, limiting the use of passive antennas in these ecosystems.

Over the past two decades, active PIT monitoring systems (hereafter, "mobile antennas") have become increasingly popular in fish movement and survival studies (e.g., Ellis et al. 2013; Kelly et al. 2017). Mobile antenna users circumvent the limitations of passive antennas by actively moving the antenna(s) through the study system to detect tagged organisms (Cooke et al. 2013). Similar to passive antennas, the probability of tag detection for mobile antennas is influenced by tag orientation and size, water salinity, the power source of the antenna, tag collision (i.e., multiple tags within read range of an antenna), and electromagnetic interference from outside sources or other antennas (Zydlewski et al. 2001; Fetherman et al. 2014; Morris et al. 2018). The ability of mobile antennas to detect tags is also influenced by environmental factors such as stream discharge, water depth (relative to antenna depth in the water column), stream width, tracking direction (relative to streamflow), and season or time of day (Aymes and Rives 2009; Cucherousset et al. 2010; O'Donnell et al. 2010; Holcombe et al. 2019). Despite the number of factors influencing tag detection, mobile antennas can provide reliable estimates of fish abundance, survival, and movement (Sloat et al. 2011). Furthermore, mobile antennas can reduce the effort and costs associated with mark–recapture sampling (Sloat et al. 2011; Ellis et al. 2013).

Mobile antennas may become more common in fisheries management and conservation as our need for ecological information on smaller-bodied fishes and various life stages increases. However, information regarding mobile antennas is sparse despite their increase in use and innovation over time. Consequently, our study objectives were to (1) synthesize the current literature on detection efficiency of mobile PIT antennas, (2) describe our raft-mounted mobile antenna design and determine factors influencing its probability of detecting PIT tags, and (3) summarize the techniques we used to increase observations of PIT-tagged suckers with our raft-mounted mobile array in a wadable stream.

METHODS

Literature synthesis.— We searched Google Scholar to locate both peer-reviewed publications and agency reports that used mobile antennas. We selected Google Scholar because it allows the input of search terms with Boolean operators (e.g., "AND," "OR," "NOT") and indexes a wide variety of peer-reviewed and "gray" (not peer-reviewed) literature. Searches within Google Scholar were conducted following methods similar to those of Worthington et al. (2017). All searches were conducted before March 2020 using the search terms "floating," "backpack," "trawl," "mobile," or "raft" followed by either "PIT antenna" or "PIT tag detection." The option to include patents and citations was turned off. We summarized information about antenna detection efficiency and factors affecting it from the search results. To keep detection efficiency estimates comparable between studies, we only included estimates of detection efficiency that were based on a known number of tags within a closed system (e.g., Roussel et al. 2000) or based on a measured number of individuals available for detection in an open system (e.g., Ledgerwood et al. 2005; Sloat et al. 2011). However, in an effort to thoroughly review factors that affect detection efficiency of mobile antennas, we summarized information about environmental variables that influenced detection efficiency when it was available, regardless of how detection efficiency was derived.

Mobile antenna construction and detection probability.— Our floating mobile array consisted of two PIT antennas towed using two recreational kayaks (Figure 1). The design of our antenna represents a semi-novel system, as it is a modified version of the antenna system presented by Fetherman et al. (2014). Our rectangular antennas were constructed using 12-AWG (American wire gauge) insulated stranded wire (Southwire, Carrollton, Georgia) looped through 31.8- and 50.8-mm diameter PVC piping. Antenna A measured 3.2 by 1.5 m and antenna B measured 1.9 by 1.5 m. Antenna B also had a removable plug that allowed the antenna to fill with water so it could drift deeper in the water column. Each mobile antenna's inductance was ~40 microhenries (μH). Both antennas were connected to the same multi-antenna half-duplex (HDX) tag reader (Oregon RFID, Portland, Oregon) using 20-AWG twin-axial cable and manual tuning boxes (Oregon RFID). The HDX tag reader and power source (12-V deep-cycle battery) were housed in a waterproof bin located in one of the two kayaks.

For simplicity, we used only the larger of our two antennas for detection measurements because our primary interest was determining the effects of tag depth in the water relative to the antenna, horizontal distance of the tag from the antenna, tag size, and tag orientation. We did not expect antenna size to influence the overall relationship between these variables and the probability of a tag being detected because the read ranges of both antennas were similar. We acknowledge that differences in antenna design and size likely resulted in different field sizes for each antenna. However, this difference in field size would only influence the spatial coverage of the stream the antenna reads. All trials were conducted in Spavinaw Creek, a relatively clear (under baseflow conditions) fourth-order stream (Strahler 1957) that flows west from Arkansas into Oklahoma and drains an area approximately 422 km^2. The average stream width of Spavinaw Creek is ~15 m, but it varies greatly through alternating riffles and deep, bluff pools.

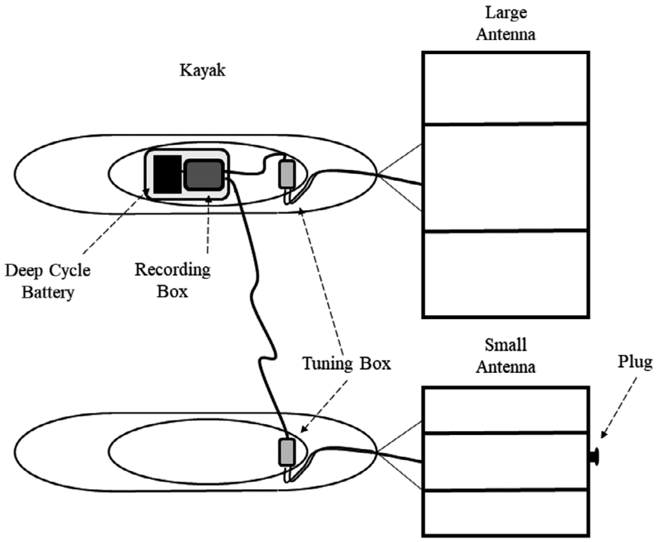

FIGURE 1. Diagram depicting the mobile PIT antenna deployment from kayaks. Antennas were constructed with 31.8- and 50.8-mm diameter PVC that encased 12-AWG insulated wire connected to a tuning box powered by a deep-cycle battery. Tuning boxes were adjusted based on inductance of the antenna.

We estimated the maximum water depth (depth$_{\mathrm{MAX}}$) where the antenna detected both HDX PIT tag sizes (4 × 23 mm and 4 × 32 mm; Oregon RFID) with our antenna flat on the water surface over pool habitat in Spavinaw Creek. Each PIT tag size was attached to a pole and placed directly under the antenna parallel and perpendicular (i.e., using both tag orientations) to the antenna loops. A series of 4–5 measurements were taken with each tag size and orientation to estimate the maximum depth (depth$_{\mathrm{MAX}}$) where the antenna would detect the tag. These measurements identified the maximum water depth of the tag (z-axis relative to antenna edge) that the antenna could detect when tag distance (x- and y-axis relative to antenna edge) was zero. Once depth$_{\mathrm{MAX}}$ was estimated, we took 16 to 17 random measurements at various depth–distance combinations, using each tag size and orientation to determine the effect of tag position (relative to antenna) on read distance. All random measurements were bounded by depth$_{\mathrm{MAX}}$. We used the audio signal from the tag reader to determine tag detections during these random measurements and recorded the associated detection success as a binary response (1 = detected, 0 = undetected).

We estimated the relationship between a tag being detected by the antenna and water depth, distance from the antenna, tag size, and tag orientation using logistic regression models constructed with the glm function in the program R (R Core Team 2017). All possible additive combinations of depth, distance, tag size, and tag orientation were included in the candidate set. The null model (intercept only) and all possible two-way interaction models (e.g., depth × distance, depth × tag orientation) were also included in the candidate model set (Table S1 available in the Supplement in the online version of this article). If an interaction was included, then the main effects were also included as first-order terms (James et al. 2013). Candidate models were ranked using Akaike's information criterion corrected for small sample size (AIC$_c$), and models within 2.0 $\Delta\mathrm{AIC}_c$ of the top candidate model were retained as they have similar likelihoods (Burnham and Anderson 2002). To further validate our cutoff criteria, AIC$_c$ weights (w_i) were estimated for all candidate models and evidence ratios were used to determine if alternative models had similar support as the top model based on Kullback–Leibler information theory (Royall 1997; Burnham and Anderson 2002). No global model was available for our candidate set; therefore, goodness of fit was estimated independently for each model using the Hosmer–Lemeshow goodness-of-fit test (Hosmer and Lemeshow 2000). Top candidate models were further evaluated for predictive accuracy using a validation data set of 50 random combinations of depth (z-axis relative to antenna), distance (x- and y-axis relative to antenna), tag size, and orientation (horizonal or perpendicular to antenna). Validation data were collected independent of the training data at a similar location on Spavinaw Creek. The classification breakpoint (i.e., probability level at which observations were predicted as detections [1] or nondetections [0]) was selected as the value along the logistic curve where specificity and sensitivity were maximized. Because logistic regression transforms the response into probabilities ranging from 0 to 1, the classification breakpoint represents the threshold where probability values are assigned to either the detection category (i.e., 1) or the nondetection category (i.e., 0; see James et al. 2013).

Field trials.— An ongoing mark–recapture study on Spavinaw Creek (36.324578°, –94.687412°) allowed us to address additional factors affecting the detection efficiency of our mobile array. Spavinaw Creek contains various sucker species (Northern Hog Sucker *Hypentelium nigricans*, White Sucker *Catostomus commersonii*, Black Redhorse *Moxostoma duquesnei*, and Golden Redhorse *M. erythrurum*) that were tagged with HDX PIT tags (4 mm × 23 mm; Oregon RFID) inserted into the abdominal cavity from November 2018 to March 2019. The minimum tagging size for all sucker species was 250 mm TL. Over the course of the study, the maximum TL of fish tagged was 413 mm for Northern Hog Sucker, 441 mm for White Sucker, 475 mm for Black Redhorse, and 462 mm for Golden Redhorse. The number of tagged suckers within our tracking segment increased through time and ranged from 109 to 254 during this 5-month period. During tracking events (approximately every 2 weeks), both of our kayak-mounted mobile antennas (i.e., antenna A and antenna B) were used simultaneously to search for tagged fishes across a 6-km segment of Spavinaw Creek. Each survey consisted of a single pass through the 6-km stream segment. During each site visit, a minimum of three surveys were obtained. Surveys were conducted approximately 24 h apart to allow fish to redistribute and to minimize dependencies between surveys. Surveys were conducted downstream through the study segment; however, the array was sometimes moved back upstream within the same pool to access certain stream features (e.g., backwater habitat). Mobile antennas were oriented to maximize coverage across the width of the stream channel, and the plug was sometimes removed (i.e., to fill the antenna with water) from antenna B so it would sink deeper into the water column and increase our chances of detecting of individuals within deep pools.

To investigate the relationship between physicochemical variables and detection, we compared the proportion of unique fish detections (from our tagged population of sucker species) to discharge, water temperature, gauge height, and turbidity (Table 1). The proportion of unique fish detections was estimated by dividing the number of unique fish detections during a tracking event by the estimated number of tagged sucker species within the tracking segment. To estimate the number of tagged sucker species within the segment, the known number of tagged and released fish within the tracking segment was adjusted for emigration. Emigration was estimated using detections from passive PIT antennas and intensive sampling in adjacent segments using barge-mounted electrofishing along with fyke, hoop, and gill nets. Because we estimated the number of fish available for detection, we performed a sensitivity analysis to determine the effect of error in this value on our modeled detection. This was done by varying the number of tagged fish in the stream segment incrementally up to ±50 individuals and refitting the model. Data for each predictor variable were obtained from the U.S. Geological Survey gauging station (USGS 071912213) located within our tracking segment on Spavinaw Creek. For each variable, we estimated as the average of measured values during each tracking event. We also recorded date (i.e., tracking event T_x) and number of tagged fish at large (i.e., number tagged prior to T_x adjusted for emigration as described above). Sample date is a common covariate when measuring detection in mark–recapture studies. Further, the number of tagged fish was variable across our tracking events, which may have influenced the proportion of individuals detected.

We modeled the relationship between proportion of detections and our predictor variables using beta regression in R (Zeileis et al. 2020). Beta regression was selected as our response variable approximated a continuous proportion (Douma and Weedon 2019), and our response variable appeared to fit a beta distribution better than a binomial distribution (Figure S2 available in the Supplement in the online version of this article). Beta regression allowed us to fit a linear model to our proportion data (i.e., $0 < y < 1$) by converting the proportional responses to a beta distribution using the equation

$$f(y|\mu,\phi) = \frac{\Gamma(\phi)}{\Gamma(\mu\phi)\Gamma((1-\mu)\phi)} y^{\mu\phi-1}(1-y)^{(1-\mu)\phi-1},$$

where $f(y|\mu,\phi)$ is the result from the beta density given the value (y), variate mean (μ) and precision estimate (ϕ; Ferrari and Cribari-Neto 2004), $\Gamma(.)$ denotes the gamma function, μ ranges between zero and one, and ϕ is greater than zero (Ferrari and Cribari-Neto 2004). Because our

TABLE 1. The proportion of sucker species detected using kayak-mounted mobile PIT antennas within the tracking segment of Spavinaw Creek, Oklahoma along with predictive variables: sample date, estimated number of tags in the segment (Tags available), average water temperature, average discharge, average gauge height, and average turbidity. FNU = Formazin Nephelometric Unit.

Proportion detected[a]	Sample date	Tags available	Temperature (°C)	Discharge (m^3/s)	Gauge height (m)	Turbidity (FNU)
0.00	Nov 29, 2018	109	11.60	27.34	2.27	1.00
0.00	Nov 30, 2018	109	13.20	0.91	2.27	1.30
0.00	Dec 1, 2018	107	13.80	1.09	2.29	3.65
0.03	Dec 2, 2018	107	12.75	1.11	2.29	1.40
0.00	Dec 17, 2018	162	11.95	1.19	2.30	0.50
0.00	Dec 18, 2018	167	12.00	1.15	2.30	0.50
0.00	Dec 19, 2018	176	12.20	1.15	2.30	0.50
0.22	Jan 9, 2019	214	10.10	1.18	2.51	0.40
0.06	Jan 10, 2019	217	10.60	1.14	2.51	0.40
0.00	Jan 11, 2019	217	9.70	1.19	2.51	0.60
0.11	Jan 24, 2019	214	9.30	1.93	2.56	1.00
0.08	Jan 25, 2019	214	9.40	2.16	2.57	1.00
0.03	Jan 26, 2019	220	10.20	2.17	2.57	1.10
0.06	Feb 8, 2019	220	9.00	1.24	2.51	1.00
0.08	Feb 9, 2019	220	9.90	1.24	2.51	1.20
0.11	Feb 10, 2019	220	9.50	1.24	2.51	1.20
0.06	Feb 27, 2019	254	11.60	20.93	2.87	12.20
0.14	Feb 28, 2019	254	11.60	16.54	2.80	7.80
0.03	Mar 1, 2019	254	11.65	13.65	2.76	6.55

[a] Fish were corralled towards antennas as the goal was detecting as many individuals as possible; therefore, the proportion of fish detected may be inflated relative to sampling where corralling of fish was not done.

response data (y) had several estimates of zero, it was transformed using

$$y_{adj} = \frac{(y(n-1)+0.5)}{n},$$

where y_{adj} is the transformation of y and n is the sample size (Smithson and Verkuilen 2006; Douma and Weedon 2019). Finally, we assumed $y_{adji} \sim B(\mu_i, \phi_i)$ and that $y_{adj1}, \cdots, y_{adji}$ were random and independent. This allowed us to modify the prior beta equation and model ϕ similar to μ, which are displayed below in their simple linear forms:

$$g_1(\mu_i) = \eta 1_i = x_i^{\top} \beta_i$$

$$g_2(\phi_i) = \eta 2_i = z_i^{\top} \gamma_i$$

where $g_1(.)$ is the logit link function and $g_2(.)$ is the log-link function, $\eta 1_i$ and $\eta 2_i$ are linear predictors for all values i (e.g., $\eta 1_i = \beta_1 x_{i1}, \cdots, \beta_k x_{ik}$ where x_{i1} is the intercept), and $\beta_i = (\beta_1, \cdots, \beta_k)^{\top}$ and $\gamma_i = (\gamma_1, \cdots, \gamma_h)^{\top}$ are regression coefficients for the equations given $k+h<n$ (Smithson and Verkuilen 2006). Modeling ϕ similar to μ allowed us to determine if any of our predictive variables likely influenced the amount of deviance present within our data (Smithson and Verkuilen 2006; Douma and Weedon 2019). Prior to construction of candidate models, Spearman's rank correlations were compared for all predictive variables. Variable combinations with correlation $r > |0.70|$ were considered highly correlated (Akoglu 2018), and one of the two were excluded a priori from the analysis (discharge and gauge height, $r = 0.71$; date and number of tagged fish, $r = 0.96$; date and gauge height, $r = 0.93$). We removed the variables gauge height and number of tagged fish, as it allowed for the retention of the most variables. Our candidate model set included all possible variable combinations for μ (i.e., one to four variables were allowed) and zero to two variables were used for ϕ (i.e., constant ϕ to two variables influencing ϕ). We limited predictors for ϕ because the sample size ($n = 19$ dates) of our data set was relatively small, and maximum likelihood estimation failed for most preliminary models that included more than two ϕ coefficients. Candidate models were ranked using AIC_c as described for the antenna detection probability analysis (Table S3). McFadden's pseudo-R^2 values (p^2; McFadden 1974) were estimated for all beta regressions with similar likelihoods (i.e., $\Delta AIC_c \leq 2.0$) to estimate the variance explained by each model (Zeileis et al.

2020). Model assumptions were assessed visually using residual diagnostic plots similar to Ferrari and Cribari-Neto (2004).

We attempted to improve the efficiency of our own tracking efforts over time by noting issues encountered using our mobile array. We developed a list of techniques and tips to improve efficiency when using raft-mounted mobile antennas in wadable streams. Though this information is qualitative, we used it to develop recommendations for maximizing tag detection.

RESULTS

Literature Synthesis

We found a total of 39 publications addressing mobile PIT antennas, 32 of which were peer-reviewed articles, and the remaining 7 were agency reports. Publication dates ranged from 2000 to 2019. Thirty-one of the 39 publications identified factors affecting tag detection or detection estimates. From this subset, 20 publications focused on backpack-mounted antennas, 7 targeted trawl-mounted antennas, and 4 detailed raft-mounted antennas (i.e., antennas deployed from a floating object). Maximum reported tag detection was highest using backpack-mounted units (range = 0.0–100.0%), followed by floating units (47.0–93.0%) and then trawl-mounted units (0.7–4.8%; Table 2). However, the ranges of tag detection reported in the literature overlapped for all mobile antenna types (Table 2). PIT tag orientation was the most studied (15 of 21 publications) factor affecting detection range of mobile antennas (Table 3). The least studied factors affecting tag detection using mobile antennas were the number of passes and bias introduced by antenna operator (2 and 1 of 21 publications, respectively; Table 3).

From our literature review, we determined that detection efficiency of mobile PIT tag antennas could be influenced in a "simple" (i.e., positive or negative) or "complex" (i.e., mixed, positive and negative) manner. Tag size (Kelly et al. 2017) and the number of passes (Richer et al. 2017) always increased the probability of tag detection. Alternatively, the distance between the tag and the antenna (Weber et al. 2016), tag collision (Morris et al. 2018), stream discharge (Holcombe et al. 2019), outside electrical interference (Fetherman et al. 2014), and salinity (Ledgerwood et al. 2006) always reduced the probability of tag detection. Along with these simple directional relationships, four nondirectional relationships were also observed. Tag orientation (Burnett et al. 2013), time of day (Morris et al. 2015), antenna operator (O'Donnell et al. 2010), and fish behavior (Banish et al. 2016) had mixed influences on the detection efficiency of PIT tags by mobile antennas.

Mobile Antenna Construction and Detection Probability

We estimated $\text{depth}_{\text{MAX}}$ for our new mobile antenna separately for each orientation and tag size combination by attempting to detect tags positioned at various depths at a fixed location directly under the antenna. When the smaller HDX PIT tags (4×23 mm) were positioned vertically, our average (±SD) $\text{depth}_{\text{MAX}}$ was 132.7 (±0.9) cm, whereas $\text{depth}_{\text{MAX}}$ was 126.4 ± 11.7 cm when the tag was positioned horizontally. When 4×32 mm HDX PIT tags were positioned vertically, our $\text{depth}_{\text{MAX}}$ was 138.4 ± 5.4 cm. The same tags had a $\text{depth}_{\text{MAX}}$ of 133.4 ± 1.8 cm when positioned horizontally. Across tag sizes and orientations, our estimated $\text{depth}_{\text{MAX}}$ was 132.7 ± 6.7 cm.

Our top-ranked model for estimating PIT tag detection with our mobile antenna included an interaction between tag distance from the antenna and water depth of the tag (Figure 2). The classification breakpoint for this model was 0.76, with probabilities >0.76 being classified as detections and probabilities ≤ 0.76 being classified as nondetections. Both water depth and tag distance were negatively related to the probability of a tag being detected by our mobile antenna, but greater horizontal distance from the antenna resulted in a steeper decline in detection probability of a tag with increased water depth. For example, the predicted probability of detection dropped below 0.76 when the tag was horizontally 68.6 cm from the antenna at a depth of 0.0 cm (i.e., at the water surface). Conversely, when the tag was horizontally 0.0 cm from the antenna (i.e., directly under the antenna), the predicted probability of detection did not drop below 0.76 until it reached a depth of 113.0 cm (Figure 2). This suggests that distance from the antenna (i.e., x- and y-axis relative to the antenna) had a stronger influence on the probability of a tagged fish being detected compared to depth (i.e., z-axis relative to the antenna).

No other candidate models were within 2.0 ΔAIC_c of our top model (Table S1). Our top model had a w_i of 0.90. The next best model was the additive combination of tag, distance, and depth ($\Delta\text{AIC}_c = 5.7$, $w_i = 0.05$). We did not average models because the evidence ratio ($0.90/0.05 = 18.0$) suggested little support for the alternate model (Burnham and Anderson 2002). The Hosmer–Lemeshow goodness-of-fit test indicated that our top model fit the training data ($\chi^2 = 9.66$, df = 8, $P = 0.29$). Using the test data, we determined that our model was able to correctly predict a tag being detected 97.0% of the time. Conversely, the model was able to accurately predict a tag not being detected 90.0% of the time. Combined, the overall predictive accuracy of our top model was 93.0%.

Field Trials

The top-ranked model for estimating the proportion of tags detected with our active antennas included μ terms for discharge and turbidity and ϕ terms for sample date

TABLE 2. Estimated detection of PIT tags using different active antennas and tracking methods (antenna movement: up = upstream, down = downstream) from a literature review. We classified antenna types as backpack (i.e., wearable), trawl (i.e., trawl-mounted), or raft (i.e., floating or deployed from watercraft). Size and type (full duplex [FDX], half duplex [HDX]) of PIT tag used in each study and the estimated tag detection (mean or range) were reported from 25 publications. Blank cells indicate information we were unable to determine for the study.

Study	Tag type	PIT tag size (mm)	Antenna type	Antenna movement	Estimated detection efficiency (%)
Roussel et al. (2000)[a]	HDX	4 × 23	Backpack	Up	73.9–95.6
Roussel et al. (2000)[a]	HDX	4 × 23	Backpack	Up	83.8–91.9
Bubb et al. (2002)	FDX	2 × 12	Backpack	Up	80.0
Ledgerwood et al. (2005)			Trawl	Down/up	2.0
Cucherousset et al. (2005)	FDX	2 × 12	Backpack	Up	40.9–100.0
Ledgerwood et al. (2006)			Trawl	Down/up	1.0–4.0
Hill et al. (2006)	FDX	4 × 23	Backpack		25.0–38.0
Cookingham and Ruetz (2008)	FDX	2 × 12	Backpack		80.0–100.0
Cucherousset et al. (2007)	FDX	2 × 12	Backpack		71.4
Enders et al. (2007)	HDX	4 × 23	Backpack		10.5–56.2
Linnansaari et al. (2007)	HDX	4 × 23	Backpack	Down	62.5–100.0
Kurth et al. (2007)	FDX	2 × 12, 4 × 23	Backpack		89.5–100.0
Keeler et al. (2007)	HDX	2 × 12	Backpack	Down/up	80.00
Cucherousset et al. (2008)	FDX	2 × 12	Backpack	Up	62.5–100.0
Breen et al. (2009)	HDX	2 × 12	Backpack		55.0–99.0
Cucherousset et al. (2010)	FDX	2 × 12	Backpack	Down/up	0.7–43.1
O'Donnell et al. (2010)		2 × 12	Backpack	Up	18.0–85.0
Sloat et al. (2011)	HDX	3 × 11, 4 × 23	Backpack	Up	79.0–89.0
Burnett et al. (2013)	HDX	2 × 12, 4 × 23, 4 × 32	Backpack		14.0–82.0
Morris et al. (2015)			Trawl	Down/up	3.3–4.8
Banish et al. (2016)	FDX	2 × 12	Backpack		4.0–97.0
Weber et al. (2016)	HDX	2 × 12, 4 × 23	Backpack		75.0–96.0
Richer et al. (2017)	HDX	4 × 32	Raft	Down/up	47.0–93.0
Kelly et al. (2017)[a]	FDX	1 × 8	Backpack	Up	7.0–90.0
Kelly et al. (2017)[a]	FDX	2 × 12	Backpack	Up	0.0–77.0
Morris et al. (2018)			Trawl	Down/up	0.9–3.5
Holcombe et al. (2019)			Trawl	Down/up	0.7–2.2

[a] Studies were split in two components based on how detection efficiency was reported.

and discharge (Table 4). Ten other models were within 2.0 ΔAIC_c of our top model (Table S3). All of our similar models (i.e., those within <2.0 ΔAIC_c of top model) included discharge and turbidity as μ coefficients, with half also including sample date and temperature (Table 4). Coefficients for ϕ varied between models; however, ϕ was never fixed across models with equal support. Values of p^2 fell between 0.05 and 0.06 for models with two μ coefficients and fell between 0.19 and 0.20 for models with four μ coefficients (Table 4). Though we are unaware of exact interpretations for different p^2 values, McFadden (1979) suggested that models with p^2 values between 0.20 and 0.40 explain the majority of variance present within the data. The top ranked model appeared to have appropriate fit based on diagnostic plots recommended by Ferrari and Cribari-Neto (2004).

Our top model indicated that discharge was negatively related to the proportion of fish detected, whereas turbidity was positively related to detection (Figure 3). Results from our top model also indicated that sample date and discharge reduced variability in the proportion of fish detected. When plotted with the other predictor variables held at mean levels, the variation in our estimated proportion of fish detected decreased from December to March and as discharge increased (Figure 3). However, the maximum difference in our variance estimators (i.e., 95th to 5th quartile) varied little (range = 0.18–0.16) across our observed values of discharge (range = 0.91–27.3 m^3/s). The relationships between the predicted proportion detected and our variables remained the same when the number of tags available for detection was altered by ±50 PIT tags. However, the magnitude of

TABLE 3. Influences on PIT tag detection in reviewed studies using different tag types (full duplex [FDX], half duplex [HDX]) and types of mobile antennas (type). Tag detection efficiency is indicated as increased (+), decreased (–), or variable (+/–) relative to increases in tag size (Siz), tag orientation (Ort), distance from antenna (Dst), tag collision (Col), time of day (Tdy), water salinity (Sal), stream discharge (Dis), outside interference (Int), and number of antenna passes (Pas) along with differences between antenna operators (Opr) or fish behaviors (Bhr).

Reference	Tag type	Type	Siz	Ort	Dst	Col	Tdy	Sal	Dis	Int	Pas	Opr	Bhr
Roussel et al. (2000)	HDX	Backpack		+/–	–								
Morhardt et al. (2000)		Backpack	+	+/–	–	–							
Ledgerwood et al. (2000)		Trawl		+/–			+/–						
Jørgensen et al. (2003)		Trawl	+	+/–	–	–							
Cucherousset et al. (2005)	FDX	Backpack		+/–	–								+/–
Ledgerwood et al. (2005)		Trawl		+/–		–	+/–	–					
Ledgerwood et al. (2006)		Trawl		+/–		–	+/–	–					
Linnansaari et al. (2007)	HDX	Backpack		+/–	–	–							
Breen et al. (2009)	HDX	Backpack					+/–						+/–
Cucherousset et al. (2010)	FDX	Backpack											+/–
O'Donnell et al. (2010)		Backpack					+/–		–		+	+/–	
Fischer et al. (2012)	HDX	Boat	+	+/–	–								
Burnett et al. (2013)	HDX	Backpack	+	+/–	–								
Fetherman et al. (2014)	HDX	Raft[a]		+/–	–					–			
Morris et al. (2015)		Trawl		+/–		–	+/–		–				
Banish et al. (2016)	FDX	Backpack											+/–
Weber et al. (2016)	HDX	Backpack			–					–			+/–
Richer et al. (2017)	HDX	Raft		+/–	–						+		
Kelly et al. (2017)	FDX	Backpack	+										+/–
Morris et al. (2018)		Trawl		+/–		–	+/–	–	–				
Holcombe et al. (2019)		Trawl		+/–			+/–		–	–			+/–

[a] Includes information from raft-mounted antenna and floating antenna anchored to shore.

these relationships (i.e., "steepness" of the curves) did change with the number of tagged fish available for detection (Figure S4).

DISCUSSION

Our literature synthesis and our field study indicate that the detection efficiency of mobile PIT antennas is affected by many of the same factors that influence passive antennas, such as tag size, salinity, water depth, and operator technique (Linnansaari et al. 2007; O'Donnell et al. 2010; Kelly et al. 2017; Morris et al. 2018). The effects of some of the predictors were clear (e.g., larger tags increased detection, distance from antenna decreased detection); however, four factors appeared to have variable relationships with detection probability as they did not increase or decrease detection in a consistent way. For example, perpendicular tag orientation relative to the long axis of the body increased detection efficiency in pass-over antennas, and parallel orientation relative to the long axis of the body increased detection efficiency in pass-through antennas. However, when the PIT tag was located outside a pass-over or pass-through antenna, perpendicular orientation appeared to increase detection probability (Richer et al. 2017). Managers and researchers can account for the effects of tag orientation by tagging fish in locations where tags hold their orientation (e.g., dorsal musculature; Dieterman and Hoxmeier 2009). Fixing PIT tag orientation vertically or horizontally in the fish could improve detection depending on the antenna type (i.e., pass-over or pass-through; Fetherman et al. 2014; Morris et al. 2018). Where this is not possible, tag detection could be improved by guiding fish closer to the antenna during sampling. However, altering fish behavior should only be done when it is appropriate given study objectives. For example, it may be appropriate to corral or guide fish toward the antenna when the goal is maximizing detections of fish in an area, but this would not be appropriate when evaluating fish locations for habitat use or other location-specific data. Furthermore, data collected when fish are corralled or guided towards the antenna cannot be directly compared with data where fish were not corralled or guided, as it may alter detection efficiency. We acknowledge that there may be other factors that have interactive effects on detection (e.g., tag size × salinity) and accounting for these interactions could be important under some circumstances. For example, we found that the interaction of water depth

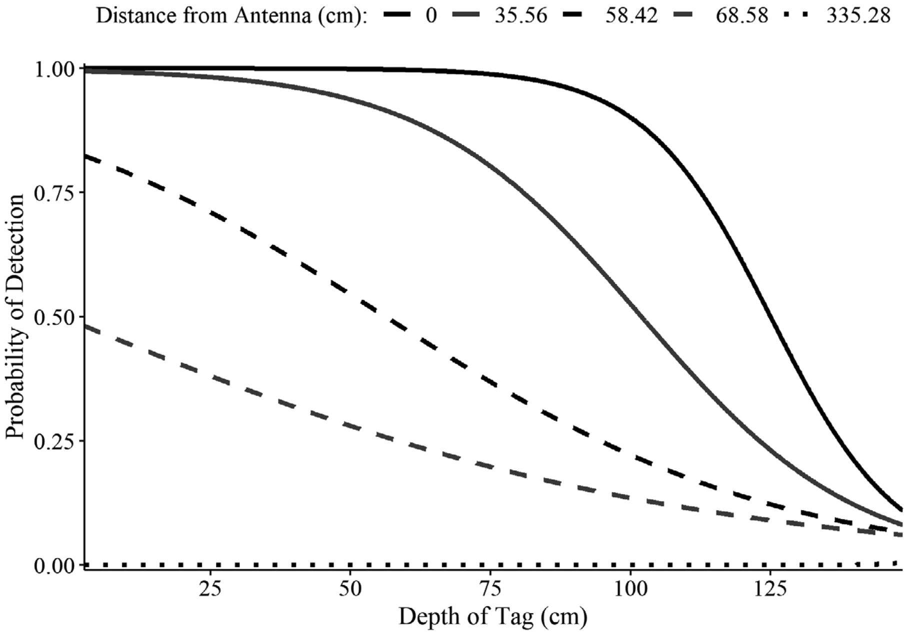

FIGURE 2. Predicted probability of PIT tag detection from our top logistic regression model plotted against tag depth relative to the mobile antenna (depth of tag) at various horizontal distances from the antenna (distance from antenna). Lines denote the 25th (0.0 cm, solid black), 50th (35.6 cm; solid gray), 65th (58.4 cm; dashed black), 75th (68.6 cm; dashed gray), and 100th (335.3 cm; dotted black) quantiles of tag distances used during the study. The 65th quantile was selected as it best displayed the interaction between depth and distance relative to the other quantiles, and any quantile below the 25th also estimated the probability of detection as 0.00.

and the horizontal distance of a tag relative to the antenna reduced the probability of detecting a tag faster than depth or distance alone.

Our review suggests that sample timing (i.e., time of day) can affect tag detection and the effect of timing appears to depend on whether fish are moving downstream (trawl-mounted antennas; Holcombe et al. 2019) or whether sampling is unlikely to be noticed by the fishes (backpack-mounted antennas; Cucherousset et al. 2005). It is possible that the observations by Cucherousset et al. (2005) were influenced by stream size (i.e., shallow water meant fish were wary of the antenna). Sample timing was sometimes separated from fish behavior (e.g., Breen et al. 2009; Holcombe et al. 2019), but discussions from these publications suggested that fish behavior (e.g., diurnal movements or migrations, fish avoiding the antenna) was the main reason that sample timing influenced detection. We suggest that managers and researchers should have a thorough understanding of the behavior of a species prior to tagging and tracking with mobile antennas, as it may influence study results. For example, if managers and researchers think sample timing influences their results, they can test the assumption following recommendations by Cucherousset et al. (2010) and then standardize as needed.

Several other variables appeared to influence PIT antenna detection efficiency in previous studies. Detection efficiency varied based on differences in habitat use (e.g., depth, large woody habitat; Roussel et al. 2000) and fish avoidance behavior (e.g., moving away from the antenna; Cucherousset et al. 2005). Targeted sampling techniques based on the species behaviors and habitat-use patterns would help offset these concerns. The search methods (i.e., how the antenna was moved through the water) used during operation of active antennas appeared to influence the number of tags detected (O'Donnell et al. 2010). O'Donnell et al. (2010) hypothesized that the experience of the antenna operator influenced how they moved the antenna through the system and thereby how many tags were detected. Establishing standard operating protocols and providing training would help minimize any potential bias caused by antenna operators.

The probability of a tag being detected by our antennas was influenced by the location of the tag relative to the antenna. Our antennas were constructed based on information from Richer et al. (2017) and Fetherman et al. (2014), and they appeared to have a similar detection range of ~1.0 to 1.4 m. Our top model describing field-based tag detections depended on an interaction between tag depth (z-axis relative to the antenna) and tag distance from the antenna (x- and y-axis relative to the antenna). We found that horizontal distance from the antenna reduced the detection probability faster than water depth, suggesting that distance was the main factor affecting the antenna's ability to detect tags. Our results differ from

TABLE 4. Variate mean parameters (μ) and precision parameters (ϕ) for multiple variable beta regression models from our candidate set that were <2 ΔAIC_c from our top candidate model for estimating the proportion of PIT tags detected with our active antennas. Included are McFadden's pseudo-R^2 values (p^2) for each model.

Variate mean parameters (μ)	Precision parameters (ϕ)	AIC_c	ΔAIC_c	p^2
Discharge, turbidity	Date, discharge	–48.78	0.00	0.05
Discharge, turbidity	Date, turbidity	–48.80	0.02	0.05
Discharge, turbidity	Date, temperature	–48.91	0.13	0.05
Discharge, turbidity	Temperature, turbidity	–49.04	0.26	0.05
Date, temperature, discharge, turbidity	Temperature, discharge	–49.70	0.92	0.19
Date, temperature, discharge, turbidity	Date, turbidity	–49.82	1.04	0.19
Discharge, turbidity	Temperature, discharge	–49.87	1.09	0.06
Date, temperature, discharge, turbidity	Date, temperature	–49.95	1.17	0.20
Date, temperature, discharge, turbidity	Temperature, turbidity	–50.29	1.51	0.20

prior work, indicating tag size and tag orientation (relative to the antenna) were the main factors affecting detection by mobile PIT antennas (Burnett et al. 2013; Richer et al. 2017). We found tag orientation was not important to the predictive potential of our model (i.e., based on AIC_c values); however, factors such as tag size and tag orientation may still influence antenna detection efficiency in other systems. For this reason, we think it is beneficial to continue to examine tag size and orientation prior to use of antennas as these factors may influence study results in unexpected ways. For example, Kelly et al. (2017) found that differences in detection efficiency of small and large tags were due to ontogenetic habitat shifts of Creek Chub *Semotilus atromaculatus*. This suggests it may be beneficial to use larger and smaller tags when tagging larger individuals to determine if tag size or fish behavior is influencing detection. Lastly, it is beneficial to test tag detection probability and efficiency when using different antenna designs (e.g., different sizes, shapes; see Fetherman et al 2014; Arnaud et al. 2015) or smaller tag sizes than commonly tested in the literature (i.e., ≤8 mm long; Burnett et al. 2013).

Our modified beta regression indicated that discharge, turbidity, and sample date were all important predictors of the proportion of tagged suckers we detected. It is not surprising that increased discharge resulted in lower detection proportions. Increased discharge is often associated with wider and deeper stream conditions (e.g., flooding). Wider stream sections prevented us from covering the entire stream in a single pass, and deeper water decreased the portion of the water column our antennas were able to scan. It was interesting that higher discharge also reduced the estimated variation in the proportion of sucker species detected; however, this reduction was small (i.e., ~0.02). We hypothesize that this was due to consistently detecting fish located in habitats where our antennas' detection fields covered the entire water column (e.g., shoreline) under higher water velocities. Northern Hog Sucker are known to use the flooded shorelines during periods of increased discharge (Matheney and Rabeni 1995), so it is logical that our detection of this species would be more consistent under conditions that confined them to areas where we can detect them. However, it is unknown if other catostomid species in Spavinaw Creek also use shoreline areas during high-discharge events. As turbidity increased, the predicted proportion of detections increased. This was likely the result of reduced visibility, making it difficult for fish to avoid the antennas or antenna operators (Cucherousset et al. 2005). The decreased variation with each consecutive sample date was likely the result of later samples overlapping the prespawning period. Suckers exhibit moderate homing abilities and have been observed staging at or near spawning grounds (i.e., fish remained in similar locations during passes, Werner and Lanoo 1994; Reid 2006).

Though qualitative, we think our techniques and tips to improve detection efficiency of mobile PIT antennas in wadeable streams will assist managers and researchers attempting to use them. Several potential problems were noted by personnel operating our mobile PIT array. These observations were related to three main concerns: (1) poor connection between the reader and antennas, (2) detection difficulties stemming from abiotic stream conditions, and (3) adapting tracking to account for fish behavior. We suggest implementing a standard testing protocol when sampling with mobile PIT antennas. Our antenna connections intermittently came loose, primarily after using our antennas to scan instream features (e.g., pushing and pulling in and out of root wads or brush piles). Not fixing loose connections would have resulted in a biased sample as the antennas would no longer be able to detect tagged individuals. Consequently, we implemented a standard practice of testing connections every 100 m using a test tag carried by the crew and an audible beeper connected to the reader box. If a poor connection was found, then the connection was fixed and we returned to the previous 100-m checkpoint. We also recommend designing the

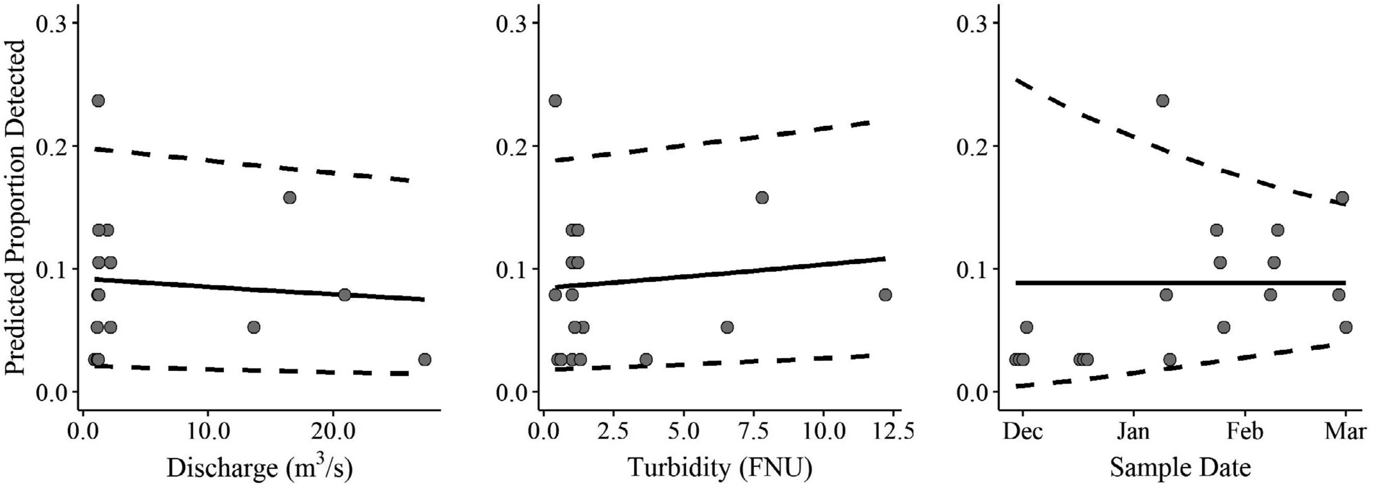

FIGURE 3. Predicted proportion of PIT-tagged sucker detections plotted against environmental conditions included in the top beta regression model for our segment of Spavinaw Creek, Oklahoma. The solid line indicates the 50th quantile, and the dotted lines indicates the 5th and 95th quantiles. Gray circles represent adjusted observed proportions of PIT tags detected.

antenna based on stream conditions, so antenna size closely matches the area of stream to be covered. For example, we built our second antenna smaller (antenna B) so it could be both pushed into instream features and deployed in deeper water (i.e., depth of some pools was >6 m). If we were not familiar with the stream we sampled, then we likely would have designed both antennas to be the same size, which would have been problematic. Lastly, tracking personnel found detection rates could be maximized if they guided fishes into areas of the stream where they were more likely to pass within detection range of our array. For example, we often left antennas floating in a stationary manner at a pinch point in the stream (e.g., confluence of the main channel and a backwater) and then waded towards the antennas, guiding fish away from us and through the antenna loops. This can be a useful technique when maximizing detection of fish that are present is more important than observing the natural location of fish in the system (i.e., habitat use). Moreover, the act of guiding fish towards the antenna worked well for us given we were only interested in maximizing the number of detections during each visit. However, we had to be careful that this method was applied in a similar manner during each sampling event to keep our passes comparable. Likewise, the use of this fish guiding practice means our detections should not be compared to samples that did and did not use a guiding technique. Therefore, methods to guide fish towards antennas should be used with caution.

To our knowledge, this paper constitutes the first formal review of mobile PIT antennas and factors affecting their detection efficiency. We were unable to include information from every mobile PIT antenna study due to our predefined criteria (see Methods). Regardless, the information summarized in this paper offers a thorough review for managers and researchers interested in mobile PIT antennas. Mobile PIT antennas have been used to monitor a variety of aquatic and semiaquatic organisms (e.g., fish, Quintella et al. 2005; crayfish, Bubb et al. 2002; salamanders, Ousterhout and Semlitsch 2014) and habitat changes (e.g., gravel bed movement, Arnaud et al. 2015). Mobile PIT antennas can be deployed in lotic, lentic, and terrestrial ecosystems (Roussel et al. 2000; Cookingham and Ruetz 2008; Ousterhout and Semlitsch 2014) and can be adjusted to sample a variety of water depths (i.e., shallow or deep, Cucherousset et al. 2005; Ledgerwood et al. 2005). Given the plasticity of this technology, it has great potential to be improved and adapted for many additional management and research applications. Our findings suggest that there are two overarching factors that influence detection efficiency of a mobile PIT antenna system: (1) how the antenna is constructed and operated relative to tag type and size, and (2) how the species of interest behave under the abiotic conditions during passes. The summarized information and recommendations made in this paper constitute a good starting point for study design; however, detection efficiency of different study-specific mobile PIT antennas will vary. Consequently, we suggest preliminary investigations of factors that may affect the detection efficiency of mobile antennas would be useful if applied to a new system.

From our literature review and field study, we developed several suggestions for future mobile antenna studies. Our data did not allow us to investigate less commonly studied variables which may influence detection (e.g., antenna operator bias). We were able to include system-specific variables that we hypothesized would influence fish detection (e.g., turbidity). Future studies might consider including other variables (e.g., season) to improve our overall understanding of tag detection. Sample size limited the number of variables we could include in our models when estimating influences on the proportion of tagged suckers detected. Future studies could bolster this sample size allowing for fitting of more complex models (e.g., more ϕ variables and interactions terms). Increasing model complexity may better describe factors influencing the proportion of tagged fish detected by a mobile antenna system. Future research investigating how biotic and abiotic variables influence the proportion of detections for different fish species within different systems would also be beneficial. We think this is especially important as our literature review suggested detection probabilities are highly variable. Few mobile PIT antenna studies have been conducted, and future work including information regarding the factors that influenced the detection ability of each antenna for each species would be beneficial so that fisheries managers and researchers can better understand the best way to use this technology.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.