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Determining discard mortality of monkfish (*Lophius americanus*) in a sea scallop dredge fishery

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Abstract

Discard mortality studies are considered a primary research priority, particularly for species and fisheries where discard rates are high. Monkfish, *Lophius americanus,* supports the most lucrative finfish fishery in New England, in addition to representing the second highest bycatch species by weight in the sea scallop dredge fishery. Despite its commercial importance, no data exists with respect to monkfish discard mortality estimates for any gear type. The goals of this study were to evaluate the discard mortality process for monkfish captured in sea scallop dredge gear, estimate mortality rate and develop best handling/management practices to mitigate the impact of monkfish bycatch in the sea scallop dredge fishery. Discard mortality was estimated during a field study conducted between June and October 2017 onboard sea scallop commercial fishing vessels on Georges Bank in the Northwest Atlantic Ocean. Pop-up satellite tags were affixed to 60 monkfish to track survival from 14-28 days post-capture. From these monitored individuals, high predation rates were observed (n = 18 out of 26 mortalities) and the bulk of mortalities (n = 21) occurred within the first 24-hours of discarding. However, in light of having no clear method for disentangling capture-related and tag-induced predation, predation was noted exclusively as one or the other to account for uncertainty and provide an upper and lower bound of mortality. This approach suggested that the discard mortality rate was between 17.9 and 54.1% for monkfish discarded by scallop dredges and that elevated air temperatures (above thermal preferences) may contribute to increased mortality. Based on these results, it appears that monkfish discard mortality is lower than previous assumptions of 100%, and potential best-practice management suggestions moving forward may include minimizing fishing in areas of high monkfish abundance or scheduling rotating time/area closures during periods when air temperature exceeds monkfish thermal tolerance of 13 °C.

<A>Introduction

Understanding whether or not non-target organisms survive the capture-and-handling process remains a challenging issue facing marine fisheries today (Halpern *et al.,* 2007; Veldhuizen *et al.,* 2018; Cook *et al.,* 2019). This is because the fate of discarded fish is typically unknown and contributes to uncertainty in stock assessments that can make establishing appropriate landing limits difficult for fisheries managers (Crowder and Murawski, 1998; Alverson, 1999). To account for this uncertainty, conservative discard mortality (DM) rates are often incorporated into stock assessments (up to 100%; NEFSC, 2012; Palmer *et al.,* 2014), until provided with updated DM rates from direct investigations (Capizzano *et al.,* 2016). While this practice may be appropriate for more susceptible species, the larger body of literature suggests species-specific DM rates are often lower than these often naive assumptions. Not only does this lead to an overestimation of total fishery removals, but furthermore it makes it challenging for fishery managers to establish effective management measures (e.g., total allowable catch). DM rates, which represent the combined at-vessel mortality (AVM) and post-release mortality (PRM), are typically estimated with experiments that simulate fishery conditions and subsequently observe the fate of discarded individuals (Pollock and Pine, 2007). These observations can be generated via a variety of methods including containment of experimental subjects (i.e., field net pens or on-deck holding tanks; Mandelman *et al.,* 2013; Knotek *et al.,* 2015), traditional mark-and-recapture studies (Rudershausen *et al.,* 2014), or electronic monitoring and/or biotelemetry approaches (Capizzano *et al.,* 2016, 2019; Knotek *et al.,* 2020). The use of electronic tags has grown more common because unlike confinement studies, this approach better reflects the discarding process wherein tagged animals are able to swim freely and interact with their environment after being discarded (Portz *et al.,* 2006; Pollock and Pine, 2007). In addition, electronic tagging methods provide long duration, high-rate longitudinal data that permit a more thorough evaluation of fate compared to other approaches (Pollock and Pine, 2007). These tagging methods may also allow for the decomposition of discard mortality into mortality that results from predation versus fisheries operations. Pop-up satellite archival transmitting (PSAT) tags are one of the most powerful electronic tagging technologies and can be used to monitor fate over extended time durations (Kerstetter and Graves, 2008; Marcek and Graves, 2014; Knotek *et al.,* 2020; Sulikowski *et al.,* 2020). These tags can be rapidly attached externally to animals and provide archived data (i.e., pressure, temperature, and light levels) that can be translated into high-resolution movement profiles (vertical and horizontal) to depict the fate of an individual. These data can then be used to generate DM rates and identify the most influential factors of the capture process.

Various approaches are available to researchers for monitoring the post-release fate of an animal; however, most of these are logistically constrained (e.g., high cost of tags and time-at-sea) to only a handful of animals that can make it difficult to estimate fishery-scale DM reliably. In light of this, a frequentist approach has included evaluating monitored animals with semi-quantitative health indicators (e.g., physical trauma, reflex impairment, or vitality indices), deriving indicator-specific DM rates from these animals, and then applying these rates to observations of indicator scores collected across the fishery to estimate fishery-scale DM (Benoît *et al.,* 2012, 2015; Depestele *et al.,* 2014; Raby *et al.,* 2014; Capizzano *et al.,* 2016, 2019; Knotek *et al.,* 2018 and 2020).

The sea scallop (*Placopecten magellanicus*) dredge fishery is the most lucrative commercial fishing industry in the U.S. Northwest Atlantic Ocean, with an estimated ex-vessel (price paid upon unloading) value of approximately $532 million U.S. dollars during the 2018 fishing year (Liddel and Yencho, 2020). Monkfish (*Lophius americanus*), are one of the most valuable finfish in the Northeast gillnet and trawl fishery and was valued at $14.8 million in 2018 in the US (Liddel and Yencho, 2020). Monkfish also represent a significant component of bycatch in the sea scallop fishery with 13% by weight of bycatch in the scallop dredge fishery during 2006 (NMFS, 2011). While some observations of vertical movement and off-bottom swimming have been reported (Rountree *et al.,* 2008; Perry *et al.*, 2013), monkfish are primarily benthic, leaving them particularly vulnerable to demersal fishing gear (e.g., scallop dredge; Richards *et al.,* 2008). Limited research on monkfish bycatch in the scallop dredge fishery suggests that while the majority of monkfish appear to be in good physical condition, behavioral and physiological impairments suggest that captured fish may be compromised as a result of the capture-and-handling process (Weissman *et al.,* 2018). Whether these perturbations ultimately result in mortality is unknown as DM rate estimates have not been reported for this species for any gear type. In light of this data gap, fishery managers and stock assessment scientists currently assume a 100% DM rate for monkfish discarded in all fisheries (Richards, 2016).

Due to the importance of these fisheries and the paucity of information concerning monkfish mortality in the sea scallop dredge fishery, the objectives of this study were to: (1) characterize the degree of physical trauma and reflex impairment incurred during capture and handling in the sea scallop dredge fishery; (2) provide fishery-specific DM rates for monkfish by recording both AVM and monitoring the fate of discarded monkfish to estimate PRM (with PSATs); and (3) identify best-handling and/or management practices that could be used to mitigate overall DM.

<A>Methods

<C>*Field studies.*--

Field studies were conducted aboard two commercial sea scallop fishing vessels (F/V *Friendship* and F/V *Reliance*) over four, weeklong cruises between June and October 2017 on Georges Bank in the Northwest Atlantic Ocean (Fig. 1). Fishing conditions and practices during these cruises reflected standard commercial operations to ensure results reflected fishery conditions (for more details see Weissman *et al.,* 2018). This included the use of a regulation compliant New Bedford style scallop dredge that was towed at 4.5 to 5 knots at fishing depths of 47.5 to 91.5 meters. Tow duration varied from 10 to 90 minutes to reflect standard practices in the fishery. Tow-specific information recorded included depth (m) and bottom seawater and on-deck air temperatures (°C). Bottom seawater temperature was measured at the start of each day using HOBO Water Temp Pro v2 temperature loggers (Onset Computer Corporation, Bourne, MA), while air temperature was recorded at the conclusion of each tow using a Thomas Scientific Traceable Lollipop digital thermometer. In addition, temperature gradient was calculated as the difference between air and bottom seawater temperatures for each tow (Knotek *et al.*, 2018 and 2020)

Following completion of each tow, the dredge was brought onboard and the catch deposited on-deck, where it was then hand-culled by the crew to remove harvestable scallops from bycatch and debris. Following advice from fishers and industry members we decided to sample monkfish for up to 30 minutes after fish were removed from the water by the dredge (i.e., the maximum duration catch would be exposed prior to discard), which has also been used by other DM studies in this fishery (Rudders *et al.,* 2017; Knotek *et al.,* 2018). Monkfish were sampled according to protocol outlined by Weissman *et al*. (2018) that began with immediate testing of four reflex responses (Table 1) scored as either present (=1) or absent (=0), with scores then being merged into an overall reflex index (i.e., 0 = full impairment; 4 = no impairment; Davis 2010). Individual animals were also measured for total length (cm) and evaluated on an ordinal injury code (1-4) according to the degree of overt physical trauma (Table 1). If a monkfish was assigned an injury score of 4 it was either moribund or dead and considered an observation of at-vessel mortality (AVM) (Eddy *et al.* 2016; Sweezey *et al.* 2020). Monkfish were examined by a single researcher throughout the cruises to reduce subjectivity in reflex and injury scoring between individuals. In addition, a subsample of monkfish that represented the distribution of injury scores and fishing conditions and practices were selected for post-release monitoring with PSAT tags. The elapsed time each animal was exposed to air (beginning with the exposure of the dredge) prior to being released was also recorded.

<C>*Post-release survival monitoring. --*

To monitor monkfish post-release, sixty PSAT (Lotek Wireless Inc., St. John's, Newfoundland, Canada; Model: PSATLIFE) tags were attached to the dorsal bone of the monkfish to evaluate vertical movement and infer individual fate. Tags were distributed across monkfish with injury codes of 1 to 3, with the majority attached to injury code 1 in order to focus on the outcome of the cryptic stress response observed by Weissman *et al.* (2018). Deployed PSAT tags measured pressure (i.e., depth) and ambient seawater temperature in 10-second intervals for up to 28 days, upon which the tags were programmed to detach from the animal, float to the surface, and transmit archived data (via the Argos satellite array) in compressed five-minute bins. Tags were attached to the monkfish by drilling a hole into one of the dorsal spines (Nemo V2 Divers Edition drill and 11.1 mm drill bit; Nemo Power Tools, Santa Clara, CA) and threading 200 lb. monofilament through the hole, which was then crimped on both sides of the spine to secure the attachment tether. The tag end of the monofilament (120 mm length) was secured to the satellite tag prior to attachment to reduce handling time (Fig. 2). Tag retention trials performed prior to fieldwork with captive monkfish (n = 3; 45 to 60 cm TL) at the University of New England Marine Science Center (Biddeford, Maine) confirmed our attachment method was appropriate for 28-day monitoring periods. In addition, the buoyancy/drag of tags did not appear to influence swimming behavior of monkfish, nor compromise animal health throughout the trial. However, based on these trials we decided to reserve tags for individuals greater than 45 cm TL to avoid obstructing movement and/or health consequences that could otherwise conflate mortality estimates.

<C>*Data analysis.--*

Monkfish DM in the sea scallop dredge fishery was evaluated in separate components of DM; AVM and PRM, with the goal of identifying (1) the most influential capture-related factors driving each source of mortality and (2) fishery-specific mortality rates. Both AVM and PRM required specific analytic approaches to effectively address each source of mortality and its data structure. Ultimately, the mortality rates from each component were combined to provide and overall fishery-specific DM rate (i.e., DM = AVM + PRM). All statistical analyses were performed with R. 3.6.0 (R Core Team, 2019) and statistical significance was accepted at an alpha level < 0.05.

<C>*At-vessel mortality analysis.--*

To evaluate the influence of fishing conditions/practices and biological characteristics (i.e., tow duration, temperature gradient, air exposure, and TL) on AVM, generalized linear models (GLM) were utilized with a binomial distribution and logit link function ("stats" package in R; R Core Team, 2019). Prior to fitting GLMs, correlation amongst covariates was examined using the Spearman's rank-order correlation test. No significant correlations were identified based on $\rho \geq 0.50$ and significance level of $\alpha = 0.05$ (Asuero *et al*., 2006). Manual stepwise forward selection was then performed according to protocol outlined by Benoît *et al*. (2010). Herein, individual covariates were sequentially added to an intercept-only model and only retained if its inclusion reduced the Akaike Information Criterion (AIC) by three or more units. The model with the lowest AIC at the end of the selection process was considered the preferred model unless other model structures (with the same number of covariates) existed that were within two AIC units (i.e., considered equally plausible models). Relevant interaction terms between tow duration and air exposure and TL and air exposure (i.e., tow duration- and size-dependent exposure effects) were also considered during the selection process if the constituent covariates of each interaction were retained during the selection process. Odds-ratios and 95% confidence intervals were calculated for the covariates selected the final model. The assumption of linearity for continuous covariates with the linear predictor of our GLM was assessed following modified protocol described by

Coehlo *et al*. (2012). This included using generalized additive models (GAM) and plots to visually inspect linearity for each covariate. GAMs were fit with a binomial distribution, logit link function, and cubic regression splines that were restrained to four degrees of freedom to avoid overfitting ("mgcv" package in R; Wood, 2011). If GAMs produced to three or more unit reduction in AIC relative to the GLM, we considered there to be strong evidence of a non-linear effect of the covariate on AVM.

To calculate an overall fishery-specific AVM rate we used an empirical bootstrapping technique that involved sampling tows and individual monkfish (from sampled tows) with replacement for each iteration (Efron and Tibshirani, 1993; Benoît *et al*., 2012). In total, 5,000 iterations were performed, with the AVM rate calculated in each iteration by dividing the number of observed mortalities (i.e., animals scored as injury = 4) by the total number of monkfish caught throughout the study. The final fishery-specific AVM rate is reported as the mean and standard deviation of AVM rates across all iterations.

<C>*Depth-time series analysis and fate assessment.--*

To determine the fate of individual PSAT tagged monkfish, depth-variance survival tests (DVSTs) and visual predation examinations were used to evaluate depth-time series after pressure-to-depth conversions ("rtide" package in R; Thorley *et al.,* 2017) and removal of tidal noise ("oce" package in R; Kelly *et al.,* 2017). DVSTs (adapted from Capizzano *et al.,* 2016; Knotek *et al.,* 2020) utilize modified Brown-Forsythe-Levene tests to compare depth variances between negative controls (i.e., movement signature of known dead monkfish) and live released monkfish to identify whether or not the movement (or lack thereof) is consistent with a mortality event (i.e., no significant difference between live-and-dead profiles; $p < 0.05$). This test was applied to equal sized sequential bins of the live released monkfish time-series to incorporate a temporal component, allowing for an estimate of time-of-death if mortality had occurred (Capizzano *et al.,* 2016; Knotek *et al.,* 2020). To avoid misclassifying extended periods of live on-bottom behavior (e.g., Rountree *et al.,* 2008) as a mortality event, which may otherwise lead to an overestimation of PRM, an additional clause was added that required monkfish to have shown no live-movement signatures for at least five days, followed by PSAT tag detachment, which would collectively confirm a mortality event. This was based on *in situ* cage trials with PSAT tagged dead monkfish used to determine the maximum length of time (i.e., five days) it would take for an animal to decompose or be scavenged to the point of the PSAT tag dislodging from its attachment site. In addition, predation events were visually identified when marked deviations from depth and temperature profiles occurred. DVSTs were not appropriate for identifying this source of mortality because depth-variance signatures of the predator would have also been different than the negative control (i.e., indicating a live animal). Live monkfish based on DVSTs and predation examinations were treated as right censored (i.e., fate unknown following the monitoring period) and mortalities as censored observations in subsequent survival analyses (Capizzano *et al.,* 2016; Knotek *et al.,* 2020). However, because we could not confidently identify whether predation events were capture-related or tag-induced (i.e., PSATs reducing predator avoidance or acting as an attractant; Cosgrove *et al*. 2015; Stansbury *et al.,* 2015), we chose to treat these observations under two mortality assumptions in separate survival analyses. Here, predation was either treated exclusively as PRM (i.e., capture-related and as censored observations; Scenario #1) or tag-induced (Scenario #2), with monkfish fate in the latter scenario revised as alive and treated as right-censored observations at the point of predation. This two-scenario approach was necessary because of the high prevalence of predation, which is further explained in subsequent sections. The results from these two mortality scenarios will ultimately provide an upper and lower bounds to PRM that takes into account uncertainties in predation moralities.

<C>*Impact of fishing conditions and practices and biological characteristics.--*

The influence of the following covariates on monkfish PRM were examined: tow duration, depth, temperature gradient, health indicators (reflex impairment and injury codes), and TL. Note that air exposure was not considered as a candidate covariate in this analysis because *a priori* evaluation of this covariate revealed that its distribution did not contain enough contrast (i.e. 80% of monkfish subjected to less than 10 minutes of exposure and a maximum duration of only 18 minutes) to evaluate the true relationship between air exposure and mortality in this fishery (i.e., up to 30 minutes; Knotek et al., 2018). Both continuous and categorical covariates were evaluated for collinearity using the Spearman's rank-order correlation test and Chi-squared tests, respectively, with individual terms considered for removal if were found to be significantly correlated. This testing resulted in the removal of the depth term given its correlation with temperature gradient (ρ

= 0.64; $p < 0.001$), which we expect to be more biologically relevant to monkfish health due to their lack of swim bladder that precludes barotrauma-related injuries associated with depth changes (Curtis *et al*., 2015).

The effects of the remaining suite of candidate covariates were then visualized under both mortality scenarios using the Kaplan-Meier (KM) estimator, which provides a non-parametric estimate of the survival function as it tracks the proportion of live monkfish through the 28-day monitoring period in the absence of censored values. KM survival functions were used to identify any differences in the underlying structure between each covariate-specific model (e.g., asymptotic versus tending to zero; Knotek *et al.,* 2018) and also as an empirical reference of survivorship that could be used to assess parametric model predictions. In addition, visual evidence of similar underlying survival functions within levels of each health indicator (i.e., degrees of reflex impairment and injury scores) prompted the use of log-rank tests to determine if levels should be combined for subsequent analyses (e.g., Benoît *et al*., 2015; Capizzano *et al*., 2016, 2019; Knotek *et al*., 2018, 2020). This led to the combination of reflex impairment scores from 0 to 3, which all had markedly similar survival functions ($\chi^2 = 0.004$ to 0.858; $p > 0.05$).

The semi-parametric Cox proportional-hazards model (CPHM; Cox, 1972; Therneau and Grambsch, 2000) was then used following methods described by Knotek *et al*. (2018) to identify which of the remaining covariates were able to predict the survival of discarded monkfish. This model is defined as:

$$\hat{h}(t) = h_0(t)\exp\left(X'\beta + Z'b\right) \qquad (1)$$

where $\hat{h}(t)$ is the hazard function, or the probability of a mortality event occurring at time t, conditional on survival to time t. This is a function of a vector of covariates X' and a Gaussian random effect Z' (i.e., individual tows), and a non-parametric baseline hazard function $h_0(t)$. No assumption is made for the shape of $h_0(t)$ and the ratio of the hazards between individuals is considered constant over time (i.e., proportional hazards). Model parameters were estimated using partial maximum likelihood (Cox, 1972; Ripatti and Palmgren, 2000).

For each mortality scenario, model development followed a two-fold approach wherein we (1) examined the relevance of the random effect and (2) identified which covariate(s) were capable of predicting monkfish mortality. This began with fitting a fully-saturated mixed-effect CPHM and computing a likelihood ratio statistic against a Chi-squared distribution. The resulting p-value was corrected for boundary testing and then used to identify whether or not a mixed-effects ($p < 0.05$) modeling approach was appropriate moving forward (Knotek *et al.,* 2018). This indicated the random effect of tow was not significant ($p > 0.98$) in either mortality scenarios, and therefore a fixed-effect modeling approach was used to determine the effect of covariates on monkfish survival. Next, covariates were selected using the aforementioned forward selection process (described in *the AVM* section) and AIC corrected for small sample sizes (AICc; Burnham and Anderson, 2002) to account for the subset of animals used for this analysis.

<C>*Post-release mortality estimates.--*

To predict post-release survival rates of monkfish in the sea scallop dredge fishery, we utilized a parametric survival modeling approach developed by Benoît *et al.* (2012, 2015).This approach is well suited for longitudinal data from our monitoring period because it has the ability to predict the time at which the survival function asymptotes (i.e., the survival rate; Benoît *et al.,* 2012, 2015). The survival model is defined as:

$$\hat{S}(t) = \pi \cdot \exp\left[-(\alpha \cdot t)^{\gamma}\right] + (1 - \pi) \qquad (2)$$

where $\hat{S}(t)$ is the probability of a monkfish surviving to time t. The probability of an individual being adversely affected by the capture event is denoted by π, with the survival function for this group described as $\exp\left[-(\alpha \cdot t)^{\gamma}\right]$, which follows a Weibull-type distribution that uses α and γ as scale and shape parameters, respectively. If monkfish were not adversely affected, they were assumed to have survived within the “fixed” monitoring window because of the short timeframe (up to 28 days) and relatively low natural mortality ($M = 0.3$) that we assumed to be negligible within this window (Johnson *et al.,* 2008; NEFSC, 2013). Model parameters were estimated using a maximum likelihood approach, with convergence and fit evaluated as the predicted survival function being within the bounds of KM 95% confidence intervals [see Benoît *et al.* (2012, 2015) for additional details]. Monte Carlo simulations based on parametric bootstrapping (n = 5,000 iterations) were used to account for parameter uncertainty and generate final estimates of survival (mean and standard deviation; details in Benoît *et al.,* 2012), which were ultimately converted into PRM (i.e., 1 – survival rate).

<A>Results

<B>Field Study Characteristics

A total of 4,961 monkfish (15-92 cm TL) were sampled. The majority of these monkfish exhibited little to no overt physical trauma (*i.e*., injury code 1), while 18.6% were scored as either injury codes 2 or 3, and 10.1% displayed the most severe physical trauma and were either dead or in moribund condition (*i.e*., injury code 4). In regards to the reflex assessments, more than half of the evaluated monkfish displayed two or three reflex responses (Table 1). The September cruise had the lowest response rate across all reflexes with 35.7% (n = 250) of monkfish presenting zero or one reflex, while monkfish sampled on the June cruise had the greatest number of responses with 58.0% (n = 936), presenting three or four reflexes (Table 1). Temperatures throughout the cruises ranged from 9.0-14.5 °C and 11.3-30.7 °C for bottom seawater and air (on-deck) conditions, respectively (Table 2). The proportions of injury codes and reflex responses presented are similar to those reported by Weissman *et al.* (2018), which addressed the relationships between predictor variables and the physical and behavioral responses of scallop fishing practices.

<B>At-Vessel Mortality

Model selection with GLMs retained the effects of all candidate covariates (i.e., air exposure, fishing depth, temperature gradient, total length, tow duration; Table 3) in the most parsimonious model to best explain the variation in AVM observed in this study. Interaction terms considered during selection did not produce a large enough reduction in AIC to warrant inclusion (i.e., ΔAIC = -0.19 to 1.81). Of the selected covariates, the odds of monkfish AVM increased by 1.5, 2.3, 7.0, and 2.4% with each unit of air exposure (min), fishing depth (m), temperature gradient (°C), and tow duration (min), respectively (Table 3). The odds of monkfish AVM also decreased by 4.4% for each unit increase in TL (cm; Table 3). In addition, we found evidence of several covariates having a non-linear effect on AVM based on a reduction in AIC when modeled with GAMs versus

GLMs (Table 3; Fig. 4). These covariates included fishing depth, temperature gradient, and total length (Table 3; Fig. 4). Lastly, we estimated the overall monkfish AVM rate in the sea scallop dredge fishery to be 9.99 ± 0.88% (mean ± standard deviation) based on the proportion of observed AVM and our bootstrapping technique.

<B>Post-Release Mortality

In total, 60 monkfish (45-92 cm TL) were subsampled and tagged with PSAT tags during the June, July, and September cruises (Tables 1; Fig. 1). This subsample included monkfish assigned to injury codes 1 (n = 34), 2 (n = 15), and 3 (n = 8), with an additional three animals sacrificed and tagged as negative controls. Of the 60 PSAT tagged monkfish, 52 tags transmitted data (including one of the negative controls) at an average of 64.6% of the 7,888 expected observations per tag. This yielded a total 253,977 observations at five-minute intervals for up to 28 days.

Depth time-series data were evaluated using DVSTs and 27 individual mortality events were identified. The majority of mortality was attributed to predation events (n = 21) that were evident by marked changes to depth and temperature profiles (Fig. 3A). Most predation events occurred within six hours of release (47.6% of events) or within the following 18 hours (33.3% of events), but three events were also identified up to three days post-release. The six capture-related mortalities not attributed to predation also occurred primarily within the first six hours after release (66.7% of events), with an additional two delayed mortalities at 34.7 and 86.8 hours post-release (Fig. 3B-C). Monkfish that survived throughout monitoring periods (n = 24) had their movements tracked from 30 to 662 hours prior to tag detachment. These animals displayed a range of vertical movement behaviors including brief vertical excursions through the water column (up to the surface in some instances) and on/off shelf movement that distinctly characterized live monkfish from both predation and non-predation mortality events.

Model selection with CPHMs revealed that reflex impairment and temperature gradient both have a significant influence on PRM under Scenario #1, while no covariates were retained (i.e., intercept-only model) under Scenario #2. In Scenario #1, the risk of PRM for monkfish decreased by 68% if the animal exhibited no reflex impairment (i.e., reflex code = 4), while the risk of mortality increased by 12% for each unit increase in temperature gradient (°C; Table 4). The survival models used to estimate PRM rates (i.e., 1 – survival rate) fit well within the respective KM 95% confidence intervals in both scenarios (Fig. 5). Fishery-specific PRM rates were estimated by these models to be 54.05 ± 7.07% under Scenario #1 and 17.95 ± 6.85% for Scenario #2 (Fig. 5).

<A>Discussion

This study provides novel insights into the post-release fate of monkfish discarded in the sea scallop dredge fishery in the U.S. Northwest Atlantic Ocean and estimates DM (AVM + PRM) between 27.9% (10.0 + 17.9%; Scenario #1) and 64.0% (10.0 + 54.0%; Scenario #2). These are conservative bounds (relative to a single estimate) that take into account high observed predation rates that current methodologies and statistical analyses cannot disentangle as either capture-related or tag-induced. Nonetheless, both estimates are substantially lower than the current assumption of 100% DM used by management for this species, which was adopted *in lieu* of having no previously directed research that investigated monkfish DM (Richards, 2016). This has become a frequent finding for many unstudied species and fisheries where fisheries managers assumed conservative DM rates, but upon directed research efforts revised these rates that had previously overestimated mortality. For example, the DM of winter skate, (*Leucoraja ocellata*) was reduced from a blanket 50% mortality across gear types (established in 2008 under Amendment #3 to the NE Skate Complex FMP; Benoît 2006) to 34 % in scallop dredge (Knotek *et al.,* 2018), 9% in bottom otter trawl (Mandelman *et al.,* 2013), and 14% in sink gillnet (Sulikowski *et al.,* 2018) fisheries. These and other findings (i.e Knotek et al., 2019) support our findings for the sea scallop fishery and point towards the potential for monkfish having lower DM rates for other gear types that routinely capture this species as bycatch, such as the sink gillnet and bottom trawl fisheries. However, additional fishery-specific research would be required to confirm DM rates for this gear types differ from the assumed 100% mortality (Richards, 2016).

A major finding from this study was the high prevalence of predation following discard (18 of the 26 mortalities). However, this also presented a major challenge for how we analyzed these data because it was unclear whether these predation events were the result of capture-related consequences, tag-induced, or some combination of the two (Cosgrove *et al.,* 2015; Stansbury *et al.,* 2015). In light of this and as mentioned previously, we opted to treat predation events under one of two scenarios where they were exclusively considered either (1) PRM or (2) tag-induced, with the latter observations removed as mortality events. Although these scenarios provided estimated upper and lower bounds of PRM (and therefore DM), this general topic within any fisheries will require additional and directed research that will need to elucidate the effects of predation (captured/and or tag related and by natural) that may simultaneously occur within the observation window.

In Scenario #1, predation events were attributed to capture (i.e., PRM) under the belief that, among other endpoints, the physiological and physical consequences of capture have reduced predator avoidance abilities and increased predation rates beyond natural circumstances (Ryer 2002). This finding was supported by the reflex impairment results, which indicated that the risk of mortality increases with increased reflex impairment. To that end, it was recently shown that monkfish captured in this fishery displayed evidence of physiological stress, which supports this mechanism for predation (Weissman *et al.,* 2018). In addition, and potentially exacerbating this scenario, is the purported behavior of opportunistic predators that have been seen following fishing vessels and predating upon discarded fish (Knotek, pers. comm.). For example, this opportunistic behavior of predators has been documented on several occasions in the sea scallop dredge fishery for dusky shark (*Carcharhinus obscurus*) and blue shark (*Prionace glauca*) on Georges Bank (R. Knotek, pers. comm.). And while large monkfish typically do not have any natural predators, sharks and swordfish have been known to eat smaller monkfish, and therefore they may be taking advantage of the compromised monkfish discarded in this study (NOAA 2020). In contrast, Scenario #2 treats predation as tag-induced. Here, predations are considered an artifact of PSATs that either attract predators (Stansbury *et al.,* 2015), reduce cryptic abilities used to evade detection (e.g., covering itself on the seafloor), or further inhibit the movement of compromised monkfish (Cosgrove *et al.,* 2015). The latter two were addressed during captivity trials, within which monkfish did not appear to show signs of impaired movement (i.e., normal swimming patterns and retained ability to cover itself on the seafloor); however, these animals were not subject to the compounding stress of capture that may ultimately alter the influence of externally attached PSATs. Nonetheless, previous applications of PSATs with smaller-sized benthic species have shown no elevated occurrence of predation (Knotek *et al.,* 2020), which may suggest that other factors associated with capture are attributing to the elevated prevalence of predation. But ultimately, without a method for disentangling these types of predation, it will continue to be a challenge that should carefully addressed by researchers, with the results presented in a manner that accounts for these uncertainties.

The remaining non-predation monkfish mortality (n = 6; i.e., Scenario #2) occurred primarily in the first six-hours (n = 4) following live-release, with two additional delayed mortalities identified at 35 and 87-hours. The rapid onset of mortality has been well-documented characteristics of PRM (Davis 2002; Barkley and Cadrin, 2012; Benoît *et al.,* 2012, 2015; Capizzano *et al.,* 2016; 2019), but delayed mortalities have only recently received attention as advancements in tagging technology have permitted longer observation periods (Knotek *et al.,* 2018, 2020). For example, delayed PRM was recently documented as occurring up to 10-days post-release in thorny skate that were captured with bottom otter trawl gear and monitored with PSATs (Knotek *et al.,* 2020). However, delayed mortalities are more difficult to attribute as DM because the mechanisms are not as well understood, and natural mortality, M, becomes increasingly more likely as monitoring windows expand (Benoît *et al.,* 2020). Therefore, while it is possible that unresolved physiological perturbations or physical injuries from the capture event are to blame, M should also be considered. Benoît and co-authors (2020) recently addressed this challenge of distinguishing PRM and M and reported that in 30-day monitoring periods, PRM estimates will become more reliable for species with lower M and higher true PRM. For example, 30-day PRM estimates for yellowfin tuna (higher M = 1.0) were expected to overestimate the true mortality (assuming it were lower than 0.2) by up to 250%, whereas PRM for southern bluefin tuna (lower M = 0.2) was only expected to overestimate mortality by 6-30%. To that end, our PRM estimates may be less susceptible to overestimation with monkfish having a relatively low M (0.3; NEFSC, 2013), and the two delayed mortalities occurring within less than 4 days of discard. Nonetheless, it is still possible that M may have been observed within this study, which may have an unintended consequence of overestimating our final PRM and DM rates.

At vessel mortality, which includes fish that did not survive capture or died before release (Donaldson *et al*., 2008), is the other crucial part of calculating the DM rate. AT vessel mortality rates have been calculated for other benthic species captured by trawl gear (Yergey *et al*., 2012, Revill *et al.,* 2013) in order to determine the contribution of AVM to DM. While some studies merely report the AVM (Yergey *et al.,* 2012), others have analyzed the variables contributing to

AVM such as total length and reproductive status (Revill *et al.,* 2013). In the current study, monkfish AVM and PRM was examined across a wide range of fishing conditions and practices that are typically observed throughout the sea scallop dredge fishery. Air temperature was identified in Scenario #1 (i.e., predation included in DM) from the suite of covariates examined to have the strongest influence on monkfish mortality, with increased temperature driving mortality rates. This relationship is commonly reported in literature, as temperature elevated above a species thermal preference have been shown to exacerbate physiological perturbations, which may also lead to impaired post-release behavior (Veldhuizen *et al.,* 2018 and Cook *et al.,* 2019). Monkfish thermal preference (relative to seawater) ranges from 4.5 to 13.0°C (Richards *et al.,* 2008), but in the current study study, monkfish were subjected to up to a 1.7 fold increase in ambient temperature (21.6°C) while on-deck (minimum of 10.2°C). This supports our finding for increased mortality in the “high” air temperature group (15.4 to 21.6°C), with air temperatures potentially having an even more profound effect on monkfish because of coinciding challenges exacerbating the physiological impact of temperature (e.g., desiccation, increased sunlight exposure, anoxic conditions; Cook *et al.,* 2019). To that end, we would expect AVM to increase during the summer months in New England (i.e., sub-optimal to elevated temperatures) and be lower in the cooler months; however, harsh winter conditions with below-freezing temperatures (outside of the lower thermal tolerance; Richards *et al.,* 2008) might reverse this trend and lead another scenario of high AVM. While our study revealed temperature had an impact on post-release mortality, because we did not evaluate the interaction of temperature and air exposure over a long enough duration (i.e., up to 30 minutes), it is possible that air exposure has a larger role in mortality than what we are able to report on. Additional investigations of animals across these conditions will be needed to confirm the how extreme whether conditions may influence monkfish AVM captured via scallop dredge.

Other factors considered but not indicated in our analysis as having an impact on mortality included the degree of physical trauma and reflex impairment indices. While these reflex impairment observations have been identified as mortality predictors for several species and gear types including yellowtail flounder (*Pleuronectes ferruginea*), little skate, and winter skate (Barkley and Cardin, 2012; Knotek *et al.,* 2018), cryptic and discolored bodies of monkfish may have limited our ability to visually evaluate physical trauma. The reflex impairment indices have been shown to reflect physiological perturbations but may be sublethal and not translatable to predicting mortality (Weissman *et al.,* 2018). The use of reflex impairment and physical trauma indices may be species and gear specific. Animal length also appeared to have no influence on AVM, which may be an artifact of size-restrictions for PSAT tagged animals (≥ 45 cm TL) that precluded an evaluation of smaller conspecifics. This is a commonly reported factor of DM that has been documented for demersal species including Atlantic halibut (*Hippoglossus hippoglossus;* Neilson *et al.,* 1989), Pacific halibut (Richards *et al.,* 1995), sole (*Solea solea*; Depestele *et al.,* 2014), and several skate species (Mandelman *et al.,* 2013; Depestele *et al.,* 2014; Knotek *et al.,* 2020). It is possible such a relationship extends to dredge-caught monkfish; however, limitations associated with tank-based studies (i.e., confinement stress) and electronic tagging make it difficult to evaluate this factor under near-realistic conditions (Weissman *et al.,* 2018).

The ultimate objective of this study was to provide best handling and or management practice advice in an effort to minimize monkfish discard mortality in the sea scallop dredge fishery. Based on the results from this study, management and other end-users (e.g., commercial fishers and industry members) should consider adopting best practices that address tow duration, sorting/discard time (i.e., air exposure), temperature gradients, fishing depths, and animal size. Overall, a practical and manageable suggestion for fishermen would be prioritizing the discard of monkfish upon landing. Another adaptive management practice which would mitigate mortality during the high temperature months which exceed monkfish temperature tolerance of 13 °C (Richards *et al.,* 2008) through a number of effective practices may include bycatch avoidance strategies similar to those developed for yellowtail flounder in this fishery. This would include providing density maps of yellowtail flounder to the scallop fishermen and recruited captains to collect and report yellowtail flounder catch to update distribution and abundance data (O'Keefe *et al.,* 2010). A similar proposed method in light of the current study would inform fishers in the warmer months of areas to avoid that would likely have high catch rates of monkfish. Another option could be to create time/area closures aligned with high catch rate areas of monkfish enacted during high temperatures months. While monkfish are not currently overfished (Ardini *et al.* 2016), it is best to proactively analyze the impacts the sea scallop dredge fishery may have on monkfish abundance so as to avoid any negative consequences for either fishery. This information will therefore have direct implications for stock assessments and be of potential benefit to not only the sea scallop fishery because it reduces the likelihood of additional accountability measures that may otherwise lead to early closures of the fishery in the future (i.e., "choke" species). In addition, increased stock estimates as a result of lower DM may increase the allocated quota for monkfish in Northeast fisheries. As air temperatures rise or are higher for a longer portion of a year due to climate change, a reassessment of any management measures enacted should be conducted to evaluate effectiveness once best handling practices were developed based upon the study results.

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Table 1. Description of health indicators used to evaluate monkfish post-capture in the sea scallop dredge fishery. The injury index was modified from Mandelman *et al.* (2013) and Knotek *et al.* (2018) and was used to address the degree of overt physical trauma via an ordinal scoring system

(1 – 4). Individual reflex responses [adapted from Weissman *et al.* (2018)] were scored on a presence/absence scale, with cumulative degree of impairment calculated for each animal using an ordinal reflex index (i.e., 0 = full impairment; 4 = no impairment). The proportion of monkfish scored within injury and reflex indices is provided for animals sampled only as observations (n = 4,961) or fitted with pop-up satellite archival transmitting tags (n = 60; separated by a "|"). Note that individual reflexes are shown as the proportion of present reflexes.

Health indicator	**Description**	**Proportion**
Injury		
Code 1	Little to no overt physical trauma (< 10 mm lacerations and no visible hemorrhaging); normal body coloration	0.71 | 0.60
Code 2	Moderate overt physical trauma (11—20 mm lacerations and minor to moderate hemorrhaging); buccal cavity filled with some sediment and/or catch; slight body discoloration	0.15 | 0.26
Code 3	Severe overt physical trauma (> 20 mm lacerations and extensive hemorrhaging); buccal cavity completely filled with sediment and/or catch; extreme body discoloration	0.04 | 0.14
Code 4	Moribund or dead	0.10 | 0.00[a]
Reflex impairment		
Back	Fish exhibited spinal arch when placed on dorsal side	0.66 | 0.73
Mouth	Fish closed jaws when stimulated via insertion of probe into mouth	0.51 | 0.67
Thrash	Fish exhibited resistance to handling via body flexion	0.27 | 0.48
VOR[b]	Fish exhibited pupil fixation when the body was physically rotated along its longitudinal axis	0.69 | 0.85
Code 0	Full reflex impairment	0.09 | 0.08
Code 1	Severe impairment (n = 3 reflexes)	0.17 | 0.06
Code 2	Moderate impairment (n = 2 reflexes)	0.26 | 0.12
Code 3	Minor impairment (n = 1 reflex)	0.31 | 0.37
Code 4	No reflex impairment	0.17 | 0.37

[a] Three additional animals were sacrificed and tagged as negative controls for the depth-variance survival test.

[b] Vestibular ocular response (VOR)

Table 2. Summary information for field study characteristics and monkfish sampled as either observation-only or PSAT tags. Values are reported as means with minimum and maximum values in parentheses.

Variable	Observation	Tagged subsample
Tows (n)	343	44
Tow duration (min)	49.9 (5.0 – 90.0)	59.9 (13.0 – 86.0)
Depth (m)	73.6 (47.6 – 91.5)	71.3 (58.5 – 84.1)
Air exposure (min)	14.0 (1.4 – 31.4)	7.0 (3.1 – 18.1)
Air temperature (°C)	18.2 (11.3 – 30.7)	15.5 (10.2 – 21.6)
Bottom seawater temperature (°C)	11.1 (9.0 - 14.5)	10.0 (8.8 – 21.1)
Total length (cm)	46.1 (15.0 – 92.0)	60.2 (45.0 – 92.0)

Table 3. Forward model selection results for generalized linear models (GLM) fit to at-vessel mortality data from monkfish caught in the sea scallop dredge fishery. The Akaike Information Criteria (AIC) value is provided for each step and the final model structure with most parsimonious fit is shown with italic lettering. Results of the final GLM are presented in the bottom portion of this table [i.e., covariate coefficient estimates (standard deviation), statistical significance, and the odds-ratio with 95% confidence intervals]. In addition, the change in AIC produced when the respective covariate is modeled with a generalized additive model (GAM) is provided.

Forward model selection	**GLM AIC**
~ 1	3145.44
~ Tow duration	3053.59
~ Tow duration + temperature gradient	3015.62
~ Tow duration + temperature gradient + total length	2973.66
~ Tow duration + temperature gradient + total length + fishing depth	2967.34
~ Tow duration + temperature gradient + total length + fishing depth + air exposure	*2964.18*

Variable	**Coefficient**	***p*-value**	**Odds ratio**	**95% Confidence interval**	**GAM ΔAIC**
Tow duration (min)	0.024 (0.003)	< 0.001	1.024	1.019, 1.029	-1.898
Temperature gradient (°C)	0.068 (0.016)	< 0.001	1.070	1.037, 1.104	-8.096
Total length (cm)	-0.045 (0.007)	< 0.001	0.956	0.942, 0.970	-2.077
Fishing depth (m)	0.023 (0.008)	0.002	1.023	1.008, 1.039	-20.731
Air exposure (min)	0.015 (0.007)	0.032	1.015	1.001, 1.029	0.002

Table 4. Forward model selection results for Cox proportional-hazards models (CPHM) fit to longitudinal survival data from dredge-caught monkfish tagged with pop-up satellite archival transmitting tags. The Akaike Information Criteria (corrected for small sample sizes; AICc) value is provided for each step and the final model structure with most parsimonious fit is shown with italic lettering. Results of the final CPHM are presented in the bottom portion of this table [i.e., covariate coefficients, statistical significance, and the hazards ratio with 95% confidence intervals]. Hazard ratios represent the proportional risk of mortality relative to the baseline group of categorical covariates (i.e., reflex code) or unit increase in continuous covariates (i.e., temperature gradient). Note that model selection was performed separately for both scenarios (1 = including predation; 2 = not including predation).

Forward model selection	**CPHM AICc**
Scenario #1	
~ 1	194.09
~ Reflex code	187.94
~ Reflex code + temperature gradient	*184.27*
Scenario #2	
~ 1	*43.43*

Variable	**Coefficient**	**Hazard ratio**	**95% Confidence interval**	***p-value***
Scenario #1				
Reflex code = no impairment[a]	-1.14	0.32	0.12, 0.85	0.02
Temperature gradient (°C)	0.11	1.12	1.02, 1.22	0.02

Scenario #2

No covariates retained

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^{a}Reflex impairment reference category = impaired animals (i.e., scores 0-3)

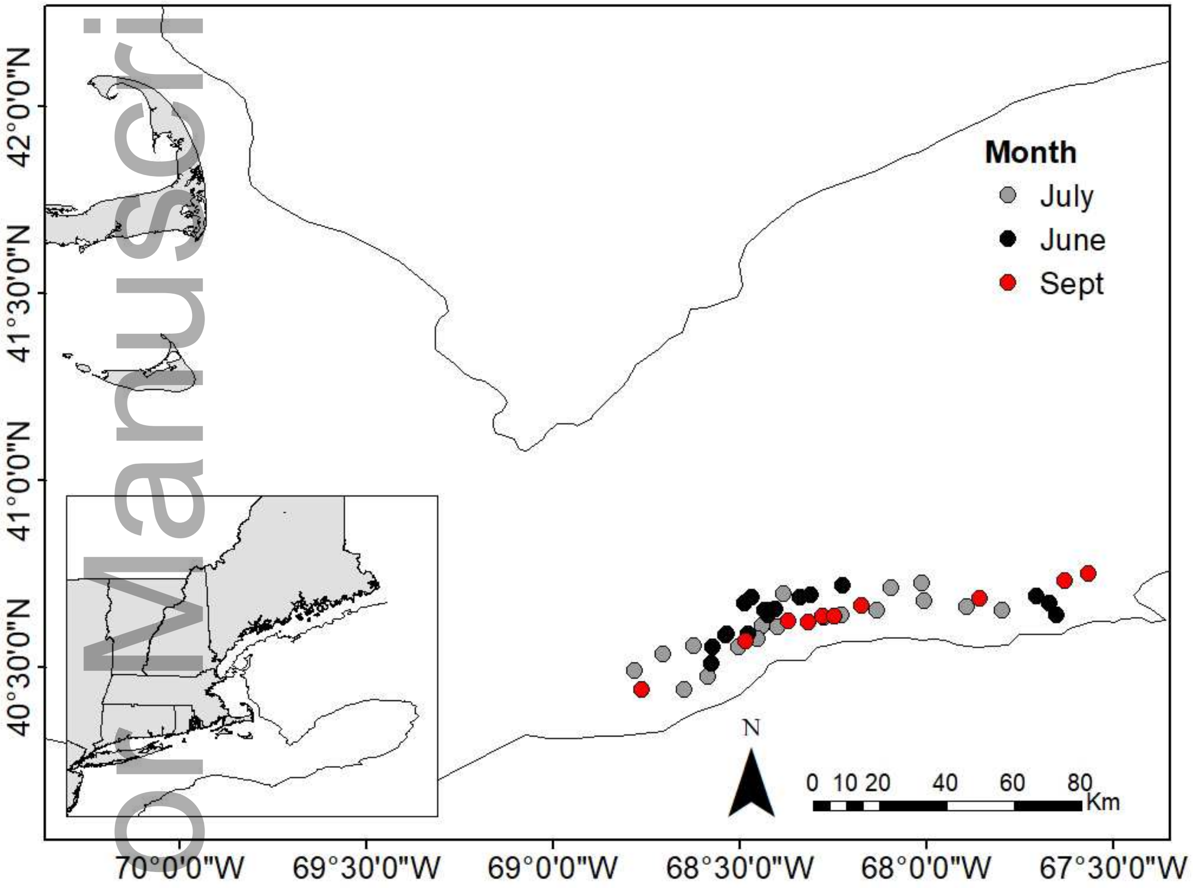
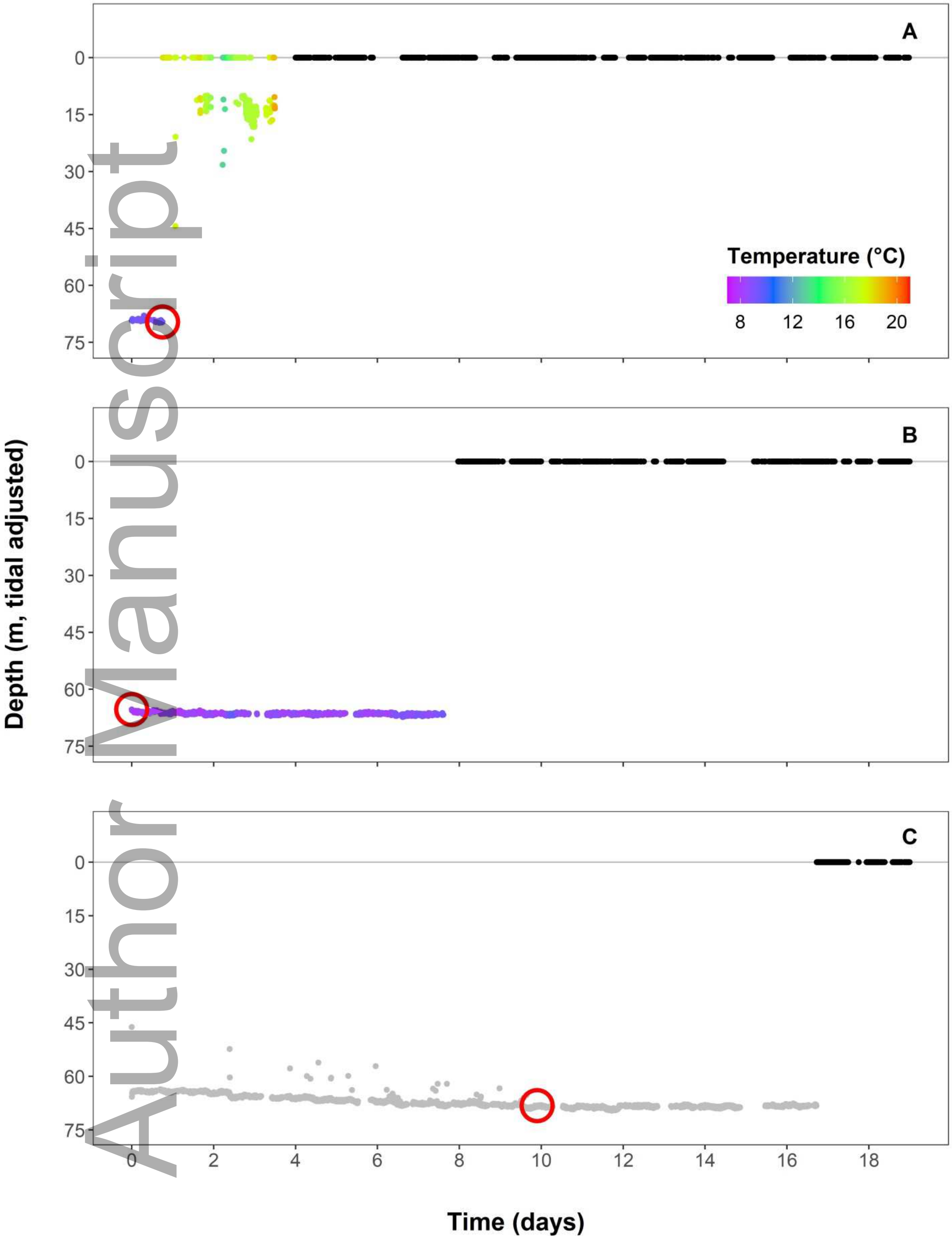


Figure 1. Individual tow locations (indicated with circles) where monkfish were sampled and tagged with Lotek PSATLIFE tags during the field study conducted in June, July, and September (2017) on Georges Bank.

Figure 2. Pop-up satellite archival transmitting (PSAT) tag (Lotek PSATLIFE) attachment method using a 120 mm 180 kg monofilament tether and four crimps to secure the PSAT tag to the bone. A Nemo V2 Divers Underwater Cordless Drill with a 11.1 mm bit was used to drill the hole into the bone of the monkfish.


A
B
C
Temperature (°C)
8
12
16
20
Depth (m, tidal adjusted)
0
15
30
45
60
75
Time (days)
0
2
4
6
8
10
12
14
16
18

960

Figure 3. Depth time-series from pop-up satellite archival transmitting (PSAT) tags that show a (A) predation event (red circle) and (B) immediate and (C) delayed post-release mortality events (PRM; red circles) of monkfish discarded by the sea scallop dredge fishery. Each depth time-series is shown in five-minute resolution with individual observations colored-coded based on the ambient seawater temperature up until the point of tag free-floating at the surface (i.e., observations shown in grey). Note that the temperature sensor on the PSAT tag associated with (C) malfunctioned and therefore we were unable to display seawater temperatures associated with the time-series. Predation was visually identified with marked changes to depth/temperature profiles and PRM was evaluated using depth variance survival tests.

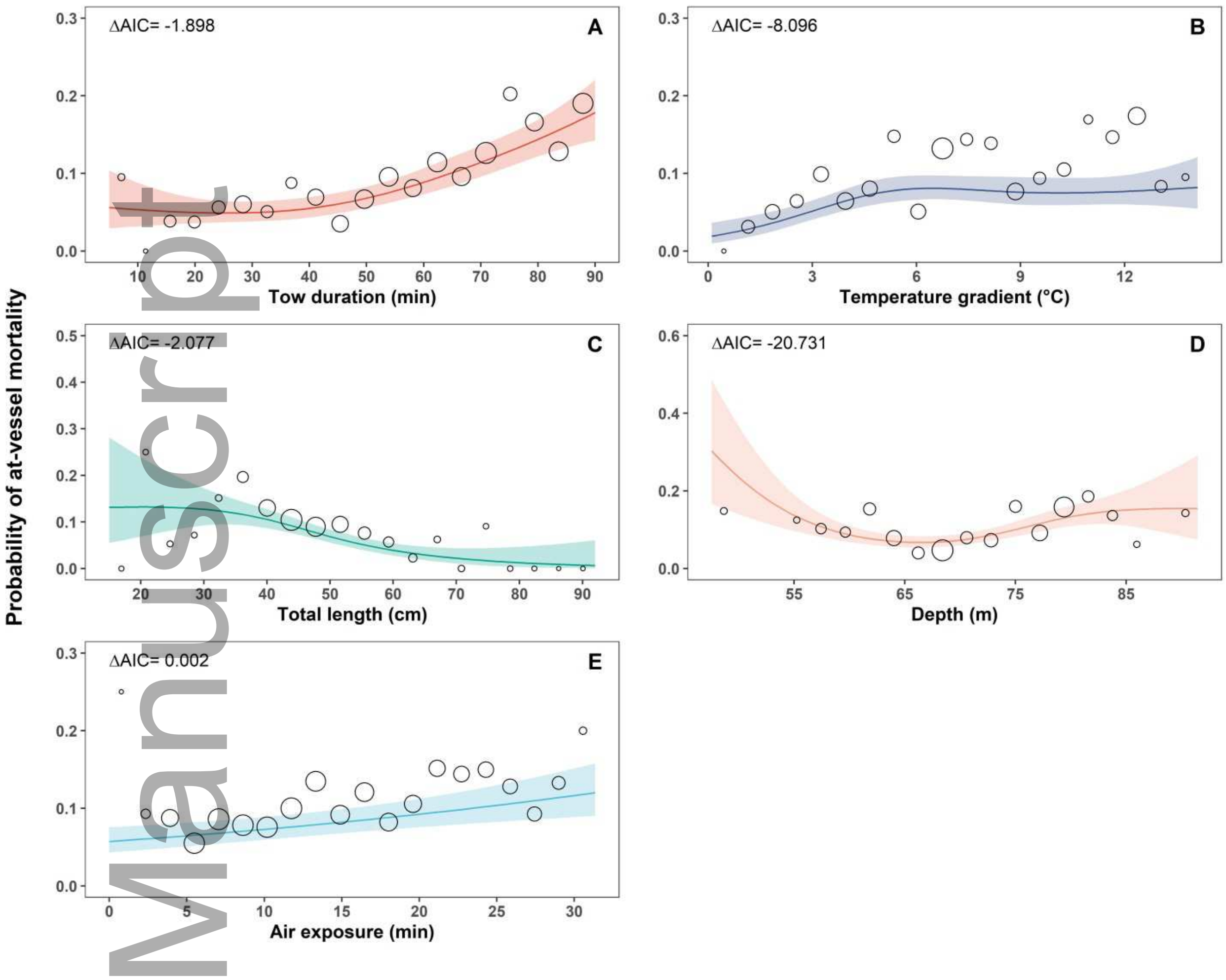


Figure 4. Predicted probability of at-vessel mortality (AVM) for monkfish using a generalized additive model (lines with shaded areas that denote 95% confidence intervals) that describes mortality as a function of (A-E) tow duration, temperature gradient (bottom seawater to air temperatures), total length, fishing depth, and air exposure. AVM probabilities were predicted across the range of values for each covariate, while remaining covariates were held constant at their means. Individual circles within each panel denote the proportion of AVM within bins of each covariate (n = 20 equally-spaced bins) and the size of circles represent the relative proportion of monkfish within each bin, compared to the total number of monkfish observed. The difference in Akaike Information Criteria (AIC) between GAM and generalized linear models for each covariate is also provided in the top-left corner of each panel.

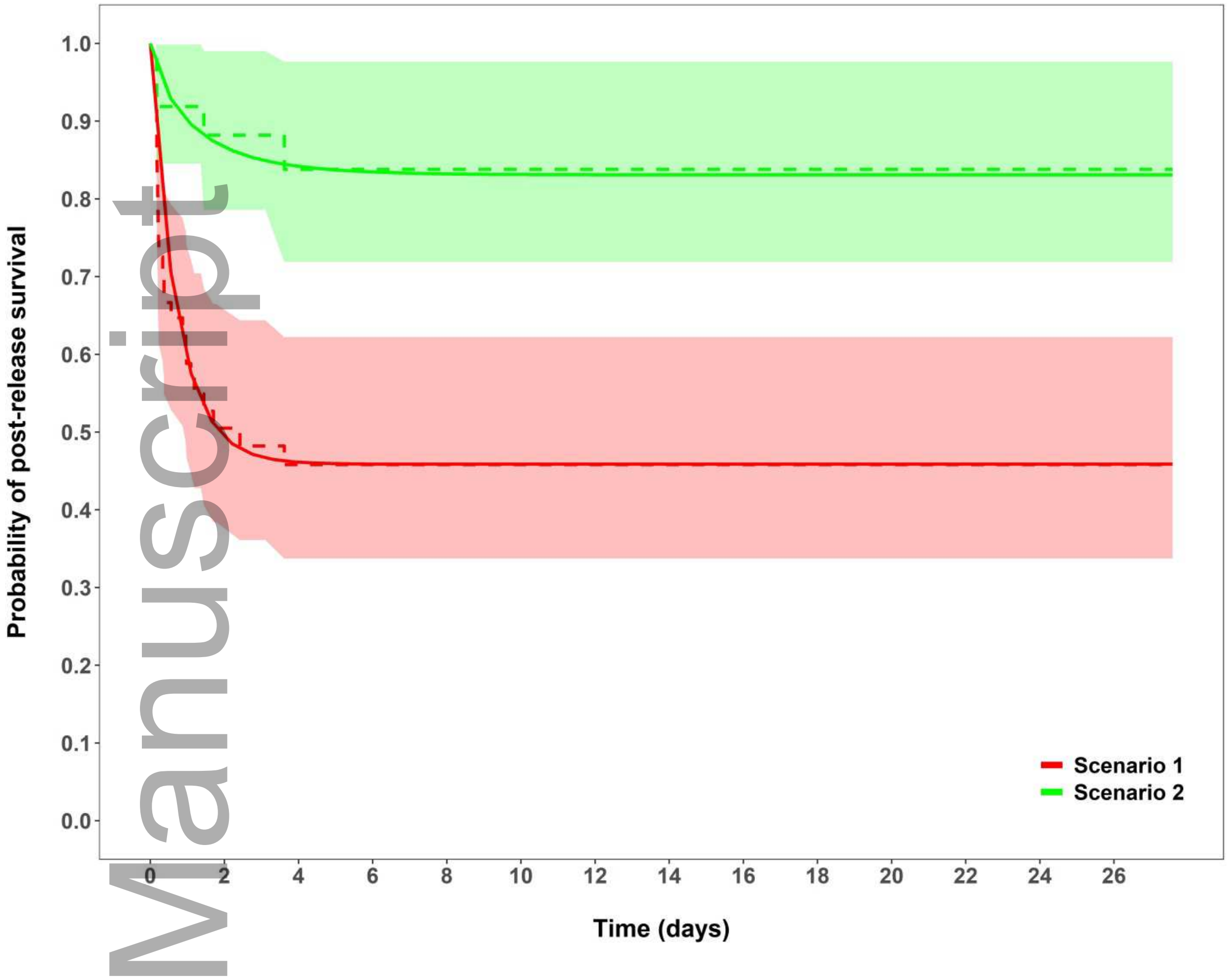


Figure 5. Probability of post-release survival over time for monkfish discarded by the sea scallop dredge fishery based on the parametric survival model fit separately to either Scenario 1 (predation included in post-release mortality; PRM) or Scenario 2 (predation not included in PRM). Model fits are overlaid onto Kaplan-Meier estimates for each scenario with 95% confidence intervals that are shown with dashed lines and shaded areas, respectively.