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At-vessel and postrelease mortality rates of bluefin tuna (*Thunnus thynnus*) associated with pelagic longline gear in the northern Gulf of Mexico

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Abstract—Bluefin tuna (*Thunnus thynnus*) of the western Atlantic Ocean are often incidentally caught in the pelagic longline fishery that targets swordfish (*Xiphias gladius*) and yellowfin tuna (*Thunnus albacares*) in the Gulf of Mexico. Data on at-vessel and postrelease mortality are lacking. Using the database of the NOAA Southeast Fisheries Science Center's Pelagic Observer Program, we estimated the mortality rate occurring at-vessel to be 54% (95% confidence interval [CI]: 46–62%) when the currently mandated weak circle hook (with a reduced diameter ≤3.65 mm) was used. To estimate rates of postrelease mortality, we deployed 41 pop-up satellite archival tags (PSATs) on bluefin tuna captured in the pelagic longline fishery operating in the northern Gulf of Mexico from May 2010 through April 2015. Data from the PSATs indicate that 29 fish survived for at least 30 d and that 4 fish died within 12 d of tagging. Six PSATs detached prior to the programed release date, and 2 PSATs did not report. We estimate a postrelease mortality rate between 12% and 29%. Combining the postrelease mortality estimate with the at-vessel mortality rate, we estimate a total mortality rate of 59% (95% CI: 47–71%) associated with capture and subsequent release of bluefin tuna in this fishery according to its current fishing practices.

The bluefin tuna (*Thunnus thynnus*) is the largest member of the family Scombridae and has a specialized cardiovascular physiology that allows it to exploit subarctic to subtropical pelagic waters (Carey and Lawson, 1973; Block et al., 2005). Bluefin tuna of the western Atlantic Ocean forage in the North Atlantic Ocean, and many of them migrate to the Gulf of Mexico (GOM) (Mather et al., 1995; Block et al., 2005; Knapp et al., 2014) to spawn, although spawning is not exclusive to the GOM (Mather et al., 1995; Richardson et al., 2016). Bluefin tuna can be found in the GOM from December through July, but the timing can vary with oceanographic conditions (Block et al., 2005; Teo et al., 2007; Galuardi et al.; 2010). During these months, bluefin tuna are incidentally caught by the U.S. pelagic longline (PLL) fleet, which targets swordfish (*Xiphias gladius*) and yellowfin tuna (*Thunnus albacares*) in the northern GOM (Springer, 1957).

Currently, the bluefin tuna in the GOM is managed as an incidental bycatch species, and no active targeting of it is allowed. As a result, various management actions have either required or resulted in substantial numbers of fish released alive or discarded dead. Beginning in 1981, the National Marine Fisheries Service (NMFS) prohibited directed fisheries for bluefin tuna on the GOM spawning grounds and established quotas for the fishery (Federal Register, 1981). To further reduce the incentive to target bluefin tuna, the NMFS enacted target species catch requirements for bluefin tuna retention (Federal Register, 1992). In 2011, the NMFS mandated that all U.S. PLL vessels fishing in the GOM use a *weak hook* with a reduced wire diameter (i.e., ≤3.65 mm) (Federal Register, 2011). A weak hook is a circle hook designed to allow a bluefin tuna and other similarly large animals to straighten the hook, thereby reducing their catch by more than 50% while not significantly reducing the catch of target species (Foster and Bergmann[1]). Additional measures were taken in 2006 with the

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[1] Foster, D., and C. Bergmann. 2010. 2010 interim report: update on Gulf of Mexico pelagic longline bluefin tuna mitigation research, 11 p. [Available from Harvesting Eng. Branch, Southeast Fish. Sci. Cent., Natl. Mar. Fish. Serv., 3209 Frederic St., Pascagoula, MS 39567.]

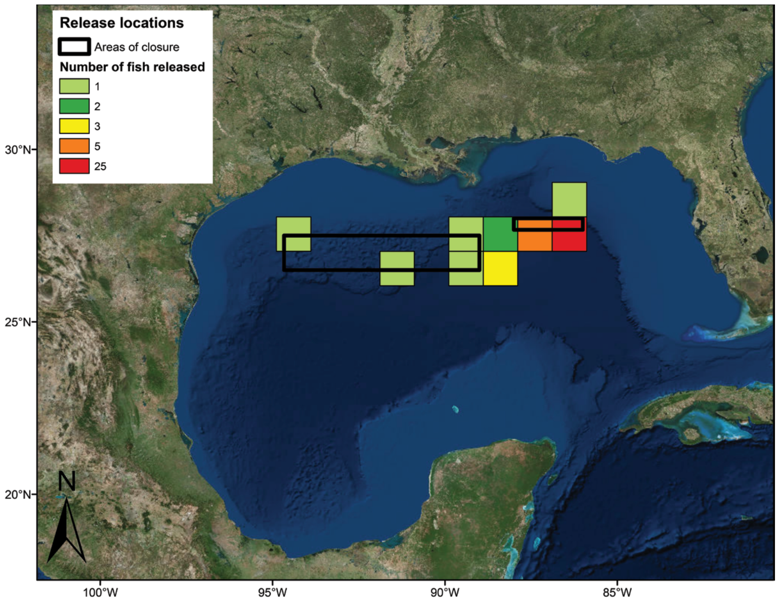

Figure 1

Spatial distribution of release locations for bluefin tuna (*Thunnus thynnus)* tagged with pop-up satellite archival tags in the pelagic longline fishery of the Gulf of Mexico from 2010 through 2015. Data for the number of fish released are presented in 1° grids of density. The 2 open rectangles indicate the areas closed to the use of pelagic longline gear during April and May. Sources for satellite image: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS user community.

implementation of Amendment 7 to the Consolidated Atlantic Highly Migratory Species Fishery Management Plan (Federal Register, 2014), which created a system to assign individual quotas for bluefin tuna to vessels and closed 2 areas that cover the majority of the spawning habitat of bluefin tuna in the northern GOM to the use of PLL gear during the peak spawning months of April and May (Fig. 1). The closure of these areas, in conjunction with the requirement to use weak hooks, has greatly reduced total discards of dead bluefin tuna.

The effectiveness of management measures that require or promote release of fish hinges on 2 components of mortality associated with interactions with fishing operations. The first component of mortality is the fraction of fish dead at-vessel upon retrieval of the gear, and the second component is the fraction of fish that die after being released. At-vessel mortality and survival have been documented from commercial longline fishing operations for several species of billfishes, tunas, and sharks (Serafy et al., 2012a; Walter et al., 2012; Musyl et al., 2015) but have yet to be quantified for bluefin tuna in the GOM PLL fishery. Similarly, the second component, postrelease mortality from fishing operations, has been quantified for bluefin tuna from recreational fisheries (Marcek and Graves, 2014; Goldsmith et al., 2017) and for other species on PLL operations (Kerstetter et al., 2003; Musyl et al., 2011a) but has not been evaluated for bluefin tuna from the U.S. GOM PLL fishery operating under normal fishing conditions.

Both components of mortality are necessary to determine the total mortality associated with fishing interactions and to evaluate the efficacy of management regulations (Coggins et al., 2007) designed to promote release of live fish. Mortality from fishing operations can have a substantial effect on populations; therefore, it is critical to consider such mortality in population assessments (Musyl et al., 2015).

For this study, we quantified both components of mortality associated with interactions of bluefin tuna with the U.S. GOM PLL fishery. We first examined the database of the NOAA Southeast Fisheries Science Center's Pelagic Observer Program (POP) to determine an at-vessel mortality rate as a function of several covariates. Next we electronically tagged bluefin tuna caught incidentally by the U.S. PLL fishery in the GOM to obtain estimates of postrelease mortality that apply to the fishery operating under normal commercial fishing practices. Fish were tagged from commercial fishing vessels, and all live fish captured, regardless of apparent condition, were tagged. Finally, we combined the results of our tagging study with the proportion of bluefin tuna reported dead at-vessel from the POP database to determine an overall mortality estimate for interactions of bluefin tuna with PLL gear in the GOM.

Materials and methods

Examination of Pelagic Observer Program database

The POP deploys NMFS-trained observers on a portion of PLL vessel trips to collect details on gear configuration, catch composition, and environmental conditions (for further details about observer protocols, see the training manual available from the Southeast Fisheries Science Center at website). To perform analyses similar to those used by Serafy et al. (2012a), we used a logistic regression to examine data for the influence of several key variables on the probability of mortality of 1498 bluefin tuna captured in the GOM PLL fishery during 1993–2017. For the logistic regression, we used the PROC GENMOD procedure in SAS/STAT[2] software

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[2] Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

(vers. 9.4; SAS Institute, Inc. Cary, NC). The following model was applied:

$$Mortality = H_i + D_j + T_k + C_l + S_m + L_n, \qquad (1)$$

where mortality = the probability of a fish being dead at-vessel;
H = the i^{th} type of hook used (circle hook, J-hook, weak hook);
D = the j^{th} maximum hook depth (in the water column, meters);
T = the k^{th} target species (swordfish, tuna, mixed);
C = the l^{th} sea-surface temperature (SST, in degrees Celcius, measured by the vessel during gear deployment);
S = the m^{th} soak duration (time from last hook deployed to first hook retrieved); and
L = the n^{th} fish length (straight fork length, in centimeters).

All factors were modeled as continuous variables with the exception of hook type and target species. To test for an effect of hook type on mortality, least square means were generated as estimates of mortality for each hook type.

Tagging

From 2010 through 2015, we deployed 41 PAT-Mk10 pop-up satellite archival tags (PSATs; Wildlife Computers, Inc., Redmond, WA) on bluefin tuna captured on PLL vessels fishing in the GOM (Fig. 1). These PSATs were programmed to archive pressure (depth), ambient temperature (in degrees Celsius), and light intensity every 10 s. Each PSAT was equipped with a corrodible *burn pin* that detaches the tag on a preprogrammed date (90–365 d) or when the PSAT has been at a constant depth (±5 m) for a 24-h period, indicating that either the tag is no longer attached to the animal or the animal has died. Upon detachment of a tag, profiles of depth and temperature and proportions of time spent in 14 user-defined depth (time at depth) and temperature (time at temperature) bins were summarized into 1-h (4 PSATs) or 4-h (37 PSATs) periods and transmitted through the Advanced Research and Global Observation Satellite system. For those cases in which the tag was physically recovered (11 PSATs), the full archival data set was obtained and analyzed.

All PSATs were equipped with a surgical-grade, nylon toggle anchor and an RD-1800 (Wildlife Computers, Inc.), a device designed to sever the PSAT link before hydrostatic pressure damages the tag (typically at a depth of approximately 1800 m). The tether rigging had 3 variations over the course of this study. The tags deployed in 2010 and 2011 (5 PSATs) were equipped with double-crimped monofilament tethers. In a concurrent study on yellowfin tuna, several tags were recovered with visible teeth marks on the PSAT and float, raising a concern that monofilament might result in an increase in attachment failures (C. Brown, unpubl. data); therefore, in 2012 tethers were constructed from stainless steel cable (22 PSATs). However, during a failed tagging attempt, a PSAT fell overboard. This PSAT, which was still equipped with a stainless steel tether, was observed to be negatively buoyant. Subsequent buoyancy testing indicated that rigged PSATs were very sensitive to small changes in weight, and the previous design with a double-crimped tether also resulted in tags being negatively buoyant. All subsequently deployed tags (14 PSATs) were rigged with a single-crimped monofilament tether, to allow the PSAT to float with the tether attached, and each of these PSATs was checked for positive buoyancy prior to deployment.

All PSATs were deployed by NMFS-trained observers aboard commercial fishing vessels that targeted yellowfin tuna with PLL gear in the GOM between the months of February and May of each year (2010–2015). Observers were given strict guidance to tag any live bluefin tuna, regardless of condition. When a fish was released by using methods similar to those of a normally operating PLL vessel, care was taken so that the fish remained in the water for tagging, and the hook, for the most part, was not removed.

Operational changes

A study of PLL gear that employed a design with alternating hook types found that a new 16/0 weak hook could reduce catches of bluefin tuna in the GOM PLL fishery by an estimated 56.5% (Foster and Bergmann[1]) from levels observed when a typical circle hook was used. In that study, hook timers, devices that measure the total time a fish spends hooked on a line, were attached to a portion of the gangion. The results of that study led the NMFS to mandate the use of these weak hooks in the GOM PLL fishery, and this regulation went into effect in 2011 (Federal Register, 2011). Prior to this rule being enacted, fish tagged in 2010 (4 fish) were captured by using regular-strength 16/0 circle hooks. In 2012, tags were deployed in conjunction with a continuation of the weak hook study (30 fish). For fish captured on a leader with an accompanying hook timer, total time on the line was obtained. All remaining fish were deployed on PLL sets by using the 16/0 weak hook (7 fish).

Determination of mortality

Postrelease mortality mostly has been estimated to occur shortly after release because of acute injury (Muoneke and Childress, 1994; Stokesbury et al., 2004; Wilson et al., 2005). However, delayed mortality due to loss of ability to feed or infection can occur several days to weeks postrelease (Burns and Froeschke, 2012). Although increasing the duration of monitoring beyond several days allows the incorporation of delayed mortalities, there is a risk of confounding results with mortality unassociated with the initial capture event (e.g., with mortality caused by predation). Consequently, some researchers have restricted their analysis to the first 5–10 d after tagging (Graves et al., 2002; Kerstetter et al., 2003; Horodysky and Graves, 2005; Marcek and Graves, 2014); however, given the relatively low natural mortality rate of adult bluefin tuna relative to other species (Fromentin and Powers, 2005), we extended the time frame from 5–10 d to 30 d, following Stokesbury et al. (2011). The penalty for use of a longer time frame is that natural (and fishing) mortality begins to bias estimates of release mortality, but it would be highly unlikely (0.8% chance) for a bluefin tuna to not survive 30 d because of natural mortality, given the currently assumed natural mortality rate for bluefin tuna (0.1/year; ICCAT, 2017).

Any fish that appeared to live past this 30-d threshold was determined to have successfully survived the capture event. Wilson score intervals and 95% confidence intervals (CIs) were calculated for the binomial proportions (Wilson, 1927). The standard method for determining mortality by using PSATs involves inferring mortality from behavior of the fish as recorded by the tag. Below, we outline this method; however, in this study, we had to address an added complication. To distinguish between a mortality event and a premature tag release, we considered whether a tag floated after it was shed by a fish or it remained on a dead fish until it reached either the release depth of the RD-1800 device or the programmed tag release time. Given the ability of bluefin tuna to swim at high rates of speed (Wardle et al., 1989) and because fish remained in the water for tagging that occurred at night often on poorly lit vessels and varying states of sea conditions, some premature tag shedding was likely to have occurred in our study, and it is commonly observed in most PSAT tagging studies (Musyl et al., 2011b). The negative buoyancy associated with some of the deployed tags complicates the interpretation of the recorded depth data because a tag attachment failure would result in the tag sinking in a similar fashion to a dead fish. In all, 27 of the 41 deployed PSATs were negatively buoyant.

Despite the negative buoyancy of those tags, we were able to distinguish between likely premature release of a tag and a fish mortality by calculating the sinking rates for each of the 10 prematurely released tags and comparing these rates to the rate (0.251 m/s) for the tag that was dropped overboard (the reference tag). In addition, there was an apparent mortality of a bluefin tuna that was tagged with a positively buoyant PSAT and tether; the sinking rate calculated for this tag was 0.408 m/s, a rate that is over 60% faster than the rate of the reference tag. Assuming that all dead fish would sink at a faster rate than the reference tag, we classified each tag according to whether it likely sunk because of a premature release (sinking rate<rate of reference tag) or because of a fish mortality (sinking rate>rate of reference tag). Fish were then assigned to 1 of 4 categories on the basis of the observed behavior of the fish as recorded by the tag: 1) survived (consistent vertical movement for ≥30 d), 2) mortality (fish was at large for <30 d, tag detachment occurred at a depth ≥1200 m, and the sinking rate was >0.251 m/s), 3) tag attachment failure (fish was at large for <30 d, and the tag was positively buoyant and detached at a depth <1200 m, or the tag was negatively buoyant and detachment occurred at a depth ≥1200 m, but the sinking rate was <0.251 m/s), and 4) non-reporting tag (tag failed to transmit any data).

To account for the uncertainty of the eventual fate of fish that were equipped with tags that either failed to report or failed to remain attached for ≥30 d, we calculated the mortality rate by using 2 methods. One method used this expression that includes the number of fish assigned to 3 of the 4 categories, yielding the highest possible mortality estimate: (mortality+tag attachment failure+non-reporting tag)/total number of tags deployed. The other method used the following expression: mortality/(survived+mortality). The first method assumes that all fish in the tag attachment failure and non-reporting tag categories were dead fish, but the second effectively considers that tag data for fish in the non-reporting tag or tag attachment failure categories are uninformative and discards those fish from the sample.

Estimation of overall mortality

Overall mortality (M) was calculated as the probability of a mortality occurring during the entire capture and release process. It is calculated as the probability of being dead at-vessel ($P(C)$) times the probability of dying after being released ($P(R)$):

$$M = P(C) \times P(R). \tag{1}$$

The variance of estimates from this equation was derived as the variance of the product of 2 assumed uncorrelated random variables (Goodman, 1960).

Results

Pelagic Observer Program database

The results of the logistic regression found that only one variable of the independent model, hook type, significantly ($P<0.05$) affected the probability of at-vessel mortality for bluefin tuna (Table 1). Therefore, we report the least square means as estimates of at-vessel mortality rate for the 3 hook types, standard (strong) circle hook (65%, 95% CI: 57–72%), J-hook (68%, 95% CI: 56–78%), and the currently mandated weak hook (54%, 95% CI: 46–62%).

Tagging

From 2010 to 2015, 41 adult bluefin tuna from PLL vessels were tagged with Wildlife Computers PSATs in the GOM (Table 2). The size range of the 41 bluefin tuna was 190–270 cm straight fork length (Table 2),

Table 1

Results of logistic regression examining the influence of hook type, target species, sea-surface temperature (SST), soak duration, straight fork length (SFL), and maximum hook depth on the probability of at-vessel mortality of 1498 bluefin tuna (*Thunnus thynnus*) captured in the pelagic longline fishery of the Gulf of Mexico during 1993–2017.

Variable	Estimate	Standard error	*P*-value
Standard circle hook	−0.464	0.129	<0.001
J-hook	−0.602	0.224	0.007
Weak circle hook	0.000	0.000	–
Mixed target	0.090	0.131	0.493
Swordfish	−0.354	0.473	0.454
Yellowfin tuna	0.000	0.000	–
SST	−0.021	0.015	0.149
Soak duration	−0.035	0.040	0.382
SFL	−0.001	0.002	0.374
Maximum hook depth	0.0046	0.010	0.711

and they were tagged in the months of February–June at SSTs ranging from 21.8°C to 29.7°C. Representing fish that successfully survived the fishery interaction, 29 PSATs remained attached for at least 30 d. Ten PSATs failed to reach the 30 d threshold, and 2 additional PSATs failed to transmit any data.

Tagged fish at large for fewer than 30 days

Ten PSATs began transmitting data less than 30 d after tagging (1–18 d). Six of these tags were equipped with tethers that we identified as negatively buoyant. Four tags sunk at a rate greater than the rate of the reference tag (0.251 m/s); therefore, the fish tracked with those tags were put in the mortality category (Table 3). Three tags had sinking rates that were slower than the rate of the reference tag, indicating likely tag attachment failures and not observed mortalities. The remaining 3 tags were equipped with positively buoyant tethers, detached from the fish at a depth <1000 m, and floated to the surface, indicating tag attachment failures.

Postrelease mortality

An upper bound estimate of postrelease mortality was obtained by treating all fish with tags that either did not report (2 PSATs) or failed to attach (6 PSATs) as potential dead fish (12 of 41 fish tagged with PSATs), giving a maximum postrelease mortality estimate of 29% (95% CI: 18–44%). Assuming that these non-reporting tags and tags that failed to remain attached were not associated with fish mortalities, and, therefore, that the fish tagged with them were removed from the sample, we determined that the most likely estimate of postrelease mortality is 12% (95% CI: 5–27%) (i.e., 4 of 33 PSATs associated with mortalities).

Hook timers

Twelve tagged fish were captured on leaders that included a hook timer, which measures the length of time a fish is on the line prior to crew engagement (Table 2). Tag data indicates an apparent mortality for only 1 fish captured on a line with a hook timer (8.3 h attached to a longline). Three additional tagged fish were associated with either attachment failures (2 PSATs) or their tag failed to report (1 PSAT). The remaining 8 PSATs were deployed on surviving fish with an average time on the line of 7.4 h (2.2–14.4 h).

Overall mortality

We estimated the probability of a mortality of a bluefin tuna occurring as a result of an interaction with, and release from, PLL gear in the GOM, using Equation 1 with the most likely estimate of postrelease mortality (12%, 95% CI: 5–27%) as $P(R)$ and $P(C)$ obtained from the logistic regression model predicted for fishing with weak hooks (54%, 95% CI: 46–62%). The resulting overall estimate of the probability of capture-induced mortality of bluefin tuna in the GOM PLL fishery, operating as it currently does with weak hooks, is 59% (95% CI: 47–71%).

Discussion

On the basis of the data presented in this study, we estimated postrelease mortality of bluefin tuna from PLL fishery operations in the GOM at a range of 12–29%, depending on the treatment of the non-reporting or premature release of tags. The highest estimates of mortality were obtained when all non-reporting tags were assumed to be associated to a mortality event. However, we considered that there is a sound basis for eliminating fish with non-reporting tags from the sample. Our non-reporting rate for this study is relatively low (5%) in comparison to the rates of other studies (Musyl et al., 2011b). Furthermore, with an RD-1800 device attached to its tether, a PSAT would detach from a sinking, dead fish before it reached the tag crush depth, making it unlikely that non-reporting was a result of such a mortality. Non-reporting, therefore, was the result of either equipment failure or damage (perhaps, due to predation) (Musyl et al., 2011b), with neither cause being informative on mortality due to a capture event. Given that we can separate attachment failures from mortalities by examining sinking rates, we removed fish associated with both non-reporting tags and attachment failures from the sample to provide what we believe is a more accurate postrelease mortality estimate of 12%. Under either assumption regarding the fate of malfunctioning tags, the postrelease mortality estimates are relatively low (12–29%), indicating that,

Table 2

Summary information for electronically tagged bluefin tuna (*Thunnus thynnus*) and the corresponding data for the pelagic longline set during which each fish was captured in the Gulf of Mexico from 2010 through 2015. An en dash indicates unknown or unrecorded data. SFL=straight fork length.

Tag number	Estimated SFL (cm)	Estimated weight (kg)	Tagging date	No. of monitoring days	Tagging depth (cm)	Time on line (h)	Hook location	Hook removed	Length of remaining leader (m)	Weak circle hook	No. of hooks per set	Hook depth (m)	Soak duration (h)
10A0919	240	227	4/15/2012	–	23	1.3	Upper jaw	No	1.2	No	425	97	5.9
11A0898	240	–	5/20/2013	–	23	–	Hinge	No	<0.3	Yes	420	97	9.4
10A0921	220	227	5/10/2011	2	25	–	Hinge	No	2.1	Yes	500	91	8.6
11A0914	270	295	3/20/2012	3	28	8.3	–	No	3	No	430	95	6.3
10A0917	240	227	4/26/2012	3	23	1.1	Hinge	No	0.9	Yes	445	97	6.4
10A1041	210	–	3/23/2012	7	23	–	Hinge	No	1.2	Yes	355	82	6.3
10A0915	270	272	3/28/2012	7	25	–	–	No	2.4	Yes	438	95	7.2
10A0896	210	–	5/10/2012	10	25	–	Hinge	No	0.9	Yes	590	82	5.8
10A1042	270	340	5/25/2012	10	23	–	Hinge	No	1.5	No	410	97	8.9
11A0981	150	181	4/21/2015	12	23	–	–	No	–	Yes	472	97	7.2
10A1030	195	–	5/11/2012	15	25	–	Hinge	No	0.6	No	520	82	7.1
10A0931	240	–	4/10/2012	18	23	4.6	–	No	0.6	No	610	82	5.5
10A0930	240	227	4/26/2012	32	23	–	Hinge	No	1.2	No	445	97	6.4
10A0938	210	–	3/28/2012	40	23	–	Hinge	No	0.6	No	520	82	4.9
10A1035	210	170	5/23/2012	42	23	2.8	Hinge	No	1.2	Yes	410	97	10.0
10A1047	210	–	4/12/2013	42	23	–	Hinge	No	<0.3	Yes	702	73	8.5
11A0978	210	–	5/18/2012	43	25	–	Hinge	No	0.9	No	530	82	7.7
10A0942	240	204	5/13/2012	48	23	–	Hinge	No	0.9	No	445	97	7.8
10A0939	240	227	4/25/2012	50	23	–	Hinge	No	0.6	No	445	97	8.0
10A0946	240	204	5/16/2012	53	23	–	Hinge	No	0.9	No	445	97	8.1
10A0898	240	227	3/1/2012	54	25	–	–	No	4.6	Yes	590	95	7.5
11A0963	195	–	4/9/2012	55	23	7.3	Hinge	Yes	–	Yes	630	82	6.5
10A0945	240	227	5/14/2012	57	23	–	Hinge	No	1.2	No	445	97	8.3
10A0916	270	295	3/22/2012	61	28	11.7	Hinge	No	2.1	No	425	95	5.7
10A0775	210	181	4/26/2012	63	23	–	Upper jaw	No	0.9	No	445	97	8.0
10A0918	240	227	4/25/2012	64	23	1.8	Hinge	No	0.9	Yes	445	97	8.0
10A0928	225	–	3/28/2013	70	28	–	Hinge	Yes	–	Yes	876	66	8.6
10A1045	240	204	4/9/2012	70	23	12.9	Hinge	No	0.3	–	460	97	6.5
11A0969	225	–	5/20/2012	81	25	6.5	Hinge	No	1.8	Yes	505	82	6.1
11A0949	240	227	5/24/2012	82	23	–	Hinge	No	0.9	No	410	97	8.1
11A0950	240	204	5/24/2012	84	23	–	Upper jaw	No	0.9	Yes	410	97	8.1
10A1032	190	159	5/12/2013	89	23	–	Hinge	No	0.6	Yes	504	82	5.8
08A0152	240	204	5/12/2010	90	15	–	Hinge	No	1.5	No	702	84	7.3
08A0153	260	363	5/22/2010	90	20	–	Hinge	No	–	No	590	82	8.0
08A0155	250	340	5/22/2010	90	20	–	–	No	–	No	590	82	8.0
08A0156	260	363	5/22/2010	90	18	–	Hinge	No	–	No	624	82	7.5
10A0929	240	181	4/24/2012	90	23	2.2	Hinge	No	0.6	No	445	97	6.5
10A0933	210	–	3/19/2012	93	23	14.4	Hinge	No	0.6	No	384	82	8.5
10A1034	210	204	5/14/2013	100	23	–	Hinge	No	3	Yes	588	82	8.4
10A0949	240	227	5/28/2012	116	23	–	Hinge	No	1.2	No	400	97	10.2
10A0943	210	181	5/26/2012	119	23	–	Upper jaw	No	1.5	No	410	97	8.3

if a fish is alive at-vessel, its likelihood of surviving after its release is remarkably good.

It is worth noting the negative buoyancy aspect of the tag harness rigging design. Musyl et al. (2015) emphasized the importance of testing for tag buoyancy with the tether and anchor mechanism attached; however, they found that most researchers failed to indicate whether these tests were conducted prior to tag deployment. Clearly, our study had this issue, and future researchers should take note. It may also be necessary to consider whether some presumed mortalities in prior PSAT studies could actually have been instances when tags equipped with negatively buoyant harnesses were shed.

No other estimates of release survival for bluefin tuna captured in PLL fisheries operating under nor-

Table 3

Summary information for pop-up satellite archival tags that were deployed on bluefin tuna (*Thunnus thynnus*) during 2010–2015 in the Gulf of Mexico and failed to reach the 30-d threshold at which fish were deemed to have survived capture. The rate of descent (sinking rate) was calculated for all negatively buoyant tags that transmitted data. The sinking rates then were compared to the rate of a reference tag (this tag was dropped overboard, and its descent rate indicates the sinking speed of a negatively buoyant tag absent of a fish). Each tagged fish that did not survive was classified in the following categories: non-reporting tag, tag attachment failure (sinking rate<reference tag), or mortality (sinking rate>reference tag).

Tag number	Tether design	Tag buoyancy	Sinking rate (m/s)	Monitoring days	Release depth (m)	Data type	Category
10A0919	Cable tether	Negative	N/A	–	–	N/A	Non-reporting
11A0898	Mono single crimped	Positive	N/A	–	–	N/A	Non-reporting
10A0896	Mono single crimped	Positive	N/A	10	22	Recovered	Attachment failure
10A1042	Mono single crimped	Positive	N/A	10	288	Transmitted	Attachment failure
10A1030	Mono single crimped	Positive	N/A	15	712	Transmitted	Attachment failure
10A0921	Mono double crimped	Negative	0.122	2	1320	Transmitted	Attachment failure
10A0931	Cable tether	Negative	0.224	18	1200	Transmitted	Attachment failure
10A0917	Cable tether	Negative	0.227	3	1546	Recovered	Attachment failure
Reference tag	Cable tether	Negative	0.251	1	1808	Recovered	N/A
10A0915	Cable tether	Negative	0.316	7	1840	Transmitted	Mortality
10A1041	Cable tether	Negative	0.319	7	1850	Recovered	Mortality
11A0914	Cable tether	Negative	0.346	3	1808	Transmitted	Mortality
11A0981	Mono single crimped	Positive	0.408	12	1768	Transmitted	Mortality

mal commercial practices exist. However, a study by Block et al. (2005) that used short experimental sets designed to capture bluefin tuna alive reported an at-vessel mortality rate of 30%, a rate that is nearly 25% lower than the overall nominal rate derived from the POP observer database (54%). Block et al. (2005) postulated that mortality rates of bluefin tuna in the GOM PLL fishery could be a result of asphyxiation due to inability to ram ventilate, thermal stress from confinement in warm surface waters, or other capture related trauma that could be exacerbated by longer time on the line.

Block et al. (2005) used relatively short sets designed to mitigate mortality. In contrast, our study operated under standard commercial fishing operations with an average soak duration of 7.5 h. Hook timer data indicate that fish in our study were on the lines for an average of 6.2 h, a period that is longer than the entire duration of the experimental sets in Block et al (2005). An additional factor related to observed mortality differences could be gear configuration. Although we did not detect significant effects of hook depth or SST on mortality in our analysis of POP data, the experimental design of their study (with a maximum hook depth of 200 m, compared with 97 m in our study; Table 2) could have allowed fish to access deeper, cooler waters and a fish's ability to access such water could have been a mitigating factor for some of the thermal stress that a fish may have experienced. Furthermore, one static SST measurement might not accurately reflect the range of temperatures at the locations where fish encountered the gear throughout sets, and the use of this single measurement could be the reason that we did not detect a significance for SST. Musyl et al. (2009) highlighted the importance of using fishery-specific features when attempting to estimate postrelease survival, and our results support this notion.

Postrelease mortality has been quantified to be relatively low in recreational fisheries (from 0% [95% CI: 0–7%] to 32% [95% CI: 14–55%]) (Goldsmith et al., 2017) and in commercial hand-line and rod-and-reel fisheries in Canada (from 3% [95% CI: 1–13%] to 6% [95% CI: 2–6%]) (Stokesbury et al., 2011). Both sets of authors calculated mortality in 2 ways; hence, separate 95% CIs are given for each estimate. Although these fisheries and the ocean conditions where they occur are very different from those of the GOM, the low rate of postrelease mortality in those studies and in our study indicates that bluefin tuna, if they survive the initial capture process, appear to have a high probability of survival regardless of the gear type used or the geographic region of release.

Nonetheless, the high at-vessel mortality rate that we estimated (54%) for weak hooks in the GOM PLL fishery would diminish the effectiveness of a no-retention policy in reducing fishing mortality and achieving stock status benchmarks (Coggins et al., 2007), in isolation of other measures. The relatively low postrelease mortality from our study, however, does provide support for encouraging live release of bluefin tuna. Currently, live bluefin tuna can either be retained or released with control over the total retention rate through an individual quota system for bluefin tuna, in which vessels are required to have quota of bluefin tuna available to retain live fish or to account for any dead captures. This management measure is accompanied by a closure of 2 areas in the spring to minimize encounters with bluefin tuna and by the use of weak hooks that facilitate escape.

Mitigation of bycatch of bluefin tuna in PLL fisheries has been a high priority for the NMFS. The results of this study generally indicate that management measures taken by that agency to minimize bycatch of bluefin tuna are effective, measures that reduce the probability of capture of bluefin tuna on a longline and, then, once captured, provide opportunities to vessels to retain dead fish or to release live fish. The currently mandated weak hooks do appear to have some conservation benefits. In our analysis, we observed that at-vessel mortality was 11% lower for weak hooks than for traditionally used circle hooks, and Foster and Bergmann[1] estimated that weak hooks also could reduce the bycatch of bluefin tuna by 56.5%. Gallagher et al. (2017) found a strong correlation of plasma lactate with maximum acceleration of hooked sharks, a correlation indicating that the behavioral response of the fish could influence the probability of mortality. Despite the high probability that we would observe an at-vessel mortality, our hook timer data revealed that it is possible for bluefin tuna to survive after ≥14 h on the line and that the behavioral response of an individual fish might contribute to the probability of its mortality. These findings might explain why we see a reduction in at-vessel mortality associated with the weak hook, with the more vigorous fighters that would likely die on the line able to straighten a weak hook and escape capture. Nevertheless, it is important to note that the at-vessel catch estimate is based on *observed* reduction in bycatch of bluefin tuna and that the actual fate of escapees from weak hooks remains unknown (Serafy et al., 2012b).

Because the degree of injury sustained by fish that straighten their hooks and elude observation has yet to be quantified, the total mortality estimate in our study may be considered conservative. On the other hand, it is possible that survival was enhanced for fish that would have otherwise died on the standard circle hooks because they were spared the prolonged stress and injury of being firmly hooked until gear retrieval. Further research is warranted on this topic; however, determining precisely how to track the survival of fish that have effectively escaped capture by straightening weak hooks is a serious, perhaps insurmountable, research challenge. In any case, on the basis of observed interactions in the POP database, the results of our study indicate that weak hooks provide the additional benefit of increasing at-vessel survival in comparison with standard circle hooks. Further mitigation efforts could be directed to evaluation of factors that might promote an even greater at-vessel survival rate; however, changes in factors, such as gear configuration, set duration, set location, or bait, may negatively affect catches of yellowfin tuna and swordfish, the target species of PLL fisheries in the GOM.

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