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Performance of a low-cost, solar-powered pop-up satellite archival tag for assessing post-release mortality of Atlantic bluefin tuna (Thunnus thynnus) caught in the US east coast light-tackle recreational fishery

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Performance of a low-cost, solar-powered pop-up satellite archival tag for assessing post-release mortality of Atlantic bluefin tuna (*Thunnus thynnus*) caught in the US east coast light-tackle recreational fishery

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Abstract

Background: Pop-up satellite archival tags (PSATs) are a valuable tool for estimating mortality of pelagic fishes released from commercial and recreational fishing gears. However, the high cost of PSATs limits sample sizes, resulting in low-precision post-release mortality estimates with little management applicability. We evaluate the performance of a lower-cost PSAT designed to enable large-scale post-release mortality studies. The tag uses solar rather than battery power, does not include a depth sensor, and transmits daily summaries of light and temperature data rather than high-resolution habitat profiles, contributing to a substantially lower per-unit price. We assessed the tag's ability to detect mortality while also estimating the post-release mortality of juvenile (119–< 185 cm) Atlantic bluefin tuna (*Thunnus thynnus*) caught using light-tackle angling methods along the US east coast.

Results: Using high-resolution data from previously deployed PSATs and environmental information from the general tagging location, we established parameters to infer mortality for Atlantic bluefin tuna using only daily summary data. We then deployed 22 PSATs, programmed to pop off after 31 days (thus providing 30 full daily summaries), on Atlantic bluefin tuna caught using light tackle off the coasts of Massachusetts and North Carolina, USA, in 2015 and 2016. Data were recovered for 15 tags with deployments ranging from 7 days (premature shedding) to 95 days (failed pop-off) and indicated that tagged fish spent sufficient time near the surface to keep the solar-powered tags fully charged. Fourteen fish demonstrated strong temporal changes in temperature indicating vertical movement in the water column, consistent with survival. One fish was predated upon after 17 days, likely by a shortfin mako, and was considered a natural mortality, resulting in a post-release mortality estimate of 0%.

Conclusions: While low reporting rates complicated inferences about post-release mortality, the concept of using species-specific mortality parameters coupled with a reduced dataset shows promise as a cost-effective tool for detecting post-release mortality using PSATs. In addition, findings suggest that catch-and-release angling is a viable conservation strategy for juvenile Atlantic bluefin tuna caught in the US east coast light-tackle fishery.

Keywords: Pop-up satellite archival tag, Atlantic bluefin tuna, Post-release mortality, Recreational fisheries

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Background

Over the past several decades, satellite telemetry has emerged as a valuable tool for estimating mortality rates for a broad variety of terrestrial and aquatic species. These studies can not only provide key insight into a species' movement ecology and population dynamics [1, 2], but can also identify anthropogenic sources of mortality and inform conservation efforts for species of concern [3].

In the marine realm, pop-up satellite archival tags (PSATs) have been widely employed to detect and estimate post-release mortality of large pelagic fishes (istiophorid billfishes, tunas, swordfish, and sharks) caught with commercial and recreational fishing gears [4]. Such studies are critical for estimating overall fishing-induced mortality and effects on stock size and age structure [5], as well as for informing best practices to minimize post-release mortality [6–8]. PSATs are typically battery-powered and record environmental data such as light level, pressure (depth), and water temperature at regular, high-resolution intervals (often 5 min or less) for a specified deployment period before popping off the fish, floating to the surface, and transmitting archived data (or summaries of archived data) via the Argos satellite system (CLS/Argos, Toulouse, France). The habitat data can be used to readily distinguish surviving and dead fish [7, 9, 10].

While useful for detecting post-release mortality, most commercially available PSATs cost over $3000 each (e.g., High-Rate Archival X-Tag [MSRP $3600], Microwave Telemetry, Inc., Columbia, MD USA). Simulation experiments, meanwhile, have recommended that studies deploy a minimum of 100 PSATs to estimate post-release mortality within five percentage points of the "true" value [11]. However, given the operating budgets of most post-release mortality studies, the high cost per tag generally results in small sample sizes, which can lead to low-precision estimates that are of reduced utility to management [12]. This lack of precision is especially notable given that post-release mortality rates are species-specific and can also vary within a species according to fish size, gear type, fishing method, and environmental conditions [13, 14]. As a result, there has been increased interest in developing lower-cost PSAT alternatives for detecting post-release mortality of pelagic species (e.g., SeaTag-LOT, Desert Star Systems, LLC, Marina, CA USA; sPAT, Wildlife Computers, Inc., Redmond, WA USA).

The Atlantic bluefin tuna (*Thunnus thynnus*) is widely targeted by recreational anglers aboard charter and private boats along the east coast of the USA from Maine to North Carolina, where the fishery is of considerable economic importance [15]. While a variety of fishing methods are used, over the past decade significant technological advances (e.g., braided fishing line) have resulted in increasing popularity of the light-tackle fishery, which we define as the targeting of Atlantic bluefin tuna by actively casting or jigging artificial lures, primarily with spinning tackle. The fishery has become internationally known as a light-tackle, big-game angling opportunity and currently supports numerous specialized charter boat businesses and fishing tackle manufacturers. Participating anglers primarily target juvenile Atlantic bluefin tuna in the large school (119–< 150 cm curved fork length [CFL]) and small medium (150–< 185 cm CFL) size classes. In recent years, anglers have been permitted to retain one fish per vessel per day in these size classes combined (FR 82 19615, 4/28/2017), which in times of high fish availability can result in large numbers of estimated regulatory releases that from 2012 to 2016 ranged from 88 to 231% of the number of estimated fish harvested (pers. comm., National Marine Fisheries Service, Fisheries Statistics Division).

Post-release mortality of pelagic fishes is influenced by the cumulative impact of physical trauma (i.e., hook-induced tissue damage) and physiological stress, which are largely affected by the gear and method of capture [16]. Previous studies using PSATs have suggested low post-release mortality for bluefin tuna captured in recreational fisheries. Stokesbury et al. [17] deployed PSATs on large medium and giant (≥ 185 cm CFL) Atlantic bluefin tuna captured using bait rigged with barbless circle hooks in an experimental recreational fishery off the coast of Prince Edward Island, Canada, with fight times ranging from 6 to 79 min, and estimated a mortality rate of 3.4% (2 of 59 fish died after release). Marcek and Graves [18] observed a post-release mortality rate of 0% for 19 school-size (91–< 119 cm CFL) Atlantic bluefin tuna tagged with PSATs after being caught using 23–91 kg trolling tackle and fought for 5.5–12 min. Most recently, Tracey et al. [19] deployed PSATs on 59 southern bluefin tuna (*Thunnus maccoyi*), primarily of sizes comparable to the school and large school size classes (91–< 150 cm CFL), caught while trolling artificial lures or drifting with natural baits with 15–37 kg tackle (fight times ranged from 3 to 118 min), estimating a post-release mortality rate of 19%. Only five of the 59 fish tagged were caught with treble hooks, but two of those fish died, suggesting that the use of treble hooks increases post-release mortality (though the small sample size precluded statistical testing). The study also conducted physiological sampling of 233 recreationally caught southern bluefin tuna and found that physiological stress (but not post-release mortality) increased with fight time, as has been found for other pelagic species [7]. While numerous additional studies have deployed PSATs on bluefin tuna to assess movements and habitat utilization [e.g., 20–22], post-release mortality data from such research is likely not reflective of recreational fisheries due to the use of angling and handling methods intended to minimize mortality [17].

The present study assesses the post-release mortality of juvenile (119–< 185 cm CFL) Atlantic bluefin tuna caught in the light-tackle recreational fishery along the US east coast, while simultaneously evaluating the reliability and performance of a newly developed, low-cost PSAT. Reportedly longer fight times and the frequent use of treble hooks on artificial lures in the light-tackle fishery may increase physiological stress and physical damage, respectively, and could result in higher rates of post-release mortality than those found in previous studies. Successful performance of the PSAT, designed to detect post-release mortality for large pelagic fishes at a significantly reduced cost compared to other available PSATs, would enable larger study samples, providing high-precision estimates that could be incorporated into management efforts.

Methods

Tag configuration

The Desert Star Systems SeaTag-LOT was used in this study. The SeaTag-LOT is powered by a solar-charged capacitor rather than a battery and does not contain a pressure (depth) sensor. Once a tag is fully charged, which takes approximately 30 min in full sunlight, enough solar power can be stored so that the tag will continue to record and archive data for up to three days in complete darkness. While the tag records light and temperature data at 4-min intervals, the SeaTag-LOT only archives and transmits daily summary data for four light- and temperature-related measurements: a) capacitor voltage (daily average); b) solar panel voltage (daily average); c) temperature (daily minimum, maximum, and average); and d) maximum daily change in temperature per minute (ΔT min^{-1}, calculated by dividing the maximum change in temperature between measurements by four). In addition, the tag transmits day length and local apparent noon time for each day of deployment. The reduced quantity of data archived, lack of pressure sensor, and use of solar power rather than a battery contribute to the relatively low per-unit cost of this PSAT ($899 for quantities of less than 50, or roughly one quarter the price of other commercially available PSATs).

Because the SeaTag-LOT only transmits daily summary data, it was necessary to consider how the tag should be configured to detect post-release mortality specifically for bluefin tuna off the US east coast. Tag configuration included the development of thresholds, under which the tag would pop off prior to the scheduled deployment date, for three mortality scenarios: (1) a fish dies and sinks to the bottom in shallow water (i.e., on the continental shelf); (2) the fish/tag is eaten (scavenging or predation); or (3) a fish dies and sinks in water deeper than the tag's 1200 m service depth.

For scenario 1, the maximum ΔT min^{-1} recorded by the tag was used as an indicator of whether a fish was alive and moving vertically in the water column. High-resolution (~ 5 min) depth and temperature data transmitted from Microwave Telemetry High-Rate X-Tags previously deployed on school-size Atlantic bluefin tuna and white marlin (*Kajikia albida*) (J. Graves, unpubl.) were examined to determine the minimum ΔT min^{-1} typically exhibited by a living fish moving vertically in the water column, which could distinguish it from a dead fish resting at a constant depth on the sea floor (or a shed tag floating on the surface). Surviving fish generally exhibited a daily maximum ΔT min^{-1} well in excess of 0.2 °C min^{-1}; data from tags deployed on school-size bluefin tuna, for example, indicated typical daily maximum ΔT min^{-1} values between 1 and 2 °C. Tags deployed on white marlin that subsequently died and rested on the bottom for several days, meanwhile, indicated maximum ΔT min^{-1} values of less than 0.05 °C. The release threshold was thus set for 72 h with a maximum ΔT min^{-1} of less than 0.2 °C. If a tag were to pop off due to exceeding this threshold, an examination of temperature data during the low ΔT min^{-1} interval could be examined to infer that the fish was dead and resting on the bottom in cool waters versus alive and maintaining a very stable depth distribution higher in the water column. A shed tag floating on the surface could be differentiated from a tag that popped off a dead fish because the former, when floating on the surface, would begin transmitting in an "On Fish," rather than "Reporting," status.

For scenario 2, a tag's remaining in complete darkness for a certain minimum amount of time was considered an appropriate indicator of predation or scavenging. Ingestion of PSATs (and presumably the fish to which they were attached) by predators or scavengers is well-documented [8, 9, 18, 23], and tags generally remain inside the consumer's stomach for at least several days before being egested, floating to the surface, and transmitting data. Given these findings, tags were programmed to release if maintained in complete darkness for 48 h.

For scenario 3, a low-temperature threshold at which the tag would pop off of the fish before sinking below the tag service depth was determined through inspecting depth-temperature data collected off the coast of North Carolina's Outer Banks via the World Ocean Database [24]. Depth-temperature data indicated that temperatures at 1000 m depth were typically in the vicinity of 4.5 °C. While Atlantic bluefin tuna have a broad thermal range and have been recorded in temperatures as low as 3 °C [25], we judged it preferable to keep the low-temperature threshold conservative to minimize the risk of a tag pressure housing failure. In addition, previous PSAT tag research along the east coast of North America has suggested that bluefin tuna in this region rarely encounter temperatures below 8 °C [20, 26]. It is possible that a deep-diving, surviving fish could swim below a conservative low-temperature threshold and cause tag pop-off, erroneously indicating a mortality; in such a case, however, the tag would provide information (e.g., daily temperature ranges prior to pop-off) from which survival could be inferred. The low-temperature threshold for pop-off was thus set at 4.5 °C. In addition to examining whether tags popped off due to exceeding the thresholds described above, daily summary data of light level and temperature were visually examined to infer whether a fish survived the deployment duration.

Tag deployment

PSATs were deployed on large school- and small medium-size Atlantic bluefin tuna caught onboard recreational charter vessels using typical light-tackle methods during the 2015 and 2016 fishing seasons off the coasts of Massachusetts and North Carolina. The majority of tagged fish were caught using spinning tackle and braided line with a rated breaking strength of 36–45 kg; one tagged fish was caught on a conventional (revolving-spool) vertical jigging rod and reel with 36-kg breaking strength braided line. Artificial lures used to catch bluefin tuna included soft plastic lures rigged with single J-hooks, hard-bodied lures rigged with either treble or single hooks, and metal jigs rigged with single "assist" hooks. In addition, on a few occasions fish were caught by casting live Atlantic mackerel (*Scomber scombrus*), rigged with a single J-hook, into a school of actively feeding Atlantic bluefin tuna using spinning tackle.

Atlantic bluefin tuna were fought, handled, and released in the manner typically practiced by each fishing vessel, with no input from the tagging researcher. Bluefin tuna were tagged regardless of condition, and following the method of Marcek and Graves [18], multiple fish were not tagged if hooked within 30 min of one another in order to avoid sampling from the same school of fish and maintain a random sample to the extent practicable. Methods of securing fish for unhooking and tagging included lip-gaffing (either maintaining the fish in the water or sliding it onboard through the vessel's tuna door [a door in the transom to facilitate the landing of large fish]) or holding the fish under the operculum while supporting it against the vessel's gunwale. Gear type, fight time (hooking to capture), total time (hooking to release), hooking location in the fish, fish length (CFL), sea surface temperature, release location, and other relevant factors were recorded for each fish. In addition, the condition of each fish was assessed using a modified version of the "ACESS" condition scale developed by Kerstetter et al. [27]. Each fish's condition was rated from 0 to 8 by evaluating four characteristics on a scale of 0 (poor) to 2 (good): overall activity, color, body positioning, and bleeding (i.e., a score of 2 means little/no bleeding).

The PSATs used in this study were programmed to record light level and water temperature every 4 min over the course of 31 days (or 30 full daily summaries), after which they were to detach from the fish via an ignition release, float to the surface, and transmit data. Tags were light-activated and maintained in sunlight for at least 30 min prior to deployment to ensure a full solar charge. The PSATs were rigged with 16 cm of 91-kg test monofilament fishing line attached to a hydroscopic nylon intramuscular tag anchor, following Marcek and Graves [18]. Each tag anchor was inserted to a depth of approximately 10 cm into the fish's dorsal musculature 10 cm posterior to the origin of the first dorsal fin and 5 cm ventral to the base of the first dorsal fin, where it was able to interlock with the pterygiophores supporting the dorsal fin [28]. After tagging, at the discretion of the fishing crew, some fish were revived boat-side prior to release using a lip-gaff while slowly moving the vessel forward at about 2 kt.

PSATs will sometimes release from fish prior to the scheduled release date (i.e., are shed), which could occur during routine swimming (for example, if the tag anchor pulls out of the dorsal musculature), or due to other reasons, such as a predation event in which the tag, rather than being ingested by the predator, is dislodged and floats to the surface. It is important to establish a threshold deployment duration to determine which prematurely released PSATs should be included in the post-release mortality estimate [18, 29]. While previous post-release mortality studies have indicated that most capture-induced mortalities tend to occur within 48 h of release [6, 19, 30, 31], the 5 days following release has often been used as the interval during which mortalities would be considered angling-induced (as opposed to natural mortalities) [8, 18]. As a result, to avoid misinterpreting the fate of surviving fish from tags that released prematurely, only tags from fish that remained attached for 5 days or longer and whose summary data for the first 5 days were consistent with survival were included as survivors in the estimate of post-release mortality.

To determine the effect of sample size on the 95% confidence interval for the post-release mortality estimate, bootstrapping simulations based on 10,000 bootstrapped samples were performed using software developed by Goodyear [11]. For the purposes of bootstrapping, natural mortality M was assumed to be 0.14 year^{-1} and age-independent, an assumption similar to that used in the 2014 stock assessment for western Atlantic bluefin tuna conducted by the International Commission for the Conservation of Atlantic Tunas (ICCAT) Standing Committee on Research and Statistics [32]. The post-release mortality estimate for the light-tackle fishery was statistically compared with Marcek and Graves' [18] estimate for school-size Atlantic bluefin tuna caught in the troll fishery, as well as with Tracey et al.'s [19] estimate for southern bluefin tuna caught in the troll and drift fishery, using Fisher's exact tests.

Net displacement for tagged fish was calculated as the first high-quality pop-off position estimate (Argos location code 1, 2, or 3). In some cases, a high-quality location was not transmitted in the period immediately (~ 8 h) after pop-off, in which case the first reasonable location estimate received (Argos location code 0, A, or B) was used to calculate net displacement. The straight-line distance between tag deployment location and pop-off location was calculated using ArcGIS version 10.2.2 (ESRI, Redlands, California).

Results

A total of 22 PSATs were deployed on Atlantic bluefin tuna caught on light tackle during 2015 and 2016 (Table 1). Five tags were deployed off the Outer Banks, North Carolina, and 17 tags were deployed off Cape Cod and Martha's Vineyard, Massachusetts. Fish sizes ranged from 114 to 201 cm CFL (mean = 150 cm, SD = 26 cm) and fight times ranged from 4 to 78 min (mean = 21 min; SD = 20 min). The time that the fish's head was out of the water during the hook removal, measuring, and tagging process ranged from 0 (fish tagged in the water) to 3 min (mean = 75 s; SD = 51 s).

Twenty of the 22 fish were caught on artificial lures, while two fish were caught on live mackerel rigged with a single J-hook. Of the 20 fish caught on lures, 12 were caught on lures rigged with one or two single hooks, seven were caught on lures rigged with two treble hooks, and one was caught on a lure rigged with both a treble and single hook. Two of the 22 fish (9%) were hooked internally. For one bluefin tuna, caught on a live mackerel, the hook was not visible (i.e., was in the esophagus/stomach) and the line was cut. The second fish, caught on a lure with two treble hooks, was hooked both in the corner of the jaw and in the posterior section of the palate, just anterior to the first gill arch, and hooks were removed prior to release. Twenty fish were hooked in various external locations. Two fish (9%) exhibited heavy bleeding after capture from hook wounds in the ventral musculature; other fish exhibited light or moderate bleeding resulting from hook and lip-gaff wounds.

Fourteen of the 22 PSATs successfully transmitted data. Six of the 14 tags were shed prior to the scheduled pop-off date, with deployments ranging from seven to 25 days. In addition, one tag (Fish #10) failed to pop off at the end of the scheduled deployment period and ultimately was shed from the fish after 95 days, providing daily summary data throughout the deployment. One of the tags that failed to report (Fish #19) was physically recovered when it washed ashore in Nags Head, North Carolina, and 46 days' worth of data were recovered. A diagnostic analysis performed by the manufacturer revealed that the tag's electronics functioned normally, but that the burn chamber of the tag had been flooded, preventing pop-off. In addition, the antenna of the tag was broken off, impeding the transmission of data following shedding. As a result, pop-up location and net displacement information were not available. For five of the 15 tags for which data were recovered, the number of daily summaries transmitted was fewer than the total number of days for which the tag was deployed, with the number of summaries ranging from 83 to 93% of total deployment days. We suspect that this resulted from the fact that daily summaries were binned based on light rather than a 24-h clock—as a result, consecutive calendar days spent by a bluefin tuna at depth could result in the generation of only a single "daily" summary.

Based on daily summary data for the reporting 14 tags and the one tag which was recovered, coupled with the thresholds established for three mortality scenarios, we inferred that 14 of 15 fish survived through the deployment period (Fig. 1). Net displacement for surviving fish tagged off North Carolina in March of 2015 and 2016 (4 reporting tags) ranged from 35 to 377 km over deployment periods ranging from 23 to 95 days. For surviving bluefin tuna tagged off Massachusetts (9 reporting tags), net displacements ranged from 61 to 304 km over deployments ranging from seven to 30 days. Daily capacitor voltage from tags on surviving fish generally remained near the maximum (3.6 V) throughout deployment, indicating that the tag (and fish) spent a sufficient amount of time near the surface to keep the tag fully charged and well above the minimum capacitor voltage of 2.2 V needed for full processing capability. Average solar panel voltage, meanwhile, was lower due to the tag's spending a significant portion of each day in darkness (at night and when fish dove into deeper waters). Daily maximum ΔT min^{-1} values were generally well in excess of the 0.2 °C min^{-1} threshold, with the exception of Fish #10 (Fig. 2), which for five consecutive days had maximum daily ΔT min^{-1} values below 0.2 °C min^{-1} (at which time pop-off should have occurred had it not failed), indicating a highly constricted thermal range. However, the water temperature measurements corresponding to those days (16.7–19.3 °C) suggest that the fish was at a shallow, stable depth, rather than resting on the bottom (in which case temperatures would have been considerably lower).

Table 1 Catch and tag information for released Atlantic bluefin tuna

Fish	Date deployed	Location	Curved FL (cm)	Hooking location[a]	Hook type[b]	Fight time (min)	Condition (0–8 scale)	Full days deployed on fish[c]	Minimum straight-line displacement (km)	Mean displacement per day (km)
1	3/9/2015	NC	195	JC	S	37	6	30	61	1.97
2	3/19/2015	NC	173	JC	T/S	37	5	30	173	5.58
3	3/22/2015	NC	157	RF	S	23	7	–	DNR[d]	–
4*	8/10/2015	MA	145	VM	T	16	5	7	96	12
5	9/18/2015	MA	114	JC	S	8	6	30	61	1.97
6	9/18/2015	MA	152	DP	S	21	7	–	DNR	–
7*	9/25/2015	MA	157	JC	S	17	8	25	226	8.69
8*	9/28/2015	MA	165	JC	S	21	8	25	275	10.58
9[e]	9/28/2015	MA	183	JC	S	72	7	27	259	9.25
10[f]	3/1/2016	NC	193	UJ	T	78	5	95	377	3.89
11*	3/9/2016	NC	201	LJ	S	28	6	23	35	1.46
12[g]	8/5/2016	MA	117	JC	S	9	7	17	143	6.81
13	8/5/2016	MA	135	JC	S	18	7	–	DNR	–
14	8/7/2016	MA	137	JC/TH	T	7	7	–	DNR	–
15	8/7/2016	MA	130	UJ	S	4	7	–	DNR	–
16	8/7/2016	MA	122	JC	S	8	8	–	DNR	–
17	8/7/2016	MA	132	JC	T	8	6	30	144	4.65
18*	8/7/2016	MA	137	JC	S	8	6	9	130	13
19[h]	8/7/2016	MA	140	JC/VM	T	9	3	46	DNR	–
20*	8/8/2016	MA	147	JC	S	20	8	21	304	13.82
21	8/27/2016	MA	132	JC/DP	T	7	4	–	DNR	–
22[i]	8/31/2016	MA	127	JC	T	4	7	29	283	9.13

Catch and tag information for 22 Atlantic bluefin tuna caught with light-tackle recreational fishing gear off Massachusetts (MA) and North Carolina (NC) and tagged with pop-up satellite archival tags. Asterisks denote tags that were shed prior to the scheduled pop-off date

[a] Hooking locations are deep (DP), jaw corner (JC), lower jaw (LJ), roof of mouth (RF), top of head (TH), upper jaw (UJ), and ventral musculature (VM)

[b] Fish were caught with either single (S) or treble (T) hooks

[c] While the number of daily summaries acquired generally corresponded to the tag deployment duration, there were five instances in there were fewer daily summaries than deployment days: Fish 2 (25 summaries, 30 day deployment); Fish 10 (88 summaries, 95 day deployment); Fish 18 (8 summaries, 9 day deployment), Fish 20 (19 summaries, 21 day deployment), and Fish 22 (27 summaries, 29 day deployment)

[d] "DNR" refers to tags that did not report

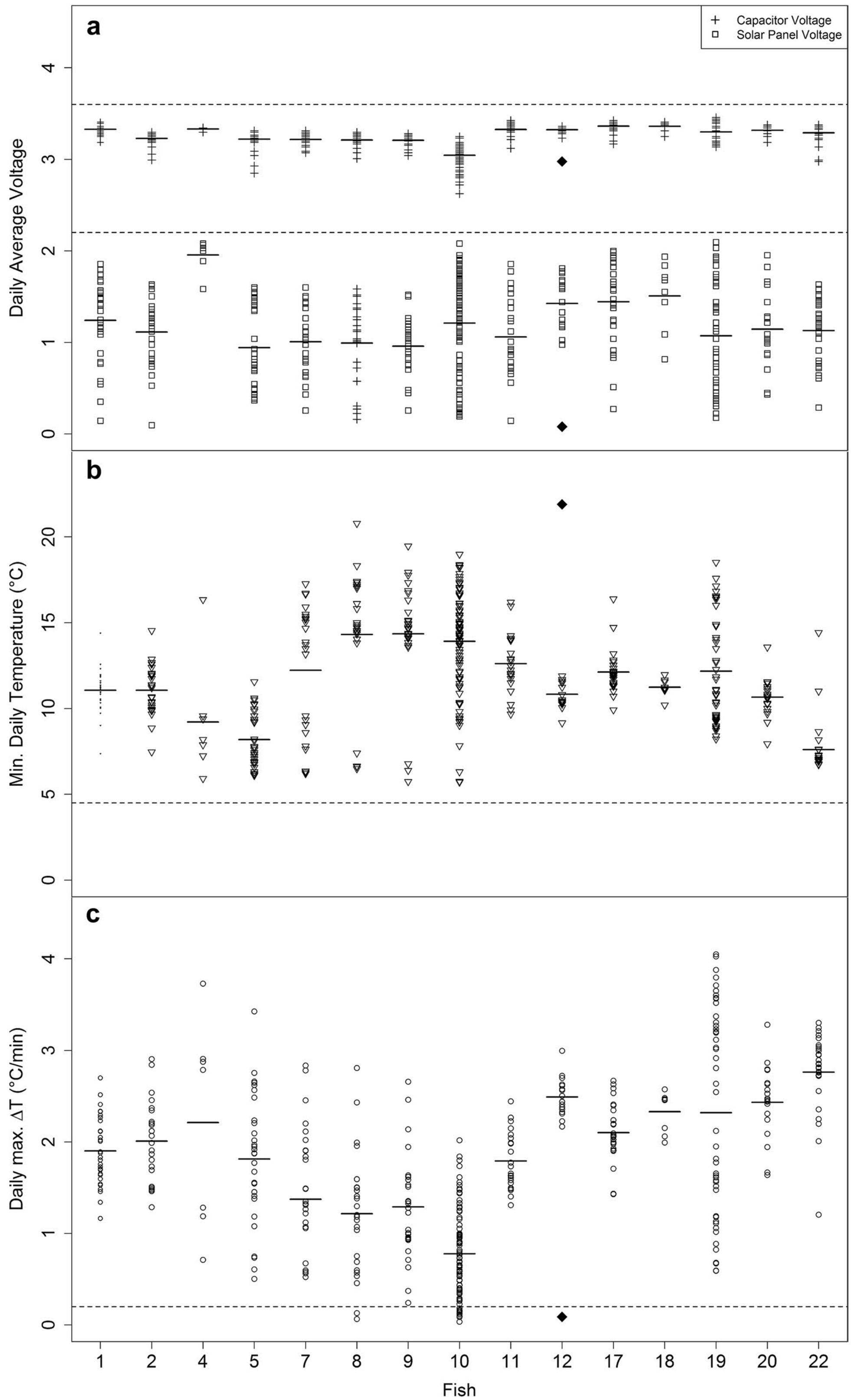
[e] The tag had been light-activated 3 days prior to deployment and thus was only deployed for 27 days

[f] The tag did not pop off as scheduled, but was eventually shed after 95 days, when data for the duration of the deployment were transmitted

[g] The tag/fish was predated upon 17 days after deployment and began transmitting 3 days later

[h] The tag did not transmit data but was physically recovered on a beach in Nags Head, North Carolina, and data were retrieved

[i] The tag had been light-activated the day before deployment and thus was only deployed for 29 days


a
Capacitor Voltage
Solar Panel Voltage
Daily Average Voltage
b
Min. Daily Temperature (°C)
c
Daily max. ΔT (°C/min)
Fish
1
2
4
5
7
8
9
10
11
12
17
18
19
20
22

(See figure on previous page.)

Fig. 1 Daily average solar panel and capacitor voltage (**a**), minimum daily temperature (**b**), and daily maximum ΔT min^{-1} (**c**) for the 15 Atlantic bluefin tuna for which tag data were recovered. Short horizontal solid lines represent the mean daily summary values for each fish. The horizontal dashed lines in **a** refer to the maximum and minimum solar capacitor voltages (3.6 and 2.2 V); the horizontal dashed line in **b** refers to the minimum temperature threshold for pop-off (4.5 °C); the horizontal dashed line in **c** refers to the daily maximum ΔT min^{-1} threshold for pop-off (72 h at less than 0.2 °C). The black diamonds for Fish #12 correspond to the daily summary data from when the tag/fish were presumably inside a lamnid shark, characterized by darkness (reflected by low solar panel voltage), a high minimum temperature, and a low daily maximum ΔT min^{-1}

As a result, even in the event of pop-up as designed, inference of survival rather than mortality would have been possible.

The tag deployed on Fish #12, a 117-cm CFL bluefin tuna caught south of Martha's Vineyard, Massachusetts, in August 2016, appears to have been consumed 17 days after capture. A short recorded day length on that date suggests that the tag—and presumably the fish—were ingested, at which time the tag ceased sensing light. Because the tags deployed in this study binned daily summaries based on light, only a single "daily" summary bin during the time for which the tag was inside the predator is available, indicating a stable temperature ranging from 21.89 to 23.97 °C (mean: 23.2 °C) and a maximum ΔT min^{-1} of 0.09 °C. The tag was presumably egested after 2 days, when it floated to the surface and began transmitting due to having exceeded the darkness threshold (> 48 h in darkness). The mean temperature while the tag was in darkness slightly exceeded the maximum temperature recorded the day before the tag was ingested (22.9 °C) and the day after the tag was egested (22.0 °C). This fish was considered a natural mortality for the purposes of calculating post-release mortality due to the long interval between catch-and-release and putative mortality.

While bluefin tuna were primarily targeted using light-tackle jigging and casting methods during tagging trips, there were some occasions on which fish were captured using conventional stand-up trolling/bait-fishing tackle, enabling comparisons of fight times between fishing methods. Fight times for fish caught on light tackle (including fish that were not tagged; $n = 41$; mean = 20 min; SD = 19 min) increased with fish size and did not differ significantly from fight times for fish that were caught on conventional tackle ($n = 9$; mean = 17 min; SD = 8 min) (Student's t test $p = 0.50$) (Fig. 3). In addition, light-tackle fight times did not differ from those for 24 southern bluefin tuna tagged by Tracey et al. [19] corresponding to the large school- and small medium size classes caught on conventional tackle ($p = 0.9$).

Estimates of post-release mortality were dependent on the treatment of the seven tags that did not report and were not recovered. When non-reporting and unrecovered tags were excluded from the analysis, the post-release mortality was estimated to be 0% because data from all 15 reporting/recovered tags indicated survival beyond the five-day threshold. Fisher exact tests revealed no significant differences between a 0% post-release mortality estimate and the recreational post-release mortality estimates for juvenile bluefin tuna from Marcek and Graves [18] (0%; $p = 1$) and Tracey et al. [19] (19%; $p = 0.2$). Assuming 0% post-release mortality, bootstrapping simulations based on 10,000 bootstrapped samples estimated the 95% confidence interval for the "true" post-release mortality rate based on 15 PSATs to range from 0 to 6.7%. In a more conservative analysis, in which the seven non-reporting and unrecovered tags were considered mortalities, the post-release mortality estimate increased to 31.8% (bootstrapped 95% confidence interval: 13.6–54.5%).

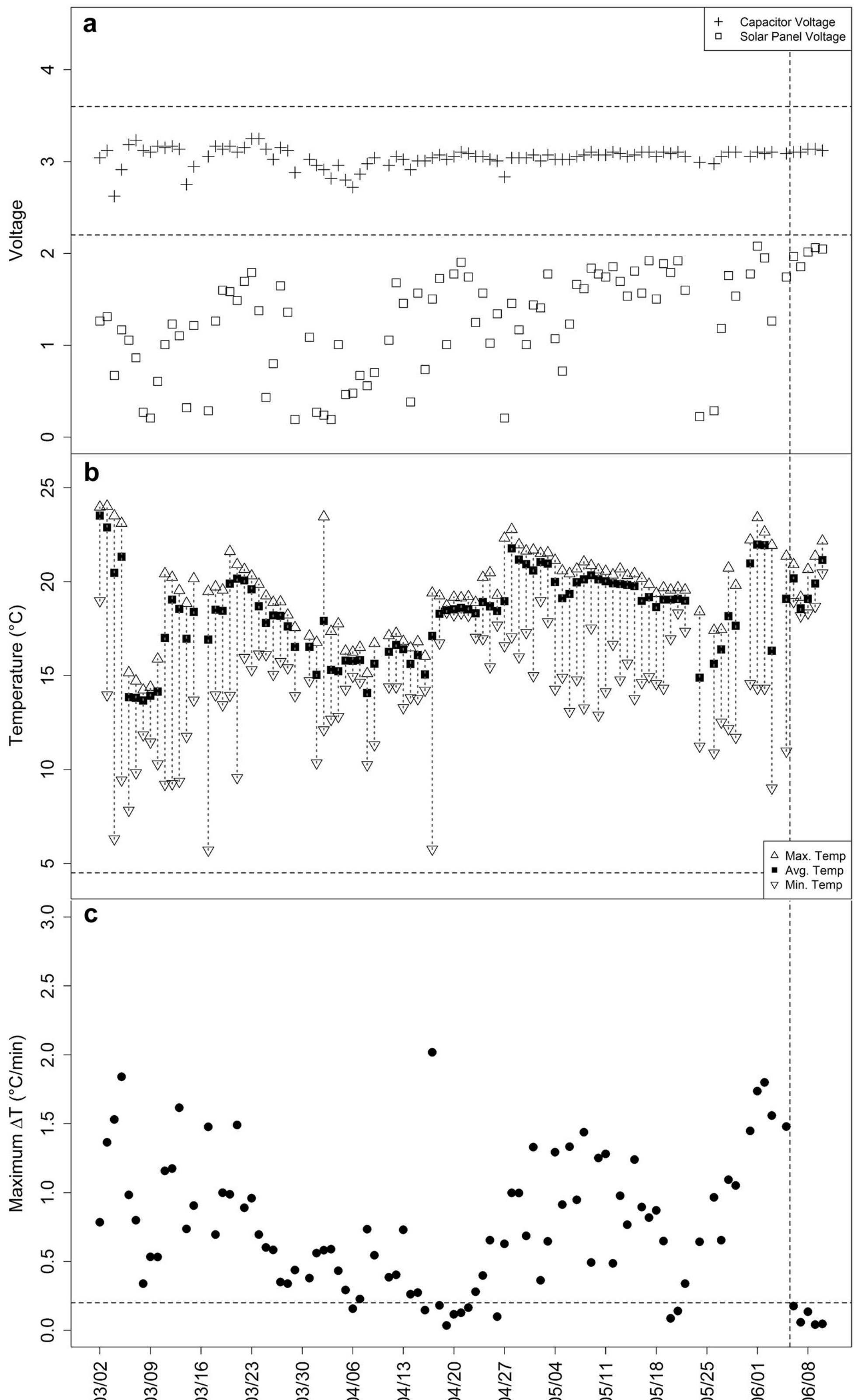
Discussion

Post-release mortality

Based on data from reporting and recovered tags, our results suggest a low post-release mortality rate for large school- and small medium-size Atlantic bluefin tuna caught using light-tackle methods off the US east coast.

(See figure on next page.)

Fig. 2 Daily summary data for voltage (**a**), temperature (**b**), and daily maximum ΔT min^{-1} (**c**) for a SeaTag-LOT deployed on Fish #10 (193 cm CFL) on 3/1/2016, which was shed after 95 days (indicated by the vertical dashed line) following failed pop-off after 30 days. Solar capacitor voltage is near the maximum voltage of 3.6 V (horizontal dashed line) throughout deployment and is similar to voltage after shedding, indicating that the fish was spending sufficient time near the surface to keep the tag fully charged. The broad temperature range exhibited by the fish throughout the deployment indicates extensive vertical movement in the water column, which becomes much more compressed after tag shedding. Daily maximum ΔT min^{-1} is generally maintained above the pop-off threshold of 0.2 °C while the tag is on the fish, with the exception of five consecutive days in April, and decreases to below the threshold once the tag is shed and is floating at the surface


a
Capacitor Voltage
Solar Panel Voltage
Voltage
b
Temperature (°C)
Max. Temp
Avg. Temp
Min. Temp
c
Maximum ΔT (°C/min)
03/02
03/09
03/16
03/23
03/30
04/06
04/13
04/20
04/27
05/04
05/11
05/18
05/25
06/01
06/08

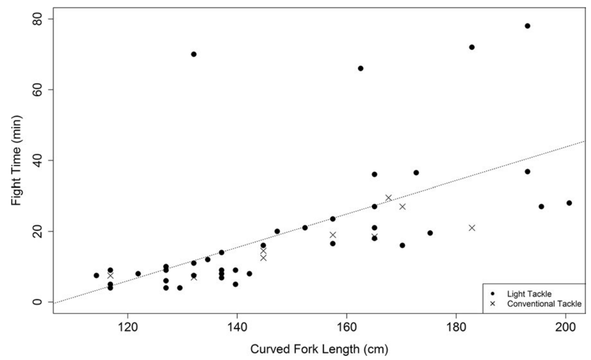


Fig. 3 Fight times for Atlantic bluefin tuna caught using light-tackle ($n = 41$) and conventional ($n = 9$) fishing methods. Fight times did not significantly differ between the two gear types, and fight time was significantly correlated with fish size ($p = 2.3 \times (10)^{-6}$; multiple $R^2 = 0.37$)

The bluefin tuna tagged in this study were subjected to a broad range of hooking locations with variable levels of bleeding and an assortment of handling methods. The data from all reporting and recovered tags were consistent with survival.

How non-reporting tags are interpreted can dramatically affect estimates of post-release mortality; if all non-reporting tags are interpreted to be mortalities, estimates can be biased substantially upward [11]. Given these concerns, previous studies using PSATs have either excluded non-reporting tags from post-release mortality estimates or have offered multiple estimates that exclude non-reporting tags and consider non-reporting tags to be mortalities [6, 30, 33]. The level of uncertainty that non-reporting tags introduce into estimates of post-release mortality highlights the critical importance of high reporting rates for these types of studies.

While we provide post-release mortality estimates that both include and exclude tags that did not report/were not recovered, we contend that only including the 15 tags for which data were recovered (i.e., our 0% post-release mortality estimate) is the most appropriate approach for estimating post-release mortality in this study. This investigation was one of the first uses of the Desert Star Systems SeaTag-LOT and thus may have been particularly vulnerable to non-reporting tags. The recovery of a failed tag from a surviving fish (Fish #19), which had both a flooded burn chamber (impeding pop-off) and a broken antenna (impeding data transmission), along with data transmitted from another tag on a surviving fish (Fish #10) whose pop-off release mechanism failed, suggest that tag failure was not uncommon and likely was a factor for the other non-reporting tags.

The most plausible explanation for the one mortality observed in this study is that the tag (and fish) was consumed by a lamnid shark, most likely a shortfin mako (*Isurus oxyrinchus*), which were observed in the vicinity of the tagging location at the time of tagging. Predations on juvenile PSAT-tagged bluefin tuna by lamnids have been inferred in previous studies based on elevated, stable temperatures regardless of depth while the tag was in darkness [18, 19]. The temperatures recorded by the tag while in darkness correspond to stomach temperatures measured for seven juvenile mako sharks (mean temperatures 18.9–25.9 °C; ambient sea surface temperature 18–21 °C) by Sepulveda et al. [34]. According to Sepulveda (unpubl.), the degree of stomach temperature elevation may become minimal once sea surface temperatures exceed 20 °C, which is consistent with the tag data.

It is important to distinguish any mortalities occurring after tagging as having been a result of the catch, tagging and release experience (i.e., a fishing mortality) or a natural mortality. Applying the five-day threshold to distinguish natural and fishing mortalities, we consider the predated fish to be a natural mortality since it occurred more than 5 days after release. Goodyear [35] has developed a method to estimate the median number of tag-days needed to observe a natural mortality on a PSAT-tagged fish using a Monte Carlo estimation based on 1,000,000 trials. Applying a natural mortality estimate of 0.14 for western Atlantic bluefin tuna [32], the number of tag-days needed to observe a natural mortality with 50% probability was estimated to be 1815 tag-days. A total of 444 full tag-days were observed in this study, approximately one quarter of the number of tag-days needed to observe a natural mortality with 50% probability. While it is thus well within the realm of possibility that a natural mortality would have been observed over the course of this study, it cannot be discounted that behavior and survivability could have been negatively impacted by the catch-and-release event in the days following release—for example, due to long-term physiological stress, internal bleeding or infection, or the added stress of carrying a PSAT [8, 30, 36].

While fish in this study were caught on both single and treble hooks, and were subjected to varying levels of air exposure, no post-release mortalities were detected. No fish caught on treble hooks with reporting tags ($n = 5$) were inferred to have died, compared to the 40% post-release mortality rate ($n = 5$) reported by Tracey et al. [19] for southern bluefin tuna caught on treble hooks. Studies on other species have offered conflicting conclusions on the comparative effects of single versus treble hooks [13, 37, 38]. Although no post-release mortalities were observed in this study, treble hooks did typically lead to greater degrees of physical injury. In addition, fish caught with treble hooks typically required longer handling times in order to remove the hooks, as has been observed for other species [13]. Air exposure has been linked to increased post-release mortality in recreational fisheries [8, 39], and it is recommended as a best practice that treble hooks not be used when fish are to be released, and also that fish not be removed from the water during the unhooking process. Removal of Atlantic bluefin tuna from the water that are to be released is also prohibited by the U.S. National Marine Fisheries Service (NMFS) Highly Migratory Species Management Division (79 FR 71510, 12/2/2014).

We found that fight times for bluefin tuna caught on light tackle were not significantly different from those of fish caught on conventional stand-up tackle. The lack of evidence that fight times are longer with light-tackle methods likely results from the fact that while the rods and reels used are generally lighter in weight and fish are typically fought without the aid of a harness, the line's breaking strength is generally not different from that used in more standard bluefin tuna fishing practices.

Tag performance and recommendations

Fourteen of the 22 PSATs deployed in this study (63.6%) transmitted data. Marcek and Graves [18] and Tracey et al. [19], who also assessed the post-release mortality of juvenile bluefin tuna using PSATs scheduled for short-term (< 6 mo) deployments, observed reporting rates of 95% (20 tags) and 100% (59 tags), respectively, which are markedly higher than the present study's reporting rate. PSATs may not report for a variety of reasons. These include mechanical failure, which can prevent pop-off or data transmission; biofouling, which can result in negatively buoyant tags; pressure housing failure; and tag damage resulting from predation or scavenging [4, 9, 40]. In addition, some researchers have hypothesized that species such as bluefin tuna that undertake extensive vertical movements may induce expansion and contraction of the tag body, which could lead to failure [4, 41]. As noted above, a high tag reporting rate is critical for studies of post-release mortality; even if a tag is considerably less expensive than others and provides sufficient data for inferring post-release mortality, a high percentage of tag failures can negate these lower costs by introducing considerable uncertainty into results, thus compromising management advice.

Six of the 14 tags (42.9%) were shed from fish prior to the specified pop-off date, but data from the six tags indicated that fish were moving vertically in the water column prior to shedding, consistent with survival. Premature shedding of PSATs is well-documented in studies of large pelagic fishes [30, 40, 42]. The most plausible reason for tag shedding is that the nylon tag anchor did not fully lock between dorsal fin pterygiophores when a tag was deployed [18]. Another possibility is that the threaded nylon bolt connecting the tag body to the nosecone/tether assemblage failed. The bolt is designed to shear when the tag ignition release is fired. However, the bolt could have been compromised (torqued) due to overtightening during tag preparation, or could have been sheared due to stresses during deployment.

In addition to addressing these issues resulting in low reporting and high shedding rates, we recommend that transmitted daily summaries for mortality tags correspond to the tag's internal clock, rather than light levels. Daily summaries for the tag used in this study were based on light: A "day" ends when the tag has been in darkness for 2 h, at which time the previous day's data is summarized and a new day begins. The new day will "end" following the tag's exposure to light and subsequent exposure to darkness for two consecutive hours. While helpful for geolocation purposes, this data structure can be confusing and lead to daily summary data based on days of differing lengths—especially if a vertically migrating fish dives into mesopelagic depths and multiple daily summaries for a single day are generated. Meanwhile, if a fish remains in relatively deep, dark waters for multiple days, a single daily summary for multiple calendar days will be generated, as happened in several instances during the present study. Similarly, if a tag is predated upon, only a single daily summary is generated, even if the tag is within the consumer's stomach for several days. Simply deriving daily summaries based on a 24 h clock will provide a far more straightforward and uniform dataset for interpretation.

Conclusions

Catch-and-release recreational fishing for large school- and small medium-size Atlantic bluefin tuna along the US east coast using light-tackle angling methods appears to be a viable conservation strategy. Post-release mortality estimates using light tackle do not differ notably from previous studies employing different gear types nor do fight times, which could be considered a proxy for physiological stress.

Despite a relatively high failure rate, which can complicate post-release mortality estimates and must be addressed, the Desert Star Systems SeaTag-LOT shows promise as an example of a low-cost tool for detecting post-release mortality. The maintenance of high solar capacitor voltage for tags deployed on Atlantic bluefin tuna suggests that solar power is a viable means of powering PSATs deployed on a range of pelagic species. The daily summary data appear to provide sufficient information to infer the fate of released fish, although in this study there were no detected mortalities resulting from exceeding the low temperature (sinking in deep water) or low ΔT min^{-1} (resting on the bottom) thresholds. Studies on different species (or different size classes of a single species) will require the development of species-specific thresholds for pop-off. Future work should focus on improving tag design and deploying tags on other species to assess performance.

Abbreviations
PSAT: pop-up satellite archival tag; CFL: curved fork length; ICCAT: International Commission for the Conservation of Atlantic Tunas; NMFS: National Marine Fisheries Service.

Authors' contributions
WMG designed the study, conducted fieldwork, analyzed data, and drafted the manuscript; AMS assisted in project planning and in drafting and editing of the manuscript; JEG assisted with developing parameters for tag pop-off and study design, and contributed substantially to the drafting of the manuscript. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate
The experimental protocols used in this study were approved by the College of William & Mary's Institutional Animal Care and Use Committee (IACUC-2014-08-06-9715-jegrav and IACUC-2016-07-21-11321-jegrav).

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