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Comparison and cost-benefit analysis of PIT tag antennae resighting and seine-net recapture techniques for survival analysis of an estuarine-dependent fish

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ABSTRACT

Studies of fish ecology are enhanced by precise and accurate knowledge of survival, which can be estimated from capture-recapture/resighting based survival probabilities. We conducted a cost-benefit analysis of resighting by an array of 11 autonomous PIT tag antennae and recapture by seine netting, and compared the effectiveness of the two methods for recapturing/resighting marked fish in an estuarine environment. During three separate marking periods, we marked a total of 2109 fish with PIT tags, recapturing 106 by seine (5.0%) and resighting 1700 by antennae (80.6%). Antennae resulted in precise monthly survival estimates while seine netting did not, but antennae did not collect ancillary data (e.g., growth) and their use was limited to areas where fish used constricted passes <10–30 m in width. Despite a reliance on seine nets to capture fish for marking and high initial construction costs, the cost-effectiveness of PIT tag antennae (US$45–$57 per unique fish resighted) exceeded that of seine netting (US$167–$934). Considering physical capture was required to mark fish, the use of PIT tag antennae is a dual-method approach incorporating both physical captures and telemetry. This dual-method approach can collect cost-effective and highly detailed data that could enhance our ability to make informed management and conservation decisions.

1. Introduction

Ecological studies and effective fishery management strategies are enhanced by precise and accurate knowledge of survival, which is a vital parameter for determining a population's fitness (Crone, 2001). Capture-recapture/resighting (CR) methods are commonly used to determine survival for a marked population by collecting data for calculation of apparent survival probabilities ($\phi = 1 - \text{emigration} - \text{mortality}$) (Pine et al., 2003). Mathematical survival probabilities are effective tools for exploring population dynamics and testing ecological hypotheses (Pollock et al., 1990), but the quality of CR data limits the precision, accuracy, and utility of survival probabilities.

The quality of CR data is limited by methodology. Methods allowing both a high number of fish to be marked and recaptured are desirable, but CR methods in estuarine environments typically result in a high number of fish marked and a low number recaptured (e.g., Leber et al., 1998; Hampton, 2000), or a low number marked and a high number recaptured (e.g., Heupel and Simpfendorfer, 2002; Adams et al., 2009). A low recapture rate reduces the utility of survival estimates, whereas marking too low a number of fish results in a non-representative study population.

To advance the use of CR-based survival estimates in coastal estuarine systems, Adams et al. (2006) applied the first estuarine version of an autonomous passive integrated transponder (PIT) tag antenna. This CR system allowed for a high number of fish to be marked with low cost PIT tags, and resighted (as individuals were not physically recaptured) a high number of marked individuals. The single antenna in Adams et al. (2006) resighted >40% of 314 marked individuals, a resighting rate repeated by Meynecke et al. (2008). Although this single-antenna approach provided superior apparent survival estimates to previous approaches (Adams et al., 2006), precision would be increased and bias reduced by using

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multiple antennae when studying mobile species with complex habitat requirements.

We expanded upon this application with a multi-antenna array to study the juvenile life-stage of an estuarine-dependent fish, the common snook *Centropomus undecimalis*. We constructed eleven antennae over four tidal-mangrove creeks, and compared resighting of PIT tags by antennae to recapture by seine netting. The purpose of this paper was strictly to compare antenna and physical CR methods using a cost-benefit framework so that others can evaluate the application of this method for their system and research goals.

2. Material and methods

2.1. Study area

Charlotte Harbor is a 700-km^2 coastal plain estuary in southwest Florida (USA) (Hammett, 1990). The climate is subtropical, with mean seasonal water temperatures ranging from 12 °C to 36 °C and infrequent freezing air temperatures (Poulakis et al., 2003). Seagrass meadows (262 km^2; Sargent et al., 1995) dominate the benthic habitat and mangroves dominate the shoreline (143 km^2; Kish, unpublished data). This study was performed in four red mangrove (*Rhizophora mangle*) fringed, tidal, estuarine creeks, each approximately 1.6 km long, on the eastern shore of Charlotte Harbor. The creeks varied in width from 2 m passes to >60 m bays, and average depths ranged from 0.5 to 2.0 m, with the deepest occurring in the narrow passes.

2.2. Cost-benefit analysis

To conduct a cost-benefit analysis of recapture by seine net and resighting by antennae, we first compiled the overall costs associated with each method. For seine netting, the costs consisted of the seine net (US\$1000), the passive integrated transponder (PIT) tags used (US\$2.50 tag^{-1}), fuel costs (US\$0.80 L^{-1}), and labor costs (US\$15 h^{-1}). The sum of these expenditures encompassed both seine net marking and recapture costs. For antennae resightings, we started with the cost of seine netting – as seine netting was required to mark fish – and added the cost of construction materials and labor (US\$15 h^{-1}) required to build antennae.

To compare the benefit of each method, we first calculated the per year cost of each approach. For both methods, equipment used for multiple years (e.g., seine nets, antennae) had initial costs spread over all years used. Next, we determined the cost of recapturing/resighting uniquely marked individuals both a single time, and on a monthly basis each year. We then compared the utility of the data collected with each method by focusing on the quality of apparent survival estimates. Finally, we discuss the ability of each method to collect ancillary data (e.g., growth, population size) and comment on the general use of each method (e.g., suitability for different habitats, utility in different sampling conditions, etc.) as qualitative measures of benefit.

2.3. Focal species

Common snook (*C. undecimalis*) is a subtropical/tropical, estuarine-dependent, euryhaline species that is ecologically and economically important throughout its range, especially in Florida (Taylor et al., 2000). Adult *C. undecimalis* spawn in passes and inlets at the mouths of estuaries in salinities ≥25 ppt (Taylor et al., 1998); the nearshore planktonic larval stage lasts approximately 2.5 wk (Peters et al., 1998); and juveniles settle into shallow, mesohaline to oligohaline habitats (Peters et al., 1998). Juvenile *C. undecimalis* are common in or near mangrove creeks year-round, with highest densities in the fall and winter, until they reach approximately 300 mm standard length (SL) (Taylor et al., 2000; Adams et al., 2006), when they begin to enter the adult population. *C. undecimalis* larger than 300 mm SL use open estuarine and nearshore habitats (e.g., mangrove shorelines, artificial structure) from spring through fall, and presumably overwinter in riverine or creek habitats (Blewett et al., 2009).

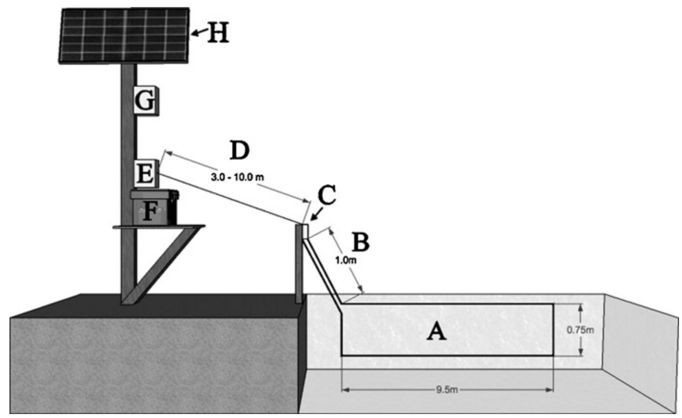

Fig. 1. Schematic of PIT tag antenna and component parts. Parts include: (a) inductor coil in swim-through orientation; (b) initial inductor coil cable length; (c) tuner box; (d) twinaxial wire; (e) reader box; (f) battery box; (g) junction box; and (h) solar panel.

2.4. Antenna systems

PIT tag antennae were originally designed for artificial freshwater environments, such as hydroelectric dams (e.g., Castro-Santos et al., 1996; Giorgi et al., 1997). Recently, two groups successfully designed single PIT tag antenna systems for application in natural marine and estuarine systems (Adams et al., 2006; Meynecke et al., 2008). We constructed antennae based on a design similar to Adams et al. (2006). The system (Fig. 1) consisted of an open loop, copper inductor coil antenna (a single loop of 660-strand, 6 gauge copper welding cable) connected to a tuning box, in turn connected to a reader box containing a data-logging computer (tuner and reader boxes purchased from Oregon RFID). Each antenna operated continuously with power from two 6 V batteries connected in series and charged by a 130 W solar panel. This antenna design permitted substantially greater coverage of creek width than the flat plate antenna of Hewitt et al. (2010), but required a moderate degree of self-fabrication.

PIT tags contain no battery, which allows for an indefinite lifespan (Gibbons and Andrews, 2004), but requires the tag to be in close proximity to the antenna for resighting. To read a PIT tag, electric charge flows through the copper inductor coil of the antenna, producing a magnetic field. When a marked fish passes the inductor coil, the magnetic field induces a charge on a coil of wire around a ferrite core in the PIT tag. The activated tag transmits its uniquely coded ID number to the antenna system. The "read range" of an antenna is defined as the maximum distance from an inductor coil that a PIT tag can be read. A computer system stores the resighting data and was retrieved by connecting a laptop computer or personal digital assistant. The copper inductor coil was oriented horizontally (flatbed: Armstrong et al., 1996) or vertically (swim-through: Adams et al., 2006) in the water column, depending upon location. We used the single swim-through design antenna from Adams et al. (2006) (Fig. 1), and deployed ten additional flatbed antennae. Flatbed antennae were identical to the swim-through antenna, except the inductor coil (Fig. 1a) was rotated 90° and laid flat across the bottom of the creek. We constructed flatbed antennae to avoid entanglement by recreational boat motors and because

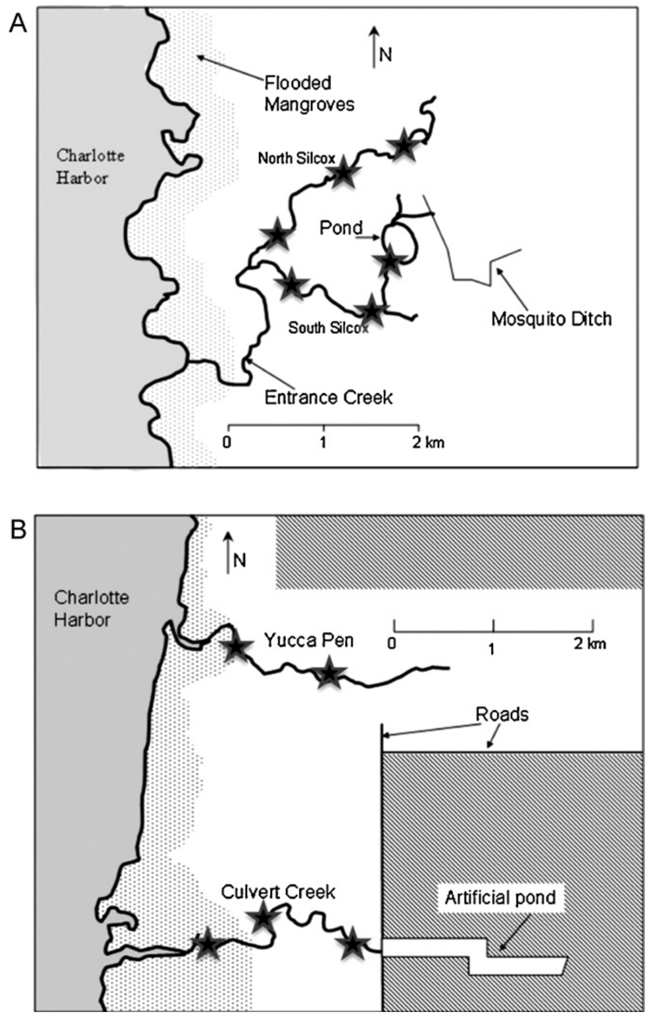

Fig. 2. Diagram of the study creeks in Charlotte Harbor, FL USA. Stars represent antennae locations.

C. undecimalis tend to swim low in the water column (Peterson et al., 1991), increasing the probability of detection by the flatbed design. The flatbed design created a PIT tag detection field upward from the bottom, whereas the swim-through design detected tags within the area encircled by the inductor coil. We placed one antenna every 0.5 km in the lower, middle, and upper strata of each creek with the exception of Yucca Pen upper (due to cost constraints) (Fig. 2).

The dimensions of the inductor coil limited the application of PIT tag antenna to constricted stretches of water, but in other studies antenna have been constructed with 30 m long inductor coils (J. Vincent Tranquilli, Oregon Department of Fish and Wildlife personal communication). Using a 12 V battery system and welding cable with 660 copper strands, we constructed rectangular flatbed inductor coils with a single loop, dimensions of 9.5 m × 0.75 m, and an initial cable length of 1.0 m (Fig. 1b). For the equipment and materials used, these dimensions maximized read range (Barbour et al., 2011). Antenna coils were run through mangrove prop roots on either side of the creek or staked to the ground using sections of PVC pipe to maintain the proper dimensions. To test read range, we repeatedly passed a 23 mm half-duplex PIT tag over each antenna at varying distances until the tag was no longer detected. Due to availability of suitable narrow creek stretches, few antennae covered 100% of creek width, but all covered >75%.

2.5. Marking and seine net recapture

Using a center bag seine (30.5 × 1.8 m, 6.3 mm mesh), juvenile *C. undecimalis* were captured (120–300 mm SL) between February 2008 and February 2011 in three separate marking periods. For marking period one, seine-net sampling occurred over a total of 44 days: February and March 2008 (1 day each), April 2008 (3 days), May 2008 (2), June 2008 (4), July 2008 (7), November 2008 (5), December 2008 (13), January and February 2009 (3 days each), and April and June 2009 (1 day each). For marking period two (9 days), we marked fish in November 2009, January 2010, and February 2010 (3 days each). For marking period three (14 days), we marked fish in October 2010 (3 days), November 2010 (5), December 2010 (1), January 2011 (4), and February 2011 (1). These physical capture events were used both to mark fish and for seine-net recapture. Seine-net sampling occurred only during periods of low tide, when *C. undecimalis* were unable to seek refuge among mangrove prop roots. Seine netting occurred throughout the length of each creek. Individual seine net pulls were not standardized, but instead designed to maximize capture efficiency for individual pulls. For example, in South Silcox Creek, we occasionally trapped juveniles in a long, narrow ditch using two seine nets pulled into each other.

Upon seine capture, we scanned all fish (documenting physical recaptures) with a handheld PIT tag reader (model no. RS601, Allflex®) and measured SL to the nearest millimeter. We marked fish with uniquely coded half-duplex (HDX) PIT tags (23 mm length × 3.4 mm diameter, 0.6 g in air; Texas Instruments TIRFID S-2000). We inserted tags into the abdominal cavity of all unmarked fish through a 3 mm incision posterior and ventral to the pectoral fin. For this mark, a previous study found 100% tag retention with no mortality for juvenile *C. undecimalis* >120 mm SL, and no need for sutures to close the incision (Adams et al., 2006).

2.6. Survival model selection and analysis

We created monthly capture histories for antennae by combining antennae resighting data with seine net marking events. We assigned each individual a “1” in months resighted or marked, and a “0” in months not resighted or marked. We collapsed antennae resighting and seine marking data into monthly sampling bins from February 2008 to June 2009 ($n = 17$) for marking period one, November 2009 to August 2010 ($n = 10$) for marking period two, and October 2010 to June 2011 ($n = 9$) for marking period three.

For seine-net capture histories in marking period one, we collapsed seine-net sampling events into discrete time periods. We then scaled the time intervals between seine-net events so that a 30-day period equaled an interval of length 1. The $n = 17$ seine-net interval lengths were coded as follows: 1.03, 0.70, 1.40, 0.43, 0.30, 0.97, 0.33, 4.2, 0.13, 0.40, 0.10, 0.27, 0.17, 0.57, 0.90, 2.30, and 1.50. We did not create capture histories for seine netting in marking period two or three due to an insufficient number of recaptures.

Following the example of Adams et al. (2006), we used a Cormack–Jolly–Seber (CJS) open population model (Cormack, 1964; Jolly, 1965; Seber, 1965) in the computer program MARK (White and Burnham, 1999) to estimate apparent survival. By collapsing continuous-time resighting data into discrete time bins for antennae capture histories, we violated an assumption of the CJS model (instantaneous sampling periods). However, through an ongoing simulation study, we have demonstrated that the mean bias associated with this violation is on the order of −4.0 to 0.0% (A.B.B., unpublished data) for the estimated parameter values in this study when using one-month intervals.

The CJS model calculates two parameters: (1) apparent survival probability ($\phi = 1 - \text{mortality} - \text{emigration}$), and (2) capture probability (p). For simplicity of survival analysis and comparison between gear types, we either estimated unique parameter values on a time-dependent (t) or independent ($\cdot$) basis. Fixing a parameter in time ($\cdot$) returns a single parameter value, which represents a single value fit between all time intervals, as opposed to calculating unique parameter values between all time intervals (t). We built and compared four simple models that allowed each of these two parameters to either vary or be constant over time. Capture probability (p) was fixed at 0 for time intervals antennae were not active or seine netting did not occur. For antennae resightings in marking period one, parameters estimates are only given from July 2008 to June 2009 since antennae were not constructed until July 2008.

To select the most appropriate of the four possible models, we used Akaike's Information Criterion (AIC) values (Akaike, 1973) and relevant biological knowledge of the system (Pine et al., 2003), such as seasonal trends in *C. undecimalis* life history. For correction of small sample size, AICc was used, which converges to AIC at high sample sizes. We defined models with ΔAICc (ΔAICc = AICc value of given model minus minimum AICc of the four model runs) values <2 as having substantial support, $4 \leq \Delta$AICc ≤ 7 as having considerably less support, and ΔAICc > 10 as having no support (Burnham and Anderson, 2004). Biological knowledge of the system suggests the appropriate model will allow p and ϕ to vary with time ($\phi(t)p(t)$), because adult *C. undecimalis* use mangrove creeks during winter and opportunistically cannibalize juveniles during this co-occurrence (Adams and Wolfe, 2006). Additionally, juvenile *C. undecimalis* movement and emigration vary seasonally, likely affecting both ϕ and p (Stevens et al., 2007; A.J.A., personal observation).

3. Results

3.1. Cost-benefit analysis

Although we only constructed ten antennae, we also included the cost of the eleventh antenna remaining from Adams et al. (2006). The final cost for antenna materials was approximately US$4000 per antenna (solar panel, reader and tuner, batteries, wiring, boxes, and wood: Fig. 1). An approximate total of 800 person–hours (inexperienced two-person team) were required to design, fabricate, deploy, tune, and test all antennae. Each person hour was valued at US$15. Therefore, total construction labor cost US$12,000 (800 h × US$15 per hour). Equipment and labor costs for the antennae totaled US$56,000 (US$12,000 for labor and US$44,000 for materials).

The PIT tag antennae array total construction cost was approximately US$56,000, resulting in a US$18,667 per year cost (US$1697 per antenna) during 3 years of data collection. In addition to construction, seine netting was required to mark fish (Tables 1 and 2). Therefore, the price difference between antennae resighting and seine recapture was the per-year cost of antennae construction (US$18,667). During the three years of use for this study, the cost effectiveness of antennae resighting was evident when calculated by unique individual or unique monthly recapture/resighting (Table 3). The cost of unique monthly recaptures/resightings was an order of magnitude higher for the seine-net technique.

Table 1
Cost (US$) for marking and seine net recapture in marking periods one, two, and three. One-time costs were spread over all sampling periods and rounded to the nearest dollar.

	Period one	Period two	Period three
Labor ($15 person h^{-1})	$13,200	$2700	$4200
PIT tags ($2.50 tag^{-1})	$2608	$1483	$1183
Fuel ($0.80 L^{-1})	$748	$153	$238
Seine net cost ($1000 total)	$333	$333	$333
Grand total	$16,889	$4669	$5954

3.2. Marking period one

We marked 1043 juvenile snook (Table 4) during 880 person-h of seine netting. These hours were also used for physical recapture, resulting in the recapture of 91 uniquely marked fish (110 total recaptures) for an 8.6% overall recapture. Antennae were functional from July 2008 to June 2009. During this time, the ten flatbed antennae averaged a vertical read range of 23.5 cm ± 1.49 SE with a range of 11–41 cm as measured at multiple temporal points (with salinities ranging 39.6–6.9‰) – a negative correlation exists between read range and salinity (Barbour et al., 2011). Antennae resighted 744 uniquely marked fish at least once (>200,000 total resightings) for a 71.3% overall resighting (Table 5). In marking period one, antennae outperformed seine netting in terms of overall recapture/resighting rate, while also resulting in almost 2000 times as many total detections.

Comparing CJS maximum likelihood estimates of apparent survival (ϕ) and capture probability (p) from the $\phi(\cdot)p(\cdot)$ model: antenna $\phi = 0.767$ (95% CI = 0.751–0.781) and $p = 0.723$ (0.701–0.744), while seine $\phi = 0.561$ (0.471–0.648) and $p = 0.0427$ (0.0329–0.0552). Based on 95% confidence intervals, both antennae apparent survival and capture probabilities were significantly ($\alpha = 0.05$) higher than seine-net estimates. Additionally, 95% confidence intervals were smaller for antennae parameters, resulting in more informative maximum likelihood estimates.

AICc results from CJS open population models (Table 6a and b) strongly supported the biologically reasonable model $\phi(t)p(t)$ (ΔAICc = 0) for data from the PIT tag antenna array, with the next most likely model receiving a ΔAICc = 99.4. Data from seine-net recaptures resulted in similar support for the biologically reasonable model (ΔAICc = 0.0) and model $\phi(\cdot)p(t)$ (ΔAICc = 0.74). Therefore, we performed model averaging on these models (Fig. 3) based upon AICc weight (Burnham and Anderson, 2002) (Table 6b).

Examining model-averaged results (Fig. 3), there was higher precision in antennae than seine-net CR data. For seine-net parameter estimates before monthly bin 5, 95% CIs were 0.01–0.83 or 0.16–0.99 for all ϕ estimates, and 0.0–1.0 for p – these estimates are excluded from Fig. 3. The high degree of precision in antennae ϕ and high p (Fig. 3) for the final six parameter estimates coincided with the full functioning of all antennae, and with the marking of a high number of fish (Table 4). Antennae resighted individual fish in multiple monthly bins at a substantially higher rate than seine netting (Table 5), driving precise monthly parameter estimates. For example, ten unique fish were recaptured in two distinct months by seine netting, and no fish were recaptured in three or more months.

Table 2
Cost (US$) for marking and antennae resighting in marking periods one, two, and three. One-time costs were spread over all sampling periods and rounded to the nearest dollar.

	Period one	Period two	Period three
Marking cost (from Table 1)	$16,889	$4669	$5954
Antennae materials ($4000 antenna^{-1} × 11 antennae = $44,000 total)	$14,667	$14,667	$14,667
Antennae construction labor (800 h × $15 h^{-1} = $12,000 total)	$4000	$4000	$4000
Grand total	$35,556	$23,336	$24,621

Table 3
For marking periods one, two, and three, the total cost (US$) of each recapture/resighting method, the cost per unique fish recaptured/resighted, and the cost per unique monthly recapture/resighting rounded to the nearest dollar.

	Period one		Period two		Period three	
	Seine	Antennae	Seine	Antennae	Seine	Antennae
Total cost (Table 1, 2)	$16,889	$35,556	$4669	$23,336	$5954	$24,621
Cost per unique fish recaptured/resighted (Table 5)	$186	$48	$934	$45	$595	$57
Cost per unique monthly recapture/resighting	$167	$14	$934	$15	$541	$15

Table 4
Cumulative number of fish marked and number recaptured by each gear type per monthly bin in marking period one. N/A designation represents months when no physical sampling occurred, or months when antennae had yet to be constructed. Capture probability (p) was fixed at 0 for these months.

Monthly bin	Month	Cumulative number of marked fish	Recaptured by seine	Resighted by antennae
1	February 2008	22	0	N/A
2	March 2008	28	0	N/A
3	April 2008	97	0	N/A
4	May 2008	117	0	N/A
5	June 2008	130	0	N/A
6	July 2008	212	1	43
7	August 2008	212	N/A	29
8	September 2008	212	N/A	31
9	October 2008	212	N/A	43
10	November 2008	515	6	211
11	December 2008	769	45	354
12	January 2009	955	34	421
13	February 2009	1036	12	384
14	March 2009	1036	N/A	407
15	April 2009	1042	3	321
16	May 2009	1042	N/A	178
17	June 2009	1043	0	88

In comparison, 515 unique fish were resighted in at least 2 months by the antenna array, and 432 in at least 3 months (Table 5).

3.3. Marking periods two and three

We marked 593 juvenile snook between November 2009 and February 2010 (marking period two) during 180 person-h of seine netting. The 180 h of physical capture resulted in the recapture of five uniquely marked fish (5 total recaptures) for a 0.8% overall recapture. We marked 473 juveniles between October 2010 and February 2011 (marking period three) during 280 person-h of seine netting. Seine netting resulted in the recapture of ten uniquely marked fish (eleven total recaptures) for a 2.1% overall recapture. Low physical recapture rates resulted in insufficient data for calculation of maximum likelihood survival estimates for marking period two or three. Therefore, these marking periods did not provide a meaningful comparison of antennae and seine net survival estimates. Instead, they highlight the quality of survival data that can be collected by antennae with only a minimum of time spent marking fish (9 and 14 days, respectively).

From November 2009 to August 2010 (marking period two), the antennae resighted 523 (Table 5) uniquely marked fish (>100,000 total resightings) resulting in 88.2% of marked fish being resighted. From October 2010 to June 2011 (marking period three), the antennae resighted 433 (Table 5) uniquely marked fish (>190,000 total resightings) resulting in a 91.5% overall resighting. This resighting data resulted in strong AICc (Table 6c and d) support for the biologically reasonable model $\phi(t)p(t)$ in both marking periods. Antennae parameter estimates were highly precise (Fig. 4), and as marked individuals were lost through mortality and emigration, variability in parameter estimates increased. Parameter estimates from marking period two identified a decrease in apparent survival between the third and fourth monthly bins (Fig. 4). This decrease in apparent survival coincided with a period when temperatures fell below the lethal tolerance of the study species (Adams et al., 2012).

4. Discussion

For coastal fish studies lasting multiple years, application of the PIT tag antennae method is a cost-effective way to greatly increase

Table 5
Incidence of single and multiple recaptures/resightings by gear type. Recaptures/resightings represent the number of unique fish recaptured/resighted in at least the given number of monthly bins. For example, in marking period (MP) one there was one fish that the antenna array resighted in twelve separate monthly bins. 1043 fish were marked in MP one, 593 in MP two, and 473 in MP three.

Number of monthly bins	Antennae resightings (MP one)	Antennae resightings (MP two)	Antennae resightings (MP three)	Seine net recaptures (MP one)
1	744	523	433	91
2	512	375	343	10
3	432	278	263	0
4	332	156	204	0
5	237	90	153	0
6	147	59	100	0
7	67	25	51	0
8	23	9	31	0
9	8	4	3	0
10	4	0	N/A	0
11	3	N/A	N/A	0
12	1	N/A	N/A	N/A

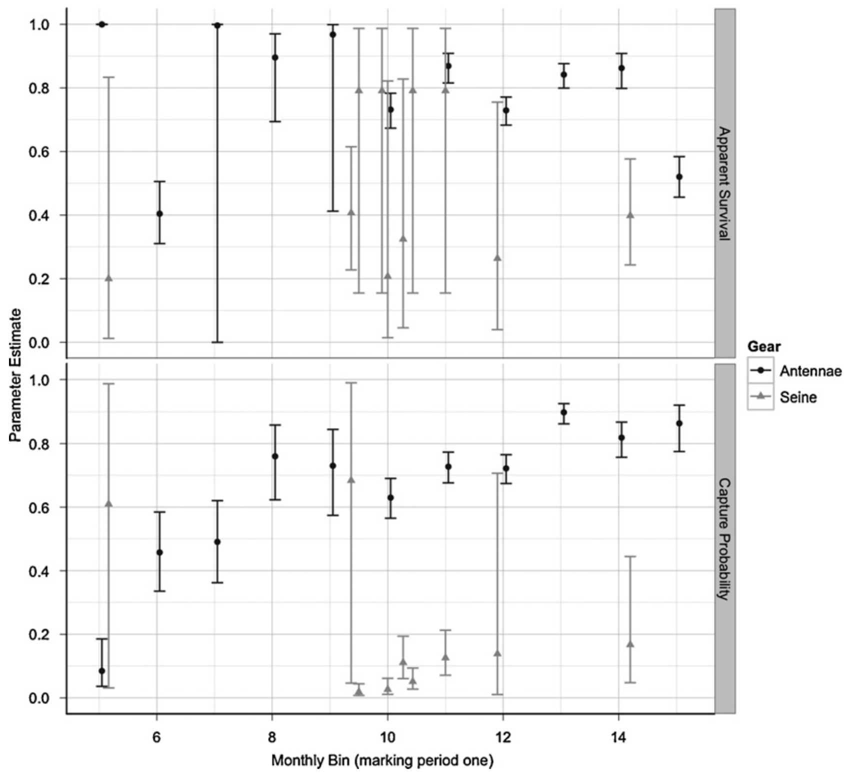

Fig. 3. Apparent survival and capture probabilities calculated from resighting by an array of eleven autonomous PIT tag antennae versus recapture by seine netting (uneven time intervals) of 1043 *Centropomus undecimalis* marked during marking period one – February 2008 to May 2009 (monthly bins 1–16). Parameters calculated using Cormack–Jolly–Seber model-averaged results. Monthly bins when seine netting did not occur or antennae were not constructed had capture probability fixed to 0 and are excluded from this figure. Monthly bins before antennae construction are also excluded. Bars represent 95% confidence intervals.

precision of survival estimates and provide otherwise unavailable information. Compared to seine netting, antennae resighted marked fish at a high rate, allowing for informative monthly estimates of apparent survival. The antennae array collected survival information with a minimum of physical capture effort, and was not limited by environmental conditions. However, while seine netting was limited by environmental conditions (e.g., suitable tides, severe weather), it was not reliant on constricted bodies of water and is therefore useful in a greater variety of habitat types. Also, while antennae were more cost-efficient than physical capture, they were unable to collect biotic covariates (e.g., fish size), which could justify the higher cost of physical recaptures in certain studies.

Table 6
AICc results and number of estimated parameters (np) from Cormack–Jolly–Seber 'Recaptures Only Model' in program MARK for the: (a) antenna array (marking period one), (b) seine net recapture (marking period one), (c) antenna array (marking period two), and (d) antenna array (marking period three). Apparent survival (ϕ) and capture probability (p) were calculated on either a time-dependent (t) or independent ($\cdot$) basis.

Model	np	AICc	ΔAICc	AICc weight
(a)				
$\phi(t)p(t)$	27	5455.3	0.0	1.0
$\phi(\cdot)p(t)$	13	5554.7	99.4	0.0
$\phi(t)p(\cdot)$	17	5634.3	179.0	0.0
$\phi(\cdot)p(\cdot)$	2	5865.3	410.0	0.0
(b)				
$\phi(t)p(t)$	24	936.4	0.0	0.59
$\phi(\cdot)p(t)$	18	937.2	0.7	0.41
$\phi(t)p(\cdot)$	17	991.8	55.4	0.0
$\phi(\cdot)p(\cdot)$	2	997.6	61.2	0.0
(c)				
$\phi(t)p(t)$	17	3045.2	0.0	1.0
$\phi(t)p(\cdot)$	10	3092.8	47.6	0.0
$\phi(\cdot)p(t)$	10	3108.7	63.5	0.0
$\phi(\cdot)p(\cdot)$	2	3187.2	142.0	0.0
(d)				
$\phi(t)p(t)$	15	2579.8	0.0	1.0
$\phi(t)p(\cdot)$	9	2591.9	12.1	0.0
$\phi(\cdot)p(t)$	9	2621.0	41.2	0.0
$\phi(\cdot)p(\cdot)$	2	2647.1	67.4	0.0

4.1. Cost-benefit

Despite the relatively high initial investment in materials and labor to construct the antennae, the cost effectiveness and data superiority from the antenna approach validated the expense. Physical capture was required to mark fish, a necessity of any capture-recapture/resighting (CR) study, but antennae CR was more cost-efficient than seine netting even when considering these marking costs. This cost effectiveness is compounded in long-term research programs, as antennae function for multiple years – the antenna from Adams et al. (2006) has functioned continuously for seven years. For long-term research projects, the only costs after antennae construction are marking, data upload, battery replacement after 4–7 years, and infrequent maintenance expenditures. Our cost-benefit estimates for antennae systems were conservative since we did not factor in the additional years of potential use of the antennae array. Additionally, actual use of these systems provides further information, such as data on long-term site fidelity and movement patterns, providing additional benefits beyond enhanced apparent survival estimates.

For seine-net recaptures, the level of physical effort required to replicate antennae resighting would inflate costs beyond antennae construction levels, elevate the magnitude of post-release mortality, and induce a trap-response bias (Nichols et al., 1984).

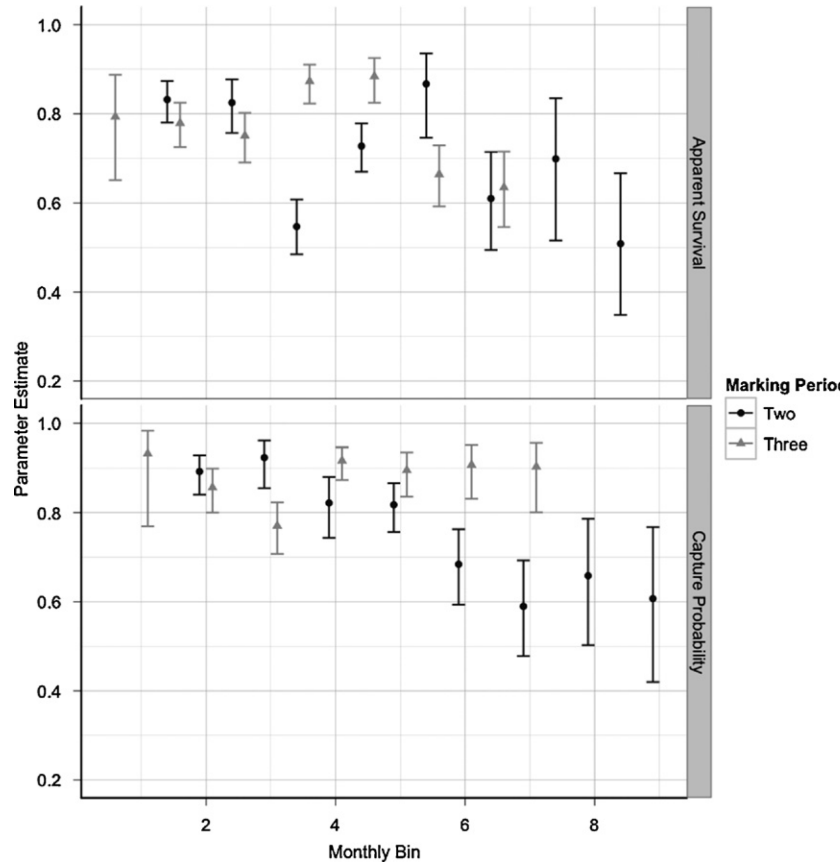

Fig. 4. Monthly apparent survival and capture probabilities calculated from resighting by an array of eleven autonomous PIT tag antennae of 593 *Centropomus undecimalis* marked during marking period two – November 2009 to July 2009 (monthly bins 1–9), and 473 *C. undecimalis* marked during marking period three – October 2010 to May 2011 (monthly bins 0–7). Parameters were calculated using Cormack–Jolly–Seber model-averaged results. Bars represent 95% confidence intervals.

Additionally, the underestimate of apparent survival in the $\phi(\cdot)p(\cdot)$ model was indicative of a negative bias related to temporary emigration (A.B.B., unpublished data), while a similar bias was likely dampened in antennae-based estimates by capture probabilities >0.5 (Zehfuss et al., 1999). Thus, we are unaware of any reasonable physical CR method that would result in sufficient recaptures to match the antennae results. This was particularly important in this study, because the magnitude of seine-net recaptures was insufficient to generate informative monthly estimates of apparent survival. In comparison, the temporally detailed survival data from antennae resighting was useful as it clearly identified a disturbance event between the third and fourth monthly bins of marking period two (Adams et al., 2012). This temporally detailed and highly precise data could be used to identify essential fish habitats or inform fisheries management models (e.g., by predicting year class strength). Additionally, although not included in this study, we have successfully used antennae resightings to generate informative monthly survival estimates by creek and fish age in an ongoing analysis of juvenile survival (A.B.B., unpublished data). This type and quality of data would not be obtainable with a seine-net approach in this study system.

4.2. Methodological comparison

PIT tag antennae were especially useful in this study, as we sampled in a complex mangrove habitat where effective sampling was often challenging (e.g., Robertson and Duke, 1990). For example, seine netting was only efficient during low tide when mangrove prop root refuge was unavailable (Thayer et al., 1987; Laegdsgaard and Johnson, 2001), but the antennae functioned continuously and throughout the full tidal cycle. Furthermore, antennae proved extremely advantageous in the summer months when low tides occurred at night and fewer juveniles inhabited the creeks. These factors made summer seine-net sampling difficult and inefficient, returning little data for the effort expended. Antennae resighting data, on the other hand, allowed survival analysis to continue into the summer and lent insight into seasonal characteristics of habitat use, such as emigration or ontogenetic shift from the juvenile habitat.

One challenge to using PIT tag antennae systems in estuarine environments was achieving proper design. Saltwater corrosion and the subtropical climate of our study area caused multiple electronic component failures during the initial months of setup and operation. These failures were reflected in the low and variable capture probabilities (p) immediately after construction. After adapting antennae components to environmental conditions, the majority of electronic failures ceased and p increased. Another design challenge was finding suitable areas to place antennae for maximum resighting efficiency. The dimensions of the copper inductor coil and the read range of the magnetic field limited antenna application to locations where fish movement was restricted to narrow areas <10–30 m in width (e.g., narrow passages in creeks) as opposed to open habitats, such as bays.

Seine netting also provided advantages and challenges when compared to PIT tag antennae. Seine netting more thoroughly sampled the entire study area, albeit during finite time windows, while PIT tag antennae only sampled fixed locations. Sampling multiple spatial points is especially important if the study species exhibits a small home range (Kramer and Chapman, 1999), as an individual with a small home range may not pass stationary antennae. Also, the physical recapture of marked individuals provided information on growth and population size, important metrics for determining habitat quality that antennae resightings cannot measure. However, the recapture inefficiency of seine nets in our system made collection of growth information difficult without a supplementary method (e.g., otolith aging).

4.3. Conclusions

Since physical capture is required to mark the study subject, the use of PIT tag antennae can be considered an effective part of a dual-method approach incorporating both physical capture and telemetry. The use of this dual-method approach has the potential to advance ecological studies of coastal fish. Although the usefulness of data from the seine nets was limited by low recapture rates and environmental conditions, PIT tag antennae functioned continuously and recaptured marked fish at high rates. Likewise, PIT tag antennae could not collect growth or population size data, while seine net recaptures could. Therefore, we argue that when used in conjunction, the two methods can provide a more complete picture of fish habitat use and survival, thereby making a stronger contribution to understanding habitat use by estuarine fishes.

Although not compared in this study, PIT tags also have longer lifespans, are less expensive, and are offered in smaller sizes than other telemetry tags, such as acoustic, GPS, or radio transmitters. While these other methods can be used in a wider variety of habitats than PIT tag antennae, the cost of these tags would make it difficult to mark a high number of individuals and battery life would prohibit long-term tracking of specific individuals. Thus, the combined use of PIT tag antennae and physical capture may be an ideal approach for cost-efficient, long-term studies of coastal or estuarine animals.

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