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ARTICLE

Estimating Discard Mortality for Dolphinfish in a Recreational Hook-and-Line Fishery

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Abstract

Minimum length limits are used to manage Dolphinfish *Coryphaena hippurus* in the U.S. South Atlantic, but rates of discard mortality are unknown for this fishery and others throughout the species' worldwide range. We estimated discard mortality for Dolphinfish in the U.S. South Atlantic, Caribbean, and Gulf of Mexico recreational hook-and-line fishery by using conventional tag–recapture data. Overall, 4,648 Dolphinfish were tagged in these areas between 2002 and 2018 through the efforts of cooperating (fishery-dependent) taggers as well as research scientists who employed gear types and fishing styles representative of the recreational fishery for this species. The condition of each tagged and released fish was classified as good or poor depending on hook trauma, bleeding, and postrelease swimming behavior. Numbers of tagged and recaptured fish in each release condition were used to estimate condition-specific discard mortality by fitting a relative risk model. The model assumption of 100% survival of fish in good condition was scaled downward by using numbers of dying fish in good condition from tank holding and satellite tagging experiments. An overall median rate of discard mortality (0.248; 95% credible interval = 0.053–0.389) for the fishery was estimated by summing the products of each condition-specific mortality rate and the proportion released in each condition. Given relatively high discard mortality rates (>20%), the results suggest that alternative management strategies (e.g., mandatory retention of hook-traumatized individuals contributing to a bag limit, regardless of size), educating fishers on the use of alternative gear types (e.g., circle hooks), modifying fishing practices (e.g., trolling with heavy drags to reduce rates of deep hooking), or a combination thereof may be more effective solutions than minimum size or bag limits to control the rates of fishing mortality for Dolphinfish.

Recreational harvest represents an increasingly greater proportion of the take in a variety of fisheries around the world (Cooke and Cowx 2004, 2007). Along with a global increase in recreational landings (Cooke and Schramm 2007), the number of dead discards in recreational fisheries has also increased (Davis 2002). Discarding in recreational

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fisheries occurs due to size and possession limits as well as a growing practice by fishers to adopt catch-and-release methods even though some or all of their catch could be legally retained (Cowx 2002). A key assumption in using catch and release as a management tool or ethical angling practice is that a large percentage of fish survive and do not experience long-term negative impacts from capture and release (Wydoski 1977).

The Dolphinfish *Coryphaena hippurus* is a pelagic marine fish predator with a global distribution (e.g., Brodie et al. 2017; Marin-Enriquez and Muhlia-Melo 2018) and is typically one of the most heavily landed recreational species by weight in the U.S. South Atlantic, Gulf of Mexico, and Puerto Rico (MRIP 2018). It is managed recreationally through size and possession limits in these regions. However, the rate of discard mortality of Dolphinfish after capture with hook and line remains unknown for this fishery (SAFMC 2011) as well as other fisheries directed for the species globally. Some of the challenges in estimating discard mortality for Dolphinfish as well as other marine species include logistics, expense, and low return rates of conventionally tagged fish (Musyl et al. 2011). These issues may partly explain why, to the best of our knowledge, a rate of discard mortality has not been previously estimated for the Dolphinfish. The issue with the fate of discards may be especially important for Dolphinfish, which may be declining in abundance in the Atlantic Ocean (Lynch et al. 2018). Estimating a rate of discard mortality supplies information that is useful for both managing and assessing this important yet data-limited species. It is recommended that studies of the discard mortality of highly migratory pelagic species be conducted on a fishery-specific basis owing to the potentially unique traumas and physiological stressors imposed by each fishery (Skomal 2007).

The number of discarded Dolphinfish has increased as a percentage of the annual catch in the U.S. Atlantic, Gulf of Mexico, and Puerto Rico based on federal recreational fisheries data (MRIP 2018; Figure 1). This 20–30% discarding rate (by number) for Dolphinfish in recent years compares to a 28% discarding rate (by weight) across multiple major U.S. marine fisheries (Harrington et al. 2005). The proportion of fish discarded and also discarded dead increases relative to landings as the number of individuals protected by a size limit increases (Van Badten et al. 2013). However, the trend of increasing percentages of discards even before minimum size limits were enacted for Dolphinfish in the U.S. South Atlantic region (in 2012) suggests that elective catch-and-release angling is occurring over a range of Dolphinfish sizes. Thus, estimates of the rates of Dolphinfish discard mortality are needed over this range. Estimating discard mortality for Dolphinfish provides information for assessments and helps to determine whether a minimum size limit or bag limit can achieve the goal of reducing fishing mortality for fish sizes that are targeted for protection (Radomski et al. 2001; Coggins et al. 2007).

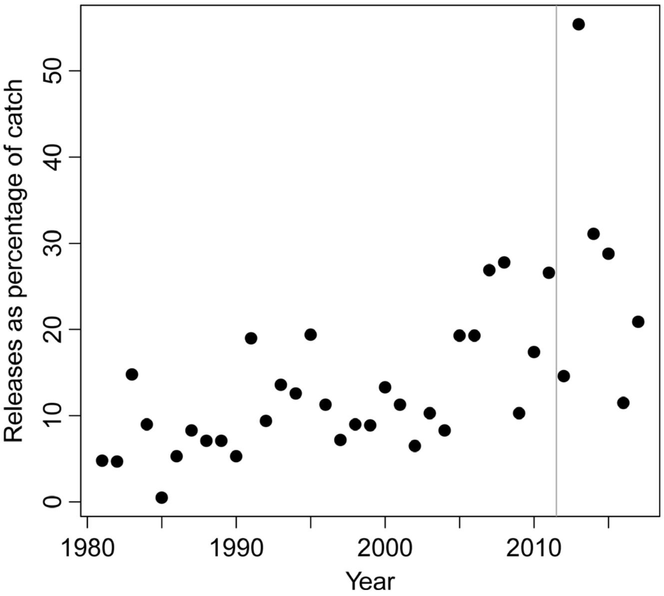

FIGURE 1. Releases of Dolphinfish as a percentage of the entire annual catch in the U.S. Atlantic, Gulf of Mexico, and Puerto Rico recreational fishery for the years 1981–2017 (MRIP 2018). The vertical gray line in the plot denotes the year (2012) in which a minimum size limit was enacted for the fishery in the U.S. South Atlantic.

Our objective in this study was to estimate a rate of discard mortality for recreationally caught Dolphinfish in the U.S. South Atlantic, Caribbean, and Gulf of Mexico. Fishery-independent researchers as well as fishery-dependent cooperating taggers targeted Dolphinfish with representative gear and tackle types in a fishery where hook trauma is common (Rudershausen et al. 2012). As such, we hypothesized that Dolphinfish in poor condition (i.e., fish that were hooked in vital areas, such as the gills, stomach/esophagus, or eyes) would have lower survival rates than fish in good condition (i.e., fish that were hooked in the jaw). A core assumption of our approach—that fish released in good condition had 100% survival and thus could be considered controls—was tested through tank holding and satellite tagging, which allowed us to observe or infer fates.

METHODS

Tagging and recapture data collection.— Two tagging programs were undertaken to capture, tag, and release Dolphinfish. The first was the Dolphinfish Research Program (DRP), an international capture–mark–recapture program that distributed individually numbered plastic dart tags (Hallprint, Hindmarsh Valley, South Australia) and utilized the expertise of recreational fishers to capture and tag fish. Fishers requested tagging kits from the DRP in a variety of ways, with the most common being through the DRP Web site (www.dolphintagging.com). Recreational fishers used a variety of fishing modes to target Dolphinfish, including trolling and bailing (casting to Dolphinfish from a drifting boat). Not all fish were tagged on the DRP trips; cooperating anglers retained a fraction of their catch. After fish release and while still onboard, fishers recorded data pertaining to Dolphinfish hooking location, obvious signs of hook trauma, and postrelease swimming behavior. These condition data were integrated from two sources within the DRP: postmarked tagging cards submitted via postal mail by anglers that participated in the program from 2002 to 2005 along the U.S. East Coast, Gulf of Mexico, and Bahamas; and data submitted electronically (online) by DRP's top fishing team who collected data in the Gulf of Mexico and off the Florida Keys from 2006 to 2017. Recaptures from various sectors of the fishery were reported through postal mail and online.

The second tagging program was undertaken between 2016 and 2018 by North Carolina State University (NCSU) research scientists operating out of Morehead City, North Carolina, and fishing in the Atlantic Ocean. Gear types and fishing styles for these fishery-independent sampling trips were selected based on a workshop that included prominent recreational captains, fishing tournament directors, and fishery managers (Rudershausen et al. 2012). Thus, gear types and fishing styles represented the recreational fishery for this species in the U.S. South Atlantic, Caribbean, and Gulf of Mexico so that information about the proportion of fish released in each condition could be applied to the fishery. These fishing styles included trolling and bailing. Unlike the DRP, all Dolphinfish that were captured during NCSU trips were tagged and released and their condition was recorded so that the proportion released by condition could be estimated for the fishery (see below). Dolphinfish on the NCSU trips were marked with Floy FM-89SL internal anchor tags (Floy Tag, Inc., Seattle) labeled with a phone number for tag reports as well as the message “Reward for Return” to incentivize reporting. Data on hooking location, signs of hook trauma, and swimming behavior were recorded for each tagged and released Dolphinfish. We collected tag reports from both recreational and commercial fishers and provided a t-shirt as a reward for each report.

Efforts by each of the two Dolphinfish tagging programs yielded detailed descriptions of the disposition of tagged fish. To avoid imprecise estimates of discard mortality that could result from low tag return rates arising from assigning multiple release categories, we separated Dolphinfish release condition into two broad groups. The first group consisted of individuals in good condition, defined as those that were jaw-hooked, displayed no obvious signs of hook trauma (aside from the jaw hooking location), were not bleeding, and swam off vigorously upon release; for purposes of modeling the rates of discard mortality, these fish were considered controls (Hueter et al. 2006). The second category was comprised of individuals in poor condition, defined as those that exhibited at least one of the following conditions: obvious hook trauma (in the eye, roof of the mouth, gills, or stomach/esophagus), bleeding, and slow or no swimming upon release. Assignment of fish condition was done similarly between the two tagging programs. The TLs of fish overlapped widely between the two condition categories and tagging programs.

Testing the assumed survival of fish in good condition.— The core assumption of the relative risk model we applied to estimate discard mortality (below) is that fish released in good condition (i.e., control fish) have a survival rate equivalent to that of fish not caught and released (Hueter et al. 2006). In other words, discard survival of fish in good condition is assumed to be 100%. Violations of this assumption will bias estimates of survival high; thus, the overall rate of discard mortality would be biased low.

We collected two experimental data sets to test the validity of the assumption of 100% survival for fish in good condition. First, we used Survivorship PAT-355 pop-off satellite archival tags (PSATs; Wildlife Computers, Redmond, Washington) to determine the postrelease fate of 19 Dolphinfish in good condition. An advantage of PSATs relative to other tagging approaches for the estimation of fish discard mortality is that PSATs will pop off once the tag exceeds a pre-programmed depth threshold (e.g., Graves et al. 2002; Moyes et al. 2006). The PSATs used for this study were 38 mm long × 11 mm wide and weighed 60 g in air. The PSATs were implanted in large Dolphinfish (mean ± SD = 881 ± 80 mm FL). For this tagging procedure, fish were removed from the water and immediately tagged in the dorsal musculature while the gills were irrigated with ambient seawater. Mean deck time ± SD was 58 ± 12 s. All 19 fish marked with PSATs swam off vigorously after release; vigorous swimming behavior was a criterion for a good-condition release. Pop-off of each PSAT was set to 31 d or when the tag sensed a mortality (criteria are described below) or tag shedding.

Postrelease survival of Dolphinfish marked with PSATs was inferred from environmental and motility data and by using previously developed methods to ascertain fates (Horodysky and Graves 2005; Kerstetter and Graves 2008; Marcek and Graves 2014; Merten et al. 2014). With these methods, variations in depth of movement over short time scales, net movement of tagged individuals, and changes in ambient light are indications that a fish is still alive. When a fish is alive, it exhibits changes in pressure (water depth) and temperature profiles. The PSATs used in this study were programmed to pop off and report daily averages of sensor data if movement and environmental data sensors did not record changes that were consistent with the aforementioned criteria. These reports were reviewed to verify the validity of the tag's determination of fate and to determine the timing of mortality relative to release. A mortality was assumed when the tagged fish sank below maximum pressure depth, stayed at a constant depth below the surface (i.e., bottom) over a 24-h period, or did not show a change in ambient light level over a 24-h period (i.e., predation event). Tag shedding was assumed when the tag floated over a 24-h period.

We estimated the postrelease survival of Dolphinfish with PSATs over a 31-d period by using Kaplan–Meier survival analyses. However, we assumed that any mortalities associated with the catch-and-release process occurred within the first 3 d of release. This appears to be an appropriate duration based on presumed recovery periods of other highly migratory pelagic species (Pepperell and Davis 1999) and the pop-off times (<5 d) that have been employed to study the fates of released billfishes marked with PSATs (e.g., Graves et al. 2002; Kerstetter et al. 2003; Horodysky and Graves 2005).

The second data set we collected for estimating the rates of mortality for Dolphinfish in good condition involved observing 28 smaller individuals (<600 mm FL), each held for 30 min in a 550-L onboard tank filled with flow-through ambient seawater. This experiment allowed us to directly determine the short-term fate of each of these individuals at the conclusion of each holding period. Only one fish was held at a time in order to avoid any confounding effects of stocking density on fate. Water temperature during the tank holding trials averaged 27.9 ± 0.5°C (mean ± SD), while dissolved oxygen averaged 6.21 ± 1.18 mg/L. Each holding period was terminated after 30 min to avoid the confounding effects of tank confinement on survival.

Model to estimate discard mortality.— We fitted a probabilistic model through Bayesian inference to estimate discard mortality (Appendix). The overall model contained five subcomponents. The first was a model to estimate the probability of tag returns for each of the two release conditions of conventionally tagged Dolphinfish. The second was a model to estimate the probability of survival of fish from the satellite tagging and tank holding experiments. The third used the probability of tag returns for each condition to calculate survival (relative risk) of fish in poor condition; this calculation corrected for less than 100% survival of fish in good condition by incorporating the probability of discard survival from satellite tagging and tank holding. This model subcomponent also converted survival probability to mortality for the fish in good condition and those in poor condition. The fourth estimated the proportion of each condition released in fishery-independent tagging trips off the coast of North Carolina. Finally, the model used the mortality probability and proportion released for each of the two conditions to estimate an overall rate of discard mortality for the fishery. Each subcomponent of the overall model is described in greater detail below.

The first part of the model included the probability of tag returns in each release condition, which was specified by a binomially distributed likelihood fitted to data on numbers of returned fish and the total number tagged in a given condition to estimate a condition-specific probability of tag return; data were pooled across years and regions but not across tagging programs. The probability of tag returns of fish in each condition was estimated by looping over the number of returns and the number tagged for each tagging program. This updated an uninformative beta prior probability distribution (beta[1, 1]) for the condition-specific probability of tag returns; this probability was shared between tagging data sets. The uninformative prior probability distribution represented the uncertainty about the return rate from individuals tagged in each condition.

The second part of the model specified the probability of survival for fish in good condition from satellite tagging and tank holding through a binomially distributed likelihood. As above, the prior probability distribution was specified by an uninformative beta distribution (beta[1, 1]). This section of the model looped over numbers of fish in good condition that were observed and surviving from these two data sets, with survival probability shared between the satellite tagging and tank holding data sets. Thus, a single value of survival probability was estimated and used to scale the estimated survival for conventionally tagged fish in good condition.

The third part of the model involved calculating relative risk (survival). Relative risk for fish in poor condition was calculated by dividing the tag return probability of fish in poor condition by the tag return probability of fish in good condition (Hueter et al. 2006) and multiplying the resulting value by the survival probability of fish in good condition from the satellite tagging and tank holding studies. The latter step adjusted the relative risk calculation for violations of the assumption that survival probability was 100% for the fish in good condition (see Results). The discard survival of fish in poor condition was then converted to mortality by subtracting the survival value from 1. The mortality probability for fish in good condition was calculated by subtracting the probability of survival of fish from the satellite tagging and tank holding experiments from 1.

Unlike the fishery-dependent DRP, in which retained Dolphinfish were not recorded, each NCSU sampling trip off North Carolina ($n = 50$ trips) allowed us to record the release condition of every Dolphinfish captured; thus, at the conclusion of these trips we had data on the proportion of fish released in each condition. However, the true proportion of Dolphinfish in each condition in the recreational fishery is unknown. For this reason, we treated the true underlying probability of fish in good condition as a stochastic element in the model and defined it as a binomially distributed random variable. In the fourth subcomponent of the overall model, this variable was assigned a beta prior probability distribution (beta[1, 1]). This portion of the model contained an equation that calculated the probability of fish being released in poor condition as 1 minus the probability of fish being released in good condition. This model subcomponent was fitted to numbers-by-condition data for each research trip with at least one individual released.

Finally, the overall model included a calculation of overall discard mortality for the recreational fishery. This value was defined as the addition of two products, with each product resulting from multiplying the estimated probability of discard mortality for each condition by the probability of sampling (catching) fish in that condition.

We ran the overall model through OpenBUGS version 3.2.1 (Spiegelhalter et al. 2010) by using three chains of initial values generated by the software. The model was updated 10,000 times. We discarded the first 1,000 of saved updates as a burn-in period. Stationarity (convergence) for each model parameter was determined by examining Gelman–Rubin statistic ($\hat{R}$) values that OpenBUGS computed for retained updates; convergence was indicated by $\hat{R}$-values less than 1.1 (Gelman 1996).

In addition to the overall model described above (i.e., the “base” model), we ran five alternative models to test assumptions and interpretations about mortality related to tank holding, satellite tagging, and the exchangeability of tag–recapture data between the DRP and NCSU tagging programs. These models were intended to account for worst-case and best-case scenarios in estimating an overall rate of discard mortality. For satellite tag data, two alternative models assumed that PSATs floating within 5 d after deployment were associated with discard mortality (e.g., a predation event that led to a floating tag). For tank holding, two alternative models assumed that tank holding did not address or account for any delayed mortality and thus excluded this data set from the analysis. Finally, owing to potential issues with exchangeability between the two tagging programs (e.g., differences between the proportions of fish in poor condition that were returned; see Results), data from each tagging program were modeled separately.

RESULTS

Overall, 3,773 and 376 control Dolphinfish (i.e., in good condition) were tagged by the DRP and NCSU tagging programs, while 305 and 194 fish in poor condition were tagged by the DRP and NCSU, respectively. Tagged fish averaged 566 ± 157 mm FL (mean ± SD) and ranged from 280 to 1,372 mm FL. In total, 86 and 13 tags from fish in good condition were returned to the DRP and NCSU program, respectively, whereas 1 and 6 tags from fish in poor condition were returned to the two programs; thus, return rates to the DRP and NCSU were 2.8% and 3.5% for fish in good condition and 0.3% and 3.1% for fish in poor condition. Regarding the hooks used to capture tagged individuals, 72.6% of the individuals in the NCSU tagging program were caught with J-hooks, while 27.4% were caught with circle hooks. For trolled Dolphinfish, 69% caught on J-hooks were hooked in the jaw (as opposed to vital tissues or organs [gills, stomach/esophagus, or eye]), whereas 75% caught on circle hooks were hooked in the jaw. For bailed Dolphinfish, 53% caught on J-hooks were hooked in the jaw, while 72% caught on circle hooks were hooked in the jaw. The hook types that were used to catch Dolphinfish tagged in the DRP were not recorded.

The observed number of tag returns and the estimated probability of tag returns were low (Table 1). The median estimated probability of returns was lower for the releases of fish in poor condition ($n = 7$ of 499 tags reported; median = 0.015; 95% credible interval = 0.007–0.029) and higher for the releases of fish in good condition ($n = 99$ of 4,149 tags; median = 0.024; 95% credible interval = 0.020–0.029). Precision was low for the probability of poor-condition returns because the return rate for fish in poor condition differed between the two tagging programs.

Observed or inferred rates of survival were high for both the tank holding and satellite tagging data sets. Among the 28 tank-held Dolphinfish that were in good condition, 22 (78.6%) were observed to have survived the 30-min holding period. During the first 3 d postrelease, there were no mortalities of satellite-tagged Dolphinfish; indeed, there was no evidence of mortality for the first 10 d postrelease (Figure 2). However, nine tags floated to surface during the first 10 d and we assumed that this was due to tag shedding. The 31-d survival of satellite-tagged fish from the Kaplan–Meier analysis was low (~20%) and resulted from five fish dying between days 11 and 21, when there were few fish at risk (e.g., $n = 10$ fish were at risk going into day 11; $n = 6$ fish were at risk going into day 15). The median discard survival of Dolphinfish from the satellite tagging and tank holding experiments was 0.848 (95% credible interval = 0.728–0.931). This result was used internally within the model to scale (decrease) the survival of tagged control fish (i.e., those in good condition) from the assumed survival rate of 100%. The estimated probability of mortality for the group in poor condition (median = 0.450; 95% credible interval = −0.066 to 0.757) was greater than that for the group in good

TABLE 1. Medians and 95% credible intervals for parameters estimated within a model used to estimate an overall rate of Dolphinfish discard mortality for the recreational fishery in the U.S. South Atlantic, Caribbean, and Gulf of Mexico. The model was fitted to tag–recapture data on conventionally tagged Dolphinfish released in good condition or in poor condition. See the Appendix for model code and parameter names. Some rates of discard mortality are less than zero and are due to calculations within the model (see Appendix).

Parameter name	Parameter description	Median	95% credible interval
p.Exp2	Probability of tag returns: poor condition	0.015	0.007–0.029
p.Control	Probability of tag returns: good condition	0.024	0.019–0.029
p.TankSat	Probability of survival: tank holding, satellite tagging	0.862	0.747–0.937
p.RR2Mort	Probability of mortality: poor condition	0.450	−0.066 to 0.757
p.ControlMort	Probability of mortality: good condition	0.138	0.060–0.254
Cond_Inv_p	Proportion released: poor condition	0.348	0.309–0.387
Cond_p	Proportion released: good condition	0.653	0.613–0.691
StudyOverallDiscardMort	Discard mortality rate for the fishery	0.248	0.053–0.389

condition (median = 0.138; 95% credible interval = 0.060–0.254). Although the median mortality was greater for the poor-condition group than for the good-condition group, the credible intervals overlapped. Thus, our data do not support the hypothesis that fish in poor condition had a lower probability of survival.

The proportion of Dolphinfish released in the NCSU program was higher for fish in good condition (median = 0.65; 95% credible interval = 0.61–0.69) than for fish in poor condition (median = 0.35; 95% credible interval = 0.31–0.39; Table 1). The median rate of overall discard mortality for the fishery was 0.248 (95% credible interval = 0.053–0.389) for the base model. Each parameter within the overall model had acceptable values for the convergence statistic ($\hat{R} < 1.1$).

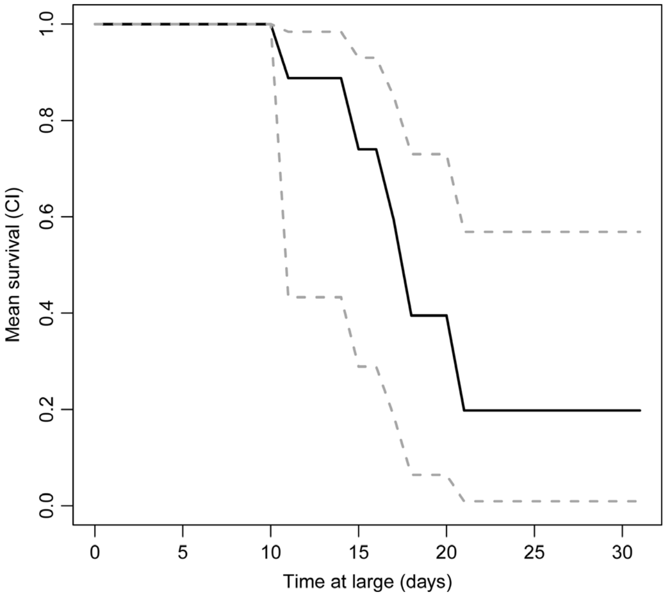

FIGURE 2. Kaplan–Meier estimate of mean survival (black solid line; gray dashed lines = 95% confidence interval [CI]) for 19 satellite-tagged Dolphinfish. These fish were considered good-condition releases (jaw hooked with no sign of trauma; swam away vigorously). Floating tags as a result of tag shedding were censored from the analysis and were not considered to be associated with discard mortality in the base model run (see Table 2).

For each of the five alternative models, the 95% credible interval for the overall rate of discard mortality overlapped with the 95% credible interval of the base model (Table 2, model 1). A model with NCSU tagging data only (model 2) resulted in a median estimate of overall discard mortality that was lower than the median from the base model, while the model including DRP tag data only (model 3) resulted in discard mortality that was higher than the median from the base model. Assuming that PSATs floating within 5 d of deployment represented mortalities (model 4) resulted in a discard mortality higher than that from the base model, while eliminating tank holding data from model fitting due to concerns that it did not account for delayed mortality (model 5) led to a decrease in overall discard mortality relative to the base model. Finally, assuming that PSATs floating within 5 d of deployment represented mortalities as well as eliminating data from tank holding (model 6) increased the median estimate relative to the base model. Median estimates of overall discard mortality from four out of five alternate models (models 2–5) fell within the credible intervals of the base model (model 1), and the median estimate for model 6 was only slightly above the upper credible limit for the base model.

DISCUSSION

The present results indicate that the discard mortality of Dolphinfish caught in this recreational fishery is ~15–40%. The precision of our estimates was low both within our base model and across five alternative models with different scenarios and data inputs. One source of low precision in estimating a rate of discard mortality was the low tag return rates; low rates of tag returns for a highly

TABLE 2. Descriptions of models fitted to estimate a proportional rate of discard mortality (median and 95% credible interval) for Dolphinfish in the U.S. South Atlantic, Caribbean, and Gulf of Mexico recreational hook-and-line fishery. Data sets included satellite tagging (pop-off satellite archival tags [PSAT]) and tank holding (Tank) from known- or inferred-fate experiments as well as two tagging programs (North Carolina State University [NCSU] and the Dolphinfish Research Program [DRP]) to collect conventional tag–recapture data from fish released in good condition or in poor condition. “Yes” indicates that the data set was used in a model fit; “No” indicates that the data set was not used. Some rates of discard mortality are less than zero due to calculations within the model (see Appendix).

Model number	Model explanation/rationale	PSAT	Tank	NCSU	DRP	Median	95% credible interval
1	Base model: all data sets included, most parsimonious interpretation of known- and inferred-fates data based on observations and literature	Yes (no mortalities)	Yes	Yes	Yes	0.248	0.053–0.389
2	DRP data excluded due to differing return rates of poor-condition fish between the two conventional tagging programs	Yes (no mortalities)	Yes	Yes	No	0.156	−0.254 to 0.360
3	NCSU data excluded due to differing return rates of poor-condition fish between the two conventional tagging programs	Yes (no mortalities)	Yes	No	Yes	0.364	0.189–0.473
4	Alternative worst-case scenario regarding survival of fish with PSATs; floating PSATs within 5 d after deployment were associated with discard mortality	Yes (6 mortalities)	Yes	Yes	Yes	0.354	0.164–0.499
5	Assumption that tank holding does not account for delayed mortality	Yes (no mortalities)	No	Yes	Yes	0.164	−0.044 to 0.316
6	Alternative worst-case scenario regarding survival of fish with PSATs and assumption that tank holding does not account for delayed mortality; floating PSATs within 5 d after deployment were associated with discard mortality	Yes (6 mortalities)	No	Yes	Yes	0.413	0.196–0.611

migratory pelagic species could be attributable to a large population size, dispersal after release, tag loss, a low reporting rate, or a high discard mortality rate (Musyl et al. 2011). In this study, we attempted to buffer against some of these possibilities by conventionally tagging a high number of fish. We also attempted to safeguard against biases in estimating discard mortality by scaling the survival of fish in good condition through the satellite tagging and tank holding experiments.

The rate of discard mortality that we estimated for Dolphinfish should be of interest to stock assessment scientists and fishery managers. Coggins et al. (2007) found that minimum size limits were ineffective at controlling the rates of fishing mortality for short-lived, highly productive species (e.g., Dolphinfish) with high fishing mortality rates when the rate of discard mortality exceeds roughly 20%. A portion of the posterior distributions of discard mortality from all six models was above the 20% threshold. Future Dolphinfish stock assessments should examine the sensitivity of population status to changes in the number of live discards when exploring management alternatives (e.g., size limits versus education).

For recreational fishers, trolling is the most common fishing style used to target Dolphinfish in the USA (SAFMC 2003; Rudershausen et al. 2012). Thus, the gear types used while trolling will strongly influence the overall rate of discard mortality for this species. For Dolphinfish, there is a high percentage of deep hooking (39%) in the troll fishery when using J-hooks/natural baits and the “dropping back” style of fishing (Rudershausen et al. 2012). The rates of deep hooking among Dolphinfish caught by trolling are due to fishing practices such as using conventional J-hooks and light drags (i.e., dropping back; Mather et al. 1975). This combination of gear type and fishing style increases the likelihood that Dolphinfish will be deeply hooked in the stomach or esophagus from swallowing trolled natural baits (Rudershausen et al. 2012). Although many fishers know that these gears and techniques increase the chances of hook trauma to Dolphinfish, they still practice them to increase the probability of boating fish once they are hooked. The practice of dropping back during trolling for Dolphinfish would be difficult to regulate as a method to reduce rates of hooking in vital areas. As ethical angling (i.e., catch and release), bag limits, and minimum size limits are becoming more prevalent, outreach efforts on gear types and fishing styles that promote postrelease survival are important to ensure the success of voluntary and mandatory management actions that involve releasing Dolphinfish.

Estimates of discard mortality in other pelagic species caught using various gear types and fishing styles are useful for comparison with our work and can help to inform outreach efforts. Our median estimate of discard mortality (~25%) is higher than estimates for other pelagic species caught by trolling circle hooks and natural baits (with or without drop back) or J-hooks with lures (no drop back) but is similar to rates for pelagic fish caught by using J-hooks rigged with natural baits and trolled (with drop back) or drifted. For example, Marcek and Graves (2014) found 0% mortality for troll-caught (J-hooks and lure or lure/natural bait combination without drop back) juvenile Bluefin Tuna *Thunnus thynnus* hooked in the buccal cavity, whereas Skomal et al. (2002) estimated 28% mortality when Bluefin Tuna were caught with J-hooks and drifted baits. Marcek and Graves (2014) concluded that the difference between the two studies was due to greater deep hooking in the drift fishery. As is the case with Dolphinfish (Rudershausen et al. 2012), dropping back with J-hooks has been shown to increase the likelihood of deep hooking and mortality in White Marlin *Kajikia albida* (35% postrelease mortality with J-hooks versus 0% mortality with 5% offset and non-offset circle hooks; Horodysky and Graves 2005), Striped Marlin *Kajikia audax* (33.3% mortality using offset J-hooks versus 17.7% mortality using non-offset circle hooks; Domeier et al. 2003), and Sailfish *Istiophorus platypterus* (23–57% deep hooking with J-hooks versus 6–16% deep hooking with non-offset and 5% offset circle hooks; Prince et al. 2007). Anglers that regularly encounter sublegal Dolphinfish or that electively practice catch and release should consider using circle hooks if trolling natural baits and employing a drop-back fishing technique.

Circle hooks are a widely recognized gear type for reducing the rates of deep hooking in vital areas compared to J-hooks across a range of freshwater and marine fisheries (reviewed by Cooke and Suski 2004). Evidence suggests that using circle hooks in the recreational troll fishery targeting Dolphinfish in the U.S. South Atlantic would reduce the rates of deep hooking (in the gills, stomach/esophagus, eyes, and roof of the mouth) compared to J-hooks. For example, with a drop-back style of trolling, Dolphinfish were deeply hooked in 39% of cases when conventional trolling tackle for Dolphinfish was used (natural baits rigged with J-hooks), but they were deeply hooked only 2% of the time when these baits were rigged with non-offset circle hooks (Rudershausen et al. 2012). The decreased deep hooking when using circle hooks does involve the tradeoff of a reduced catch rate (Rudershausen et al. 2012).

In addition to deep hooking and hook trauma, a wide variety of factors can cause discard mortality among fish caught with hook and line (reviewed by Muoneke and Childress 1994; Cooke and Suski 2005). These factors include physiological stress that manifests itself through changes in blood chemistry among exhaustively exercised fish (Skomal 2007) as well as handling time and air exposure (Cooke and Suski 2004; Cook et al. 2015; Schlenker et al. 2016), both of which can increase the rate of discard mortality among fish that otherwise would have a high probability of surviving. Air exposure in recreationally captured Dolphinfish can be considerable based on their heightened activity levels—and therefore difficulty to handle—once boated. Dolphinfish that were tagged and released in this study were subjected to a range of handling practices and onboard deck times representative of the fishery. Factors (e.g., deck time) that can influence postrelease swimming behavior complemented hooking location in our assignment of release category for each tagged Dolphinfish. Although tagging entailed extra time compared to simply unhooking and releasing the fish, this extra deck time used by experienced cooperators and research scientists to handle and release Dolphinfish was likely representative of the deck times taken by less experienced recreational fishers to release Dolphinfish without tagging them. In contrast, fight time is unlikely to be a reliable predictor of discard mortality in Dolphinfish captured with hook and line due to the variable intensity of swimming activity (combination of burst and rest swimming behavior) that is often displayed over the duration of the fight for pelagic species like Dolphinfish (Horodysky et al. 2015, 2016).

Through alternative model runs, we tested the robustness of the overall estimate of discard mortality to different interpretations of the number and timing of mortalities of tank-held and satellite-tagged Dolphinfish (Table 2). This was done because PSAT data can be interpreted in multiple ways (e.g., Hoolihan et al. 2011) and the time interval of our tank holding was short. Alternative models were also run to examine the issue of exchangeability between the two tagging programs; for example, the return rate of Dolphinfish in poor condition differed between the two programs. The credible intervals about overall estimates of discard mortality from these alternative models overlapped with the estimate from the base model. Given the proportion by release condition that we estimated in the North Carolina trolling and bailing fishery, the Dolphinfish discard mortality for these releases is roughly 15–40%.

Potential Sources of Error in Estimating Discard Mortality

Tag-based estimates of mortality can be hindered by the emigration of tagged individuals from the study area as well as unknown tag reporting and shedding rates (Skomal 2007). However, we addressed many of these issues by fitting a relative risk model to the Dolphinfish tag–recapture data. The relative risk model has a number of assumptions when used to estimate discard mortality (Hueter et al. 2006); chief among these assumptions is that fish in the best release condition (controls) do not experience mortality. We tested this assumption for conventionally tagged Dolphinfish in good condition and addressed the violation of this assumption by adjusting assumed survival downward based on survival less than 100% in the tank holding and satellite tagging studies.

In contrast to the assumption that fish in good condition survived uniformly, it is likely that the other assumptions of the relative risk model were satisfied. One of these assumptions is that after the fish recover from catch and release, long-term mortality is the same between release groups. Another is that the catchability and reporting rate are the same between release categories. Finally, it is assumed that the rates of tag shedding and tagging-related mortality are the same between release categories. We have no reason to believe that any of these additional assumptions were violated in our study.

The precision of our discard mortality estimates was low. Based on estimates within the base model, this appears to be due to the small number of fish tagged in the poor-condition group and the differing return rates of this group between the two conventional tagging programs. The cause of this difference is unknown but could have been due to how fish in good versus poor condition were categorized during release. Future tagging efforts focused on oceanic pelagic fishes should emphasize the collection of as much detailed data as possible on released fish to allow for maximum utilization of mark–recapture data.

Satellite tagging was effective at identifying mortality of jaw-hooked Dolphinfish. Although there was no evidence of discard mortality in satellite-tagged Dolphinfish during the first 10 d after release, there was evidence of mortality between days 11 and 21, which may be attributable to tag-induced trauma resulting from the large tagging dart, but we cannot conclude this definitively. The most prominent problems with using PSATs are reduced swimming ability, premature tag loss, tag-induced mortality, and increased risk of predation (Skomal 2007; Jepsen et al. 2015). In our study, one or more of these effects could have contributed to the mortality of satellite-tagged fish between days 11 and 21. Caution is warranted when using PSATs of this size on approximately 880-mm FL Dolphinfish (on average) for long-term studies owing to the potential for tagging-related wounds to negatively affect survival. In contrast to the tagging wound, the tag burden (weight in air of the tag relative to the estimated weight of the smallest fish [760 mm FL] that was PSAT tagged; tag burden = 0.014) does not lead us to believe that this burden by itself caused mortality, based on other studies that have investigated the tag burden issue. Lynch et al. (2017) found no evidence that the attachment of PSATs led to increased metabolic rate or altered swimming behavior in Sandbar Sharks *Carcharhinus plumbeus* of smaller average lengths than the satellite-tagged Dolphinfish in this study. For the tank holding experiment, it is possible that fish surviving the holding period died after release due to capture, which would have biased mortality estimates low.

The condition of Dolphinfish released by recreational anglers in the study region is difficult to estimate. This information was not available from the DRP tagging program because condition assignments were not available for all releases. For the discard mortality rates presented here, we assumed that the numbers-by-condition data from the 50 trips taken in North Carolina were representative of release condition over a larger geographic region. At a Dolphinfish fishing gear workshop, stakeholders involved in pelagic fisheries in the U.S. South Atlantic, Caribbean, and Gulf of Mexico agreed that trolling by using J-hooks rigged with natural baits and bailing by using cut natural baits affixed to non-offset circle hooks were the gear types and fishing styles most commonly used to target Dolphinfish (Rudershausen et al. 2012). The proportional releases of fish in good versus poor condition by the NCSU tagging program would be representative of a fishery with regulations such that all Dolphinfish had to be released. If ethical angling is practiced through the release of some Dolphinfish that could be legally retained (i.e., as Marine Recreational Information Program data suggest), anglers might choose to release a greater proportion of fish in good versus poor condition than was observed in the NCSU program but similar to that observed in the fishery-dependent DRP. Thus, the proportion of poor-condition Dolphinfish released by the NCSU program may be biased high relative to what actually may be occurring in the fishery. Future work on Dolphinfish discarding should estimate the proportion of releases by condition.

Conclusions

The proportion of Dolphinfish released in the recreational fishery throughout the U.S. Atlantic, Gulf of Mexico, and Puerto Rico has increased during recent decades. This study found that Dolphinfish caught with hook and line in this region have relatively high discard mortality rates; four of six model runs had median estimates exceeding 20%. This level of discard mortality has been reported for other pelagic fishes that are targeted by fisheries with J-hooks, dead or live natural baits, and drop-back fishing styles (Skomal et al. 2002; Horodysky and Graves 2005; Prince et al. 2007). The declining estimates of Dolphinfish relative abundance in the Atlantic Ocean (Lynch et al. 2018) suggest that a reduction in fishing mortality is warranted.

The Dolphinfish stock in this region has limited data to support an assessment. Our results provide condition-specific and overall estimates of discard mortality that will be useful for assessment and management. Future Dolphinfish stock assessments can utilize these discard mortality estimates to convert a proportion of the live releases into dead fish. The results from this study also provide guidance to fishery managers. Our modeling found a lower median survival of fish in poor condition, which were typically hooked in the gill, stomach/esophagus, eye, or roof of the mouth. As such, the results can be used to condone the retention of Dolphinfish with obvious hook trauma and the release of fish hooked in the jaw, the use of gears that minimize trauma (e.g., circle hooks), the use of tight drags and no drop back, and the quick release of fish to reduce air exposure. One or several of these approaches would help to reduce the rates of discard mortality and increase the effectiveness of the minimum size limits and bag limits that are intended to control fishing mortality.

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Appendix: Model Code

The following is the code for a model fitted via Bayesian methods to data on the number of tag releases and returns for Dolphinfish released in the U.S. Atlantic, Caribbean, and Gulf of Mexico and observations of satellite tagging and tank holding of Dolphinfish off North Carolina. See Methods for a description of each section of the overall model. Parameter names are defined in Table 1.

```
model  {

###### Section 1: Estimated probability of tag returns
p.Exp2 ~ dbeta(1,1)   #prior for probability of returns in poor condition
p.Control ~ dbeta(1,1)  #prior for probability of returns in good condition

for(i in 1:n.Tagging.Studies) {
```

```
x.ExpReturned2[i]~dbin(p.Exp2,n.Exp2[i])
x.ControlReturned[i]~dbin(p.Control,n.Control[i])
}

###### Section 2: Estimated probability of survival of good-condition fish, sat. tagging & tank
p.TankSat ~ dbeta(1,1)  #prior for probability of survival

for(i in 1:n.TankSat.Studies) {
x.TankSat[i] ~ dbin(p.TankSat,n.TankSat[i])
}

###### Section 3: Calculated values of relative risk (survival of poor-condition fish)
RR2 <- (p.Exp2/ p.Control) *  p.TankSat

p.RR2Mort <- 1 - RR2
p.ControlMort <- (1 - p.TankSat)

###### Section 4: Estimated proportion release by condition
Cond_p ~ dbeta(1,1)   #prior for probability of releasing fish in good condition

for(i in 1:n.trips) {
Cond_x[i]~dbin(Cond_p,Cond_N[i])
}

Cond_Inv_p <- 1 - Cond_p  #calculation for probability of releasing fish in poor condition

###### Section 5: Calculate overall discard mortality for the fishery
StudyOverallDiscardMort <- Cond_p * p.ControlMort + Cond_Inv_p * p.RR2Mort

} #end model
```