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ARTICLE

Discard Mortality of Sea Scallops *Placopecten magellanicus* Following Capture and Handling in the U.S. Dredge Fishery

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Abstract
Discard mortality can represent a potentially significant source of uncertainty for both stock assessments and fishery management measures. While the family Pectinidae is considered to be robust to the capture and handling process, understanding species-specific discard mortality rates is critical to characterize both population dynamics and to develop regulatory measures to meet management objectives. The discard mortality rate for the U.S. dredge fishery of sea scallop *Placopecten magellanicus* was estimated empirically via a retention study aboard industry vessels under commercial conditions. Over 16,000 sea scallops were assessed via a composite index of scallop vitality that consisted of semiqualitative measures of both overt trauma (shell damage) and response to stimuli. Results indicate that overall sea scallop discard mortality was 21% and consistent with the values currently assumed in the stock assessment. Survival mixture models support the utility of a simple metric of physical trauma as an effective predictor of mortality. Exposure time was also identified as a positively correlated factor that was important in describing the discard mortality process. Application of experimental results highlight the need to consider some operational characteristics of the fishery to reduce potential discard mortality.

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For many fisheries, discard mortality represents an uncertain and often unquantified component of fishing mortality (Broadhurst et al. 2006). In the dredge fishery for sea scallop *Placopecten magellanicus* in the Northwest Atlantic Ocean, discarding occurs during the portion of the capture and handling process where a sea scallop is selected for retention. This discarding can result from a variety of factors, including market conditions, product quality, high grading, and regulatory requirements (e.g., possession limits) (Fonseca et al. 2005; Tsagarakis et al. 2008; NEFSC 2014). Discarding generally tends to be a function of animal size, where it becomes economically inefficient to devote production time to processing smaller sea scallops, or from high grading, where a price differential between sea scallops of varying sizes exists in conjunction with possession limits (NEFSC 2014). While the sea scallop fishery does not have a mandated minimum landing size, age at first capture is indirectly managed via regulations focused on the dredge gear, levels of effort, and spatial management.

As a result of these measures, the total annual amount of sea scallop discards has declined since 2004 (NEFSC 2014). The 2018 sea scallop stock assessment estimated the total amount of discarded sea scallops from dredge gear in 2017 at 1,447 metric tons of meats, a decrease from the peak of 2,504 metric tons in 2004 (NEFSC 2018). While the quantity of discarded sea scallops has declined, the discard rate and discard mortality rate have likely been variable across the fishery. The survival of discarded sea scallops is likely to vary as a function of the spatial and temporal distribution of fishing effort and the wide range in environmental conditions experienced annually (NEFSC 2014). For this study, we define discard mortality as the probability of a sea scallop not surviving the processes related to harvest operations that occur immediately (at-vessel mortality) or shortly ($\leq$6 d) after release (postrelease mortality) and that do not result in landed catch. The capture and handling process can contribute to discard mortality in a number of ways, such as physical trauma (e.g., crushing or shell damage), physiological stress (e.g., thermal stress and air exposure), and increased risk of predation as a consequence of being discarded (Veale et al. 2000; Jenkins and Brand 2001; Davis 2002; Stokesbury et al. 2011; Methling et al. 2017). Given the suite of potential contributing factors, discard mortality may vary as a result of animal-specific injury levels and the ability of an animal to recover from the stress and injury imposed by the capture and handling process (Morfin et al. 2017).

Despite the potential for variability in discard mortality rates, recent sea scallop stock assessments have assumed a fixed rate of 20% (NEFSC 2010, 2014, 2018). While this rate has been constant throughout recent assessments, the discard mortality rate was also considered to be uncertain (NEFSC 2010, 2014). This uncertainty stems from a relative paucity of direct studies to estimate discard mortality for sea scallops specifically or bivalves in general (Medcof and Bourne 1964; Murawski and Serchuk 1989). The overall discard mortality rate associated with sea scallop discards is modest; however, the implications of an uncertain point estimate have a potentially wider reaching impact (Benaka et al. 2016). This impact is reflected in calculations of fishing mortality rates for the stock, as well as estimates of resource-specific reference points (D. Hart, National Marine Fisheries Service, personal communication).

The broad basis of the present study was to estimate discard mortality for sea scallops subject to the capture and handling process in the dredge fishery based on an empirical study that utilized a vitality assessment approach coupled with the short-term retention of animals. Vitality assessments included unambiguous and straightforward indices of injury condition (physical trauma) and behavioral response to stimuli that can be rapidly assessed in the field, culminating with a description of the resulting relationship between selected indices and survival (Davis 2002; Davis and Ottmar 2006; Benoît et al. 2010, 2012, 2015). In addition to vitality, relevant biological and environmental variables were also considered to estimate survival (Capizzano et al. 2016; Morfin et al. 2017). This approach allows observations over a broad range of conditions to enable the scaling of discard mortality rates to the fishery level (Benoît et al. 2012; Capizzano et al. 2016; Morfin et al. 2017).

The main objective of this study was to use rapidly assessed, semiquantitative health indicators (e.g., shell damage and behavioral response indices) in conjunction with holding-tank trials to assess sea scallop vitality and monitor survival, respectively, and derive vitality-specific discard mortality rates. These vitality-specific discard mortality rates were then applied to a broader set of vitality scores collected across the spatiotemporal footprint of the U.S. dredge fishery to generate a single estimate of the discard mortality rate. Environmental, operational, and biological factors were also considered to assess their effects on sea scallop discard mortality.

METHODS

Many experimental approaches exist to estimate discard mortality, including retention trials (net-pens, aquaria, tanks) and conventional or electronic (e.g., telemetry) tagging studies (Knotek et al. 2015; Capizanno et al. 2016). Each approach has advantages and disadvantages and should be selected on a case-by-case basis to match the characteristics of the species of interest and resources available (Benoît et al. 2015). For the benthic sea scallop fishery, which mostly comprises large offshore vessels that operate year-round, we utilized a retention-based approach. We established a vitality index for sea scallops and correlated indexed observations to survival after a period of on-board observation. This approach enabled the collection of observations that spanned the range of potential operational, environmental, and biological predictors that we hypothesized were important in the discard mortality process.

Field Experiments

Field studies were conducted over eight cruises between August of 2014 and December of 2015 onboard two commercial fishing vessels operating out of New Bedford, Massachusetts. To characterize the spatial and temporal extent of the fishery, sampling was conducted throughout the mid-Atlantic and Georges Bank resource areas in the Northwest Atlantic Ocean, across different seasons to reflect a representative range of conditions that discarded sea scallops experience in the fishery (Figure 1). Operationally, the sampling cruises approximated commercial fishing conditions so that discard mortality estimates would be representative of commercial practices. Participating vessels used commercial scallop dredge gear configured (i.e., New Bedford–style dredge or a Coonamessett Farm Turtle Deflector dredge) in accordance with current gear regulations. Tow durations varied randomly between 5 and 90 min, reflecting the range observed in the fishery. The following information was recorded for each tow: date, location, time, tow duration, exposure time (i.e., minutes sea scallops were on deck, quantified as the time between when the dredge was

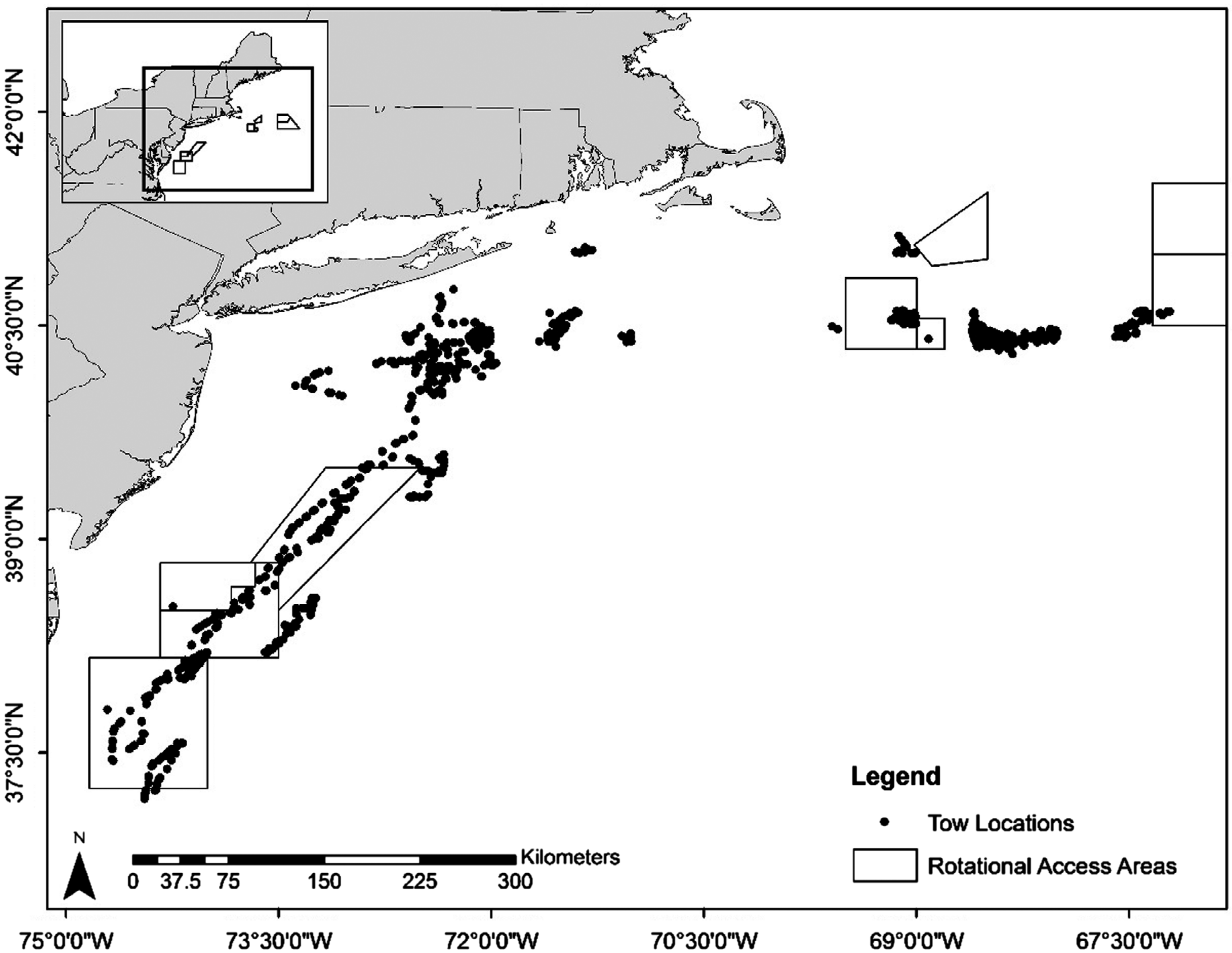

FIGURE 1. Tow locations completed during research cruises in the mid-Atlantic region and on Georges Bank in the Northwest Atlantic Ocean. Rotational access areas are spatially explicit areas managed by the Atlantic Sea Scallop Fishery Management Plan under a rotational management strategy.

emptied and the sea scallops were put in holding tanks or released), depth (m), substrate type (hard or soft), air and bottom-seawater temperatures, and estimated volume of sea scallop catch (number of bushel baskets of sea scallops).

For a sampled tow, the vessel's crew was instructed to process the catch as they would under normal fishing conditions. Those sea scallops that would be discarded during commercial operations were divided into two groups: (1) the holding tank group, which were retained for the onboard holding study, and (2) the released group, which were returned to the sea after undergoing the vitality assessment (see Table 1). Sea scallops were selected for the holding tank group to ensure that sample sizes were sufficient and representative of the different shell damage and response conditions assessed for the vitality assessment.

A modular deck tank system was employed to hold holding-tank-group sea scallops for the duration of a cruise. This system was designed to examine acute (i.e., short term) postrelease mortality by modulating the seawater temperature of the system to mirror that of the bottom water observed during a cruise (Knotek et al. 2015). A HOBO temperature logger (Onset Computer Corporation, Bourne, Massachusetts) was attached to the scallop dredge to record bottom temperature during a cruise. Water temperature within each holding tank was monitored hourly with YSI 55 sensors (YSI Incorporated, Yellow Springs, Ohio), and water temperature in the holding tanks was adjusted as needed.

Sea scallops included in the holding tank group were allowed to remain on deck for randomly selected time intervals (1–90 min) prior to being marked with a unique identifier, which allowed for monitoring of the disposition of individual sea scallops over the duration of relevant exposure times. These sea scallops were then assessed for vitality and were measured for shell height (cm) before being placed inside small-mesh wire cages within the onboard deck tank system. The cages provided easy access to individual sea scallops for monitoring and reduced the amount of movement within tanks due to wave action, thereby reducing the risk of additional trauma. Given the range of sea scallop sizes monitored via the holding tanks, occupancy in a given cage was kept at a low overall mass to minimize additional tank-related stress. Individual sea scallops were held for up to 140.6 h per cruise and were monitored for mortality at hourly intervals. Moribund animals were removed from the deck tank system and the time of death recorded. Sea scallops that survived for the duration of a retention trial were released. This protocol generated longitudinal data consisting of both right-censored (sea scallops released alive at the end of a cruise for which the eventual time of death is unknown) and uncensored (the time of death for sea scallops that died during captivity) observations (Benoît et al. 2012, 2015). In addition to the sea scallops in the holding tank group that were monitored for mortality, there were 14,000 sea scallops in the release group that were released immediately once a shell height measurement was recorded and the vitality assessment was completed.

Vitality Assessment

Sea scallops in both the holding tank group and release group underwent a vitality assessment to characterize overt physical trauma and degree of vigor by employing semiquantitative scales of shell damage and behavioral response (i.e., a whole-animal indicator of compromised physiological state; Raby et al. 2012) to handling and probing (Davis 2002; Davis and Ottmar 2006; Benoît et al. 2012, 2015; Capizzano et al. 2016). The assessment is based on ordinal categories, such that a sea scallop assigned a shell damage or response code of 1 was considered healthy, while a sea scallop assigned a shell damage or response code of 5 was considered moribund. Shell damage was assessed by visual inspection of the shell, and sea scallops were assigned a damage code based on the degree of observed shell damage (Figure 2). Sea scallops were also assigned a response code by first observing an animal's response to handling for several seconds. If no response was observed, the mantle tissue was stimulated with a probe in an attempt to elicit a response (Table 1). These predetermined responses were determined in prior

TABLE 1. Classification scheme for sea scallop responses, including the number of sea scallops assessed for each response code.

Response class	Response code	Response description	Stimulus	Number of observations
Excellent	1	Clapping prior to contact, closed shell that will not open	Probe	1,023
Good	2	Clapping during handling	Not required	328
Fair	3	Clapping in response to probing the mantle	Probe	77
Poor	4	No clapping, but mantle slightly retracts in response to probing the mantle	Probe	291
Moribund	5	Shell opens or is open and no response to probing the mantle	Probe	198

laboratory trials (based on Davis 2010) wherein various behaviors (e.g., clapping or mantle retracting) were observed and then assigned an ordinal response code that was indicative of the degree of health or vigor.

Analysis

Vitality condition.— While the vitality indicators selected to populate the sea scallop vitality evaluation were both intuitive (shell damage) and based upon laboratory trials (response), an objective of the study was to determine if they predicted sea scallop mortality. Kaplan–Meier survival analysis was used to evaluate the hypothesis that the assigned levels of shell damage and response to stimuli accurately reflected declines in sea scallop vitality and could be used as predictors of mortality. Kaplan–Meier analysis is a nonparametric analysis that allows for the estimation of the probability of survival as a function of time that accounts for right-censored data (Kaplan and Meier 1958). We visually evaluated Kaplan–Meier survival curves for levels of shell damage and response to assess the validity of shell damage and response codes as indicators of sea scallop health. Evaluation included the assessment of whether (1) all vitality codes had distinct Kaplan–Meier survival curves, (2) the survival curves reached an asymptote supporting a short-term equilibrium of the mortality associated with the capture and handling process, and (3) that survival scaled inversely with damage and response codes. Log-rank tests tested for significant differences in Kaplan–Meier curves for distinct shell damage and response codes (Cox and Oakes 1984).

Analysis of survival data.— The final objectives of the study were to estimate fishery-scale short-term discard mortality and model the effects of additional predictors on short-term discard mortality via survival mixture models. These objectives were addressed by analyzing shell damage class data along with accompanying environmental, biological, and operational variables collected during the field study.

Survival mixture models.— Survival mixture models are parametric models developed for application in fisheries by Benoît et al. (2012) and have been adapted to estimate discard mortality for a range of species and fisheries (e.g., Capizzano et al. 2016; Morfin et al. 2017; Knotek et al. 2018). An advantage of these models is that they can be generalized to account for various types of discard mortality, have a flexible functional form, and are suitable for both censored and uncensored observations (Benoît et al. 2012, 2015). They are used here to estimate code-specific discard mortality because they can estimate mortality at the asymptote of the survivorship curve, even if that asymptote has not been fully reached. In contrast, the Kaplan–Meier estimator only provides an estimate of survival at the end of the survival-monitoring period, where the asymptote may not have been reached.

The general form of a survival mixture model is a survival function comprising a mixture of released animals that are harmed as a result of the capture and handling

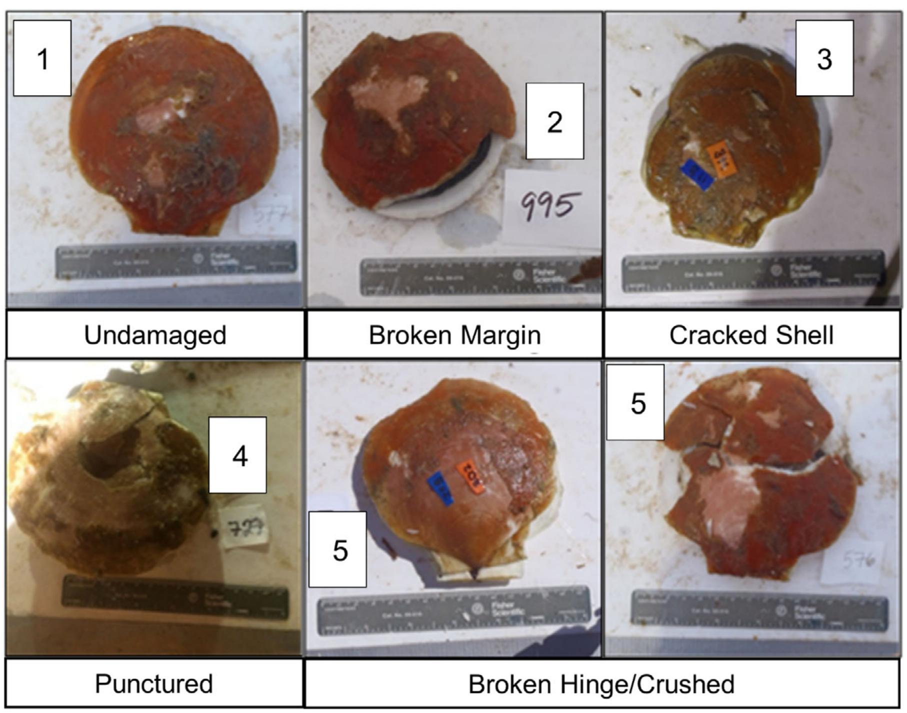

FIGURE 2. Shell damage codes assessed as part of the vitality assessment, including a description of shell damage and the ordinal damage code assigned to each shell damage class.

process and ultimately die and animals that are unaffected by this process (Benoît et al. 2012, 2015). The general model is defined as follows:

$$S(t) = \pi \bullet \exp[-(\alpha \bullet t)^{\gamma}] + (1 - \pi), \tag{1}$$

where $S(t)$ is the survival probability at time t, π is the probability that an animal was negatively impacted by the capture and handling process and provides an estimate of the discard mortality, $\exp[-(\alpha \bullet t)^{\gamma}]$ is the survival function for negatively affected sea scallops, and α and γ are the scale and shape parameters of the underlying Weibull function (for a complete description see Benoît et al. 2012). Benoît et al. (2012) developed six survival mixture model variants with differing assumptions regarding the α and π parameters. The survival mixture model variants are flexible and allow for different interpretations of the survival function by allowing the effect of a vector of a covariate (i.e., shell damage) to be parameterized as a function of either α or π or both parameters.

Development of the survival mixture models to evaluate discard mortality began with the construction of a suite of models as a function of shell damage class. A second set of survival mixture models was constructed to incorporate operational, environmental, and biological factors in an attempt to understand the effect of these covariates on discard mortality (Capizzano et al. 2016; Morfin et al. 2017). The nonparametric Kaplan–Meier analysis was then used to assess model fit by comparing the predicted survival mixture model survivor functions to the Kaplan–Meier survival estimates with 95% confidence intervals. Goodness of fit was assessed by the estimated survival mixture model survival function falling within the bounds of the Kaplan–Meier confidence intervals. Based on findings from the initial Kaplan–Meier analyses, asymptotic mortality did not correspond in rank order relative to ascending response code, indicating that the classification scheme did not provide a reliable indicator of discard mortality (e.g., response code 3 had the greatest probability of survival and response code 5 had a higher survival rate than response code 4; Figure 3). As a result of this misspecification of response codes, subsequent analyses of the data included only shell damage code.

To model fishery-scale short-term discard mortality as a function of shell damage code, we fit four variations of Benoît et al.'s (2012) survival mixture models to determine which model or models provided the best fit to sea scallop survival data. Utilizing a maximum likelihood approach, the four models fit to the data were the Weibull model, mixture model 2, mixture model 3, and mixture model 4 (Table 2; Benoît et al. 2012). Discard mortality rates were calculated using the estimated shell-damage-code-specific survival rates estimated from what was identified as the single preferred survival mixture model based on Akaike information criterion (AIC) (Burnham and Anderson 2002). The overall survival rate was estimated as the average of these estimates, weighted by relative frequency of shell damage codes collected from the release group (see Benoît et al. 2012 for details). Variability in the survival rate was estimated via Monte Carlo simulations based on bootstrapping (Efron and Tibshirani 1993; for an application to discard mortality see Benoît et al. 2012; Sulikowski et al. 2018). For each iteration, a multistep process of randomly selecting, with replacement, tows and then sea scallops within tows populated the frequency distribution of shell damage codes in the fishery and described the within-haul variability for shell damage. Values for the parameters of the survival mixture models were simulated using a parametric bootstrap by drawing values from a multivariate normal distribution based on the estimated parameters and covariance matrix from the preferred survival mixture models. These parameter values were used to estimate shell-damage-specific survival, with an overall survival rate estimated as described above. Confidence intervals were taken as the 2.5th and 97.5th quantiles of the simulated set of overall survival rate values. All analyses were completed with R 3.3.2 (R Core Team 2016).

Another objective of the study was to develop survival mixture models incorporating additional factors to understand the effects of commercial fishing practices, sea scallop biology, and environmental conditions on discard mortality. Covariates considered to be potentially important to the discard mortality process were shell damage, bottom substrate type, tow duration, sea scallop catch, depth, shell height, total exposure time, air temperature, sea surface temperature, bottom temperature, and thermal gradient (difference between bottom and air temperatures). All temperature variables were found to covary significantly; consequently, only air temperature was selected to be retained in model building as sea scallops have a known thermal tolerance (Stewart and Arnold 1994) and air temperature is a more available data source to collect compared with bottom temperature. Air temperature, shell height, sea scallop catch, and total exposure time were continuous variables but were binned to facilitate model building and assessment of survival mixture model goodness of fit, as well as to represent management-relevant benchmarks for potential future regulatory or best-practices guidance. For comparison, models were also evaluated (with results included in the Supplemental Materials available separately online) with these factors entered as continuous. Thus, all potential covariates were modeled as categorical variables with a different number of levels for each, ranging from two to five levels (Table 3). Length-bin classification was based on the 2014 stock assessment that indicated the commercial fishery generally discards sea scallops less than 9 cm (NEFSC 2014).

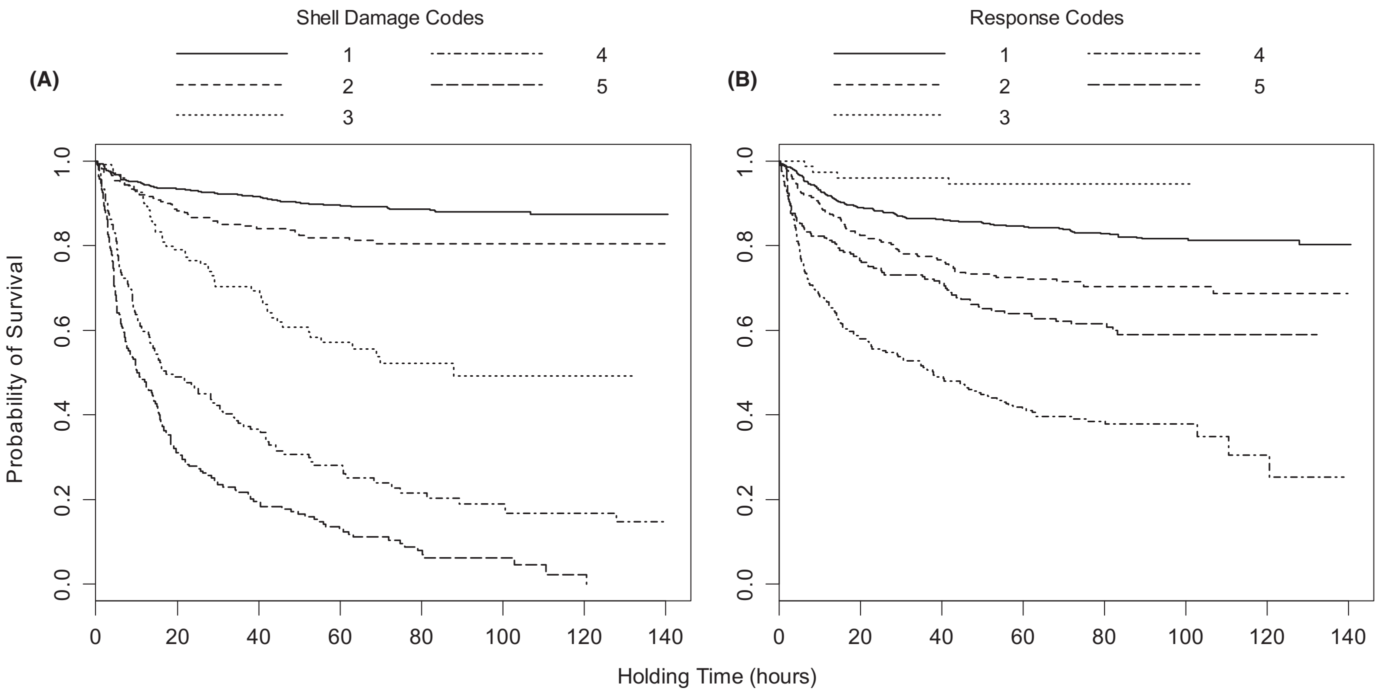

FIGURE 3. Kaplan–Meier survival curves for **(A)** shell damage codes and **(B)** response codes as a function of holding time.

TABLE 2. Survival mixture models used to model the probability of survival as a function of shell damage code with assumptions for parameters α and π (taken from Benoît et al. 2012).

Model	α	π	Interpretation
Weibull 2	$\exp(-X'\beta)$	1	Common survival function within each vitality class
Mixture 2	$\exp(-X'\beta)$	Constant	Common survival function within each vitality class for a fixed proportion of affected animals
Mixture 3	Constant	$[1+\exp(-X'\beta)]^{-1}$	Common survival function for affected animals, with the proportion affected dependent on vitality class
Mixture 4	$\exp(-X'\beta_1)$	$[1+\exp(-X'\beta_2)]^{-1}$	Common survival function within each vitality class, where the proportion of affected individuals also depends on vitality class

Bottom type was categorized as soft or hard bottom based on the vessel captain's knowledge of the type of bottom where a tow was being completed. The bins for the remaining factors (air temperature, sea scallop catch, and exposure time) were reflective of the experimental design that approximated commercial fishing conditions, and while the bins were defined by the distribution of the data, this corresponded to operational characteristics in the fishery. Log-rank tests were used to test for differences in survivorship between levels of the categorical variables (Cox and Oakes 1984). Results indicated significant differences between levels for all variables, with the exception of depth ($\chi^2 = 1.4$, df = 2, $P = 0.5$) and tow duration ($\chi^2 = 4.5$, df = 2, $P = 0.1$). The six final candidate covariates included in model development were as follows: shell damage class (five levels), bottom type (two levels), sea scallop catch (three levels), air temperature (three levels), shell height (two levels), and total exposure time (three levels) (Table 3). Based upon the hypothesis that extended areal exposure at high temperatures would impose increased physiologic challenge, an interaction of exposure time and air temperature was also explored for a model variant, with the two terms as main effects. Models were developed with stepwise forward selection, with covariates added to an intercept-only model (Venables and Ripley 2002). A covariate was retained in the full model if the difference in the AIC value was reduced by a minimum of three units (following Capizzano et al. 2016). The model with the lowest AIC or models with AIC values within three units of each other were selected as the optimal model(s).

Stepwise forward selection was used for model development because it was not feasible to fit all possible model combinations given that fitting nonlinear survival mixture models requires individual model validation.

RESULTS

Field Study Characteristics

Over eight cruises, 460 tows were completed across the resource area, with an average trip duration of 7 d (Figure 1). Cruises occurred in August and October of 2014 and May, June, July, August, and December of 2015. The number of tows completed per cruise varied from 44 to 93, as did the number of sea scallops sampled. The majority of tows (82%) occurred on soft substrate ($n = 1{,}926$), compared with 18% ($n = 431$) of tows completed on hard substrate. Summary data for tow duration, sea scallop catch, thermal gradient, depth, shell height, and exposure time included as covariates in survival mixture models are included in the Supplemental Materials.

Vitality Assessment

Most sea scallops were assigned a shell damage code of 1 (i.e., "undamaged"; Figure 2; Table 4) and a response code of 1 ("excellent"; Table 1). Results from the log-rank test indicated significant differences in survivorship between all shell damage codes and response codes. Kaplan–Meier survival estimates for shell damage were distinct and reached, or approached, an asymptote, suggesting that the holding time was of sufficient duration to capture short-term discard mortality for each class (Figure 3). Shell-damage-specific Kaplan–Meier survival curve asymptotes varied inversely with the shell damage codes as expected (Figure 3).

Analysis of Survival Data

Model selection for the survival mixture models that estimated shell-damage-specific short-term discard mortality indicated that the preferred model was mixture model 4 (Table 5). This model returned the lowest AIC and produced the best fit to sea scallop survival data for the five shell damage codes as supported by visual correspondence with Kaplan–Meier curves (Figure 4). Damage-code-specific survival rates varied inversely with damage code, ranging from 0.87 for undamaged sea scallops (shell damage code 1) to 0.02 for sea scallops with crushed shells and broken hinges (shell damage code; Table 6). Model fit and wide confidence intervals for shell damage code 3 (cracked shell) suggests that mortality may not have reached an asymptote; however, this damage code represented the lowest sample size in the study (Table 4). Conversely, shell damage code 1, with the largest sample size (63.6% of total), and to a less extent code 2, returned estimates that were much more precise than those of more severely damaged sea scallops. Because sea scallops with damage codes 1 and 2 were prevalent in the fishery (Table 4), this high precision was carried through to the estimated overall fishery-scale short-term survival estimate of 0.79 (95% CI = 0.77–0.82).

The analysis that explored the effects of environmental, biological, and operational covariates on survival resulted in a preferred model that included the effects of shell damage and exposure time (Table 7; see Supplemental Materials for the comparative model that incorporated the covariates [air temperature, scallop catch, exposure time] as continuous variables). Both covariates affected both the scale of the survival curve (α) as well as the probability that a sea scallop would be negatively impacted by the capture and handling process (π). Parameter estimates are provided in Table 8. The addition of other explanatory variables did not result in a further decrease in AIC.

TABLE 3. Description of bins for continuous variables for survival mixture model analysis with additional variables. Sample sizes for the number of sea scallops included in each bin are in parentheses.

Variable	Bin 1	Bin 2	Bin 3
Shell height	≤9 cm (1,202)	>9 cm (1,155)	
Exposure time	≤10 min (368)	>10 min and ≤30 min (1,588)	>30 min (401)
Air temperature	>−7°C and ≤13°C (600)	>13°C and ≤18°C (667)	>18°C (1,090)
Bottom type	Soft (1,926)	Hard (431)	
Scallop catch	≤5 baskets (831)	>5 and ≤10 baskets (839)	>10 baskets (687)

TABLE 4. Samples sizes for sea scallops assessed for shell damage for the holding tank and release groups, with the percent of the total.

Type	Shell damage code and total	Number of scallops	Percent of total (%)
Holding tank group	1	1,499	63.60
	2	331	14.04
	3	137	5.81
	4	171	7.25
	5	219	9.29
	Holding tank group total	2,357	
Release group	1	12,093	86.38
	2	575	4.11
	3	202	1.44
	4	271	1.94
	5	859	6.14
	Release group total	14,000	

TABLE 5. Survival mixture models for survival analysis as a function of shell damage condition, with AIC and ΔAIC values.

Model	AIC	ΔAIC
Mixture model 4	6,542.98	0
Mixture model 3	6,554.91	11.93
Mixture model 2	6,740.91	197.59
Weibull model	6,813.03	269.71

Discard mortality increased as a function of more severe shell damage and increasing exposure time (Figure 5). Sea scallops classified with shell damage code 5 not only had the lowest probability of survival but also exhibited the shortest time before mortality was observed. There was considerable uncertainty in the discard mortality estimates for extended exposure times, likely as a function of lower samples sizes, especially for animals with the most severe shell damage (i.e., shell damage codes 3–5). Increased exposure time resulted in higher discard mortality, and prolonged exposure times resulted in the lowest survival across all shell damage classes (Figure 5).

For several combinations of covariate factor levels (e.g., exposure time ≥30 min and shell damage codes 2–5), there were a small number of observations or no observations (Figure 5; see Supplemental Materials). These low samples sizes resulted in wide confidence intervals for several shell damage Kaplan–Meier survival estimates. This issue was especially apparent for the longer duration of exposure time (≥30 min). As the observations were partitioned into combinations of factor levels by damage code, this sample size became further reduced. In a small

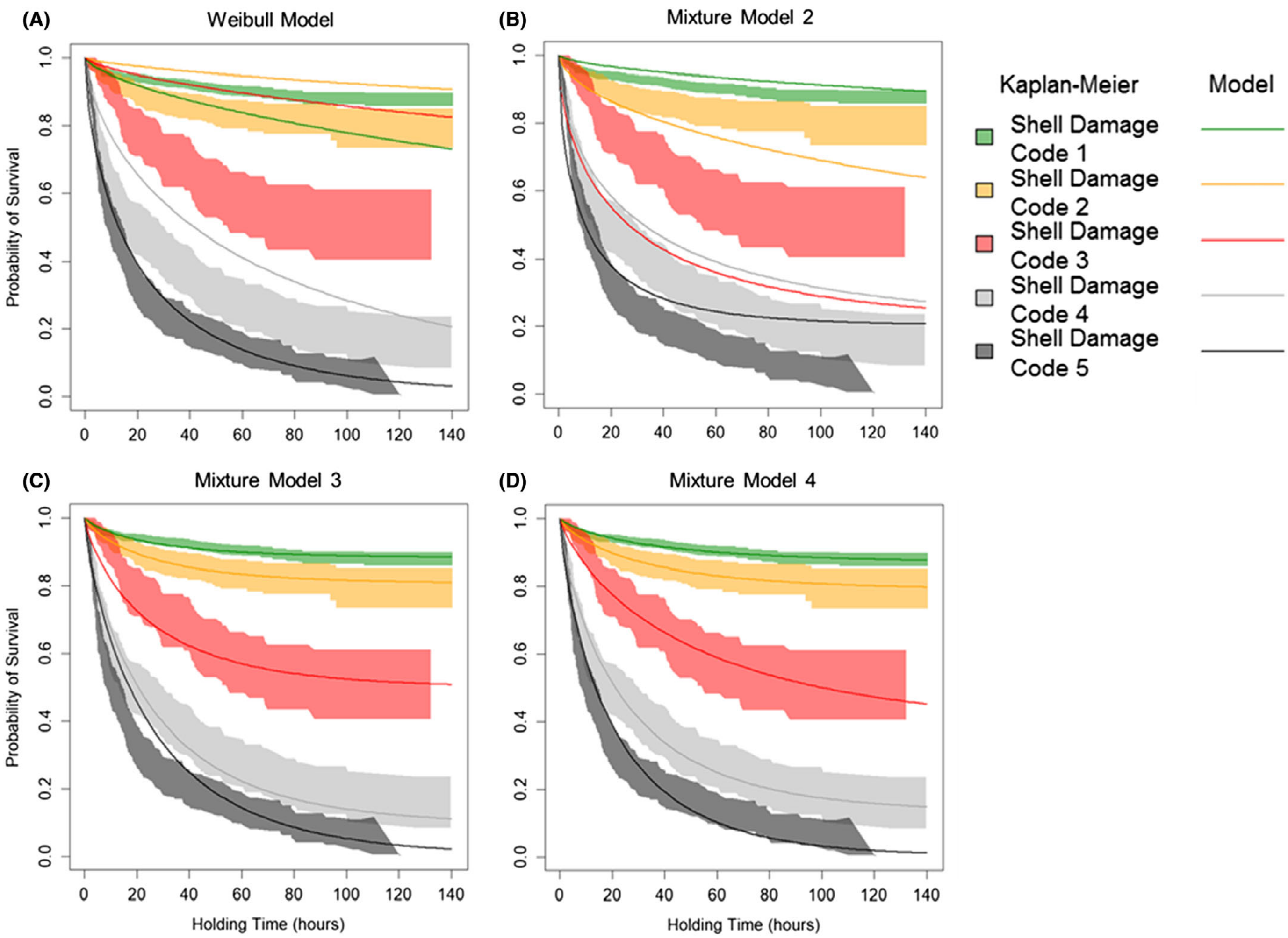

FIGURE 4. Plots of the Kaplan–Meier survival estimates and survival mixture model estimates for the probability of survival as a function of shell damage code by survival mixture model, showing the **(A)** Weibull model, **(B)** survival mixture model 2, **(C)** survival mixture model 3, and **(D)** survival mixture model 4. The Kaplan–Meier estimate is the 95% confidence interval (shaded areas) for each shell damage code. The survival mixture model estimates are the solid lines (line color indicates shell damage code).

TABLE 6. Fisherywide mean survival estimates for overall survival and survival by shell damage code, with 95% confidence intervals in parentheses.

Overall survival and shell damage code	Estimate
Overall survival	0.79 (0.77–0.82)
Shell damage code 1	0.87 (0.84–0.89)
Shell damage code 2	0.78 (0.71–0.84)
Shell damage code 3	0.32 (0.11–0.65)
Shell damage code 4	0.13 (0.07–0.24)
Shell damage code 5	0.02 (0.0–0.15)

number of cases, model predictions did not correspond well to the Kaplan–Meier confidence intervals. The survival mixture model estimates for shell damage condition code 3 at the upper bound of holding times were at the lower end of the Kaplan–Meier confidence interval for all exposure times (Figure 5). In addition to being at the lower bound of the Kaplan–Meier confidence intervals, the predicted survival mixture model survival curves did not appear to reach an asymptote, suggesting that mortality did not reach an equilibrium for these combinations of covariate levels. At exposure times less than or equal to 10 min and shell damage condition code 1, the survival mixture model estimate was lower than the Kaplan–Meier confidence interval for the entire range of holding times (Figure 5A).

DISCUSSION

A typical objective of a fishery stock assessment is the description of total fishing mortality (Hilborn and Walters 1992). Nonharvest mortality, where an animal suffers mortality but is not accounted for in the catch, can represent a significant source of the total fishing mortality for some species and gear types (Broadhurst et al. 2006). For a towed gear, nonharvest mortality can be partitioned into two separate processes. One process entails an individual encountering the gear but not being captured (i.e., incidental mortality). While often difficult to measure in the field, some studies have been able to estimate incidental mortality rates empirically (Medcof and Bourne 1964; Caddy 1973; Murawski and Serchuk 1989; McLoughlin et al. 1991; Ferraro et al. 2017; Patterson et al. 2017). The other component of the nonharvest mortality process results from an animal being captured and subsequently discarded (i.e., discard mortality; Broadhurst et al. 2006).

The current study examines the discard component of nonharvest mortality, and our experimental results suggest that sea scallops are robust to the capture and handling process in the U.S. sea scallop dredge fishery. We estimated a discard mortality rate of 21% with a 95% confidence interval of 18% to 23%, which aligns with the value currently used in the stock assessment. Prior studies for this species have produced estimates of discard mortality ranging from 10% of tagged sea scallops along the Mid-Atlantic Bight to around 15% in the Canadian Maritimes (Medcof and Bourne 1964; Murawski and Serchuk 1989; NEFSC 2010, 2014, 2018). While the discard mortality estimates from these two studies were lower relative to the present study, Medcof and Bourne (1964) only characterized sea scallops that were suffering from what they characterized as lethal damage (analogous to our shell damage categories 3–5) and as such only characterized the at-vessel mortality component of the process. It is likely that some level of cryptic mortality exists as was shown by low levels of observed mortality in the present study for shell damage codes 1 and 2. Murawski and Serchuk (1989) took a slightly different approach with tagged sea scallops, but it was unclear as to whether compromised sea scallops (i.e., suffering from trauma resulting in shell damage) were selected for inclusion in the experiment. If sea scallops that corresponded to our shell damage code 1 were

TABLE 7. Survival mixture models for survival mixture model 4 analysis incorporating additional covariates, with AIC and ΔAIC values. The columns labeled π, α, and π and α indicate where the covariate was incorporated into the model. Model 4 is shown in bold italics and was the preferred model.

Model	Variables	π	α	π and α	AIC	ΔAIC
1	~ 1				7,414.43	984.11
2	~ 1 + shell damage			Shell damage	6,542.98	112.66
3	~ 1 + shell damage + shell height			Shell damage + shell height	6,543.23	112.91
4	***~ 1 + shell damage + exposure time***			***Shell damage + exposure time***	***6,430.32***	
5	~ 1 + shell damage + exposure time + air temperature			Shell damage + exposure time + air temperature	6,542.99	112.67
6	~ 1 + shell damage + exposure time + scallop catch	Scallop catch		Shell damage + exposure time	6,547.20	116.88
7	~ 1 + shell damage + exposure time + bottom type	Bottom type		Shell damage + exposure time	6,440.68	10.36

TABLE 8. Parameter estimates with standard errors (SEs) for the preferred survival mixture model 4 for both α and π.

Parameter	Variables	Value	SE
	Gamma	–0.25	0.04
α	Shell damage code 1/exposure bin 1	3.41	0.32
	Shell damage code 2	1.19	0.70
	Shell damage code 3	0.70	0.43
	Shell damage code 4	–0.33	0.29
	Shell damage code 5	–0.68	0.28
	Exposure bin 2	0.35	0.20
	Exposure bin 3	0.40	0.26
π	Shell damage code 1/exposure bin 1	–3.08	0.32
	Shell damage code 2	1.76	0.78
	Shell damage code 3	3.69	0.87
	Shell damage code 4	4.66	0.48
	Shell damage code 5	7.15	1.89
	Exposure bin 2	0.68	0.32
	Exposure bin 3	2.66	0.39

exclusively used in the tagging experiment, then our estimate of 13% mortality for sea scallops with shell damage code 1 aligns much closer with what was reported by Murawski and Serchuk (1989). Given these considerations, the reported values in Medcof and Bourne (1964) and Murawski and Serchuk (1989) should be treated as minimum estimates and, as such, are in general agreement with the discard mortality rate reported here.

The family Pectinidae is generally characterized by high survival during the capture and handling process despite being the focus of worldwide fisheries across a wide range of environments, gear types, and operational characteristics. Despite differences among sea scallop habitats and fisheries, physical damage as a function of the capture and handling process and areal exposure represented common factors identified as important for describing sea scallop discard mortality. The European king scallop *Pecten maximus* has been shown to have low nonharvest mortality (a combination of discarding and animals that contact the dredge but are not captured) between 2% and 20%, primarily as a result of physical damage inflicted by the dredge (Jenkins et al. 2001; Beukers-Stewart and Beukers-Stewart 2009). In addition to the interaction with the gear as a focal point for trauma, the postcapture selection of animals for processing has the potential to exacerbate health implications that can negatively impact survival. The current study identified areal exposure duration as an important factor in the probability of sea scallop survival. Given this cross-cutting characteristic, operational approaches to reduce areal exposure have been effective in reducing discard mortality. Catch sorting with a mechanical tumbling device that encourages reductions in exposure time has been shown to increase survival rates for trawl-

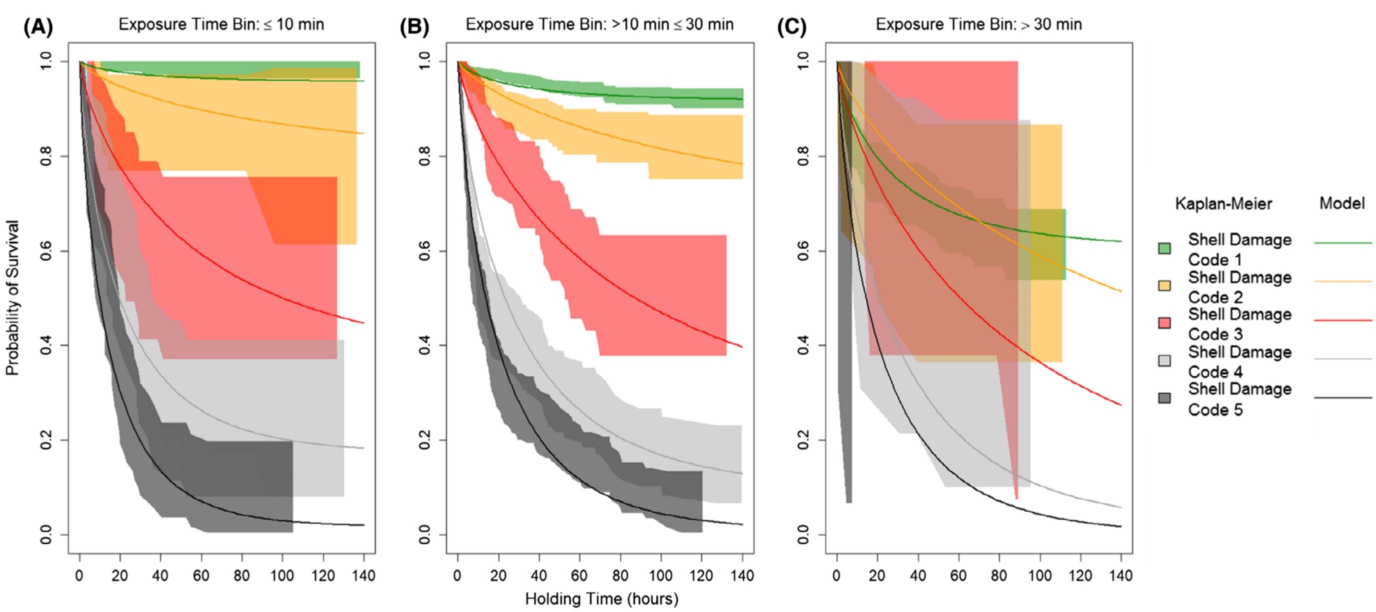

FIGURE 5. Plots of the Kaplan–Meier survival estimates and survival mixture model 4 estimates for the probability of survival as a function of exposure time and shell damage code, showing **(A)** exposure time ≤10 min, **(B)** exposure time >10 min but ≤30 min, and **(C)** exposure time >30 min. The Kaplan–Meier estimate is the 95% confidence interval (shaded areas) for each shell damage code. The survival mixture model estimates are the solid lines (line color indicates shell damage code).

captured Patagonian scallop *Zygochlamys patagonica* (Bremec et al. 2004). A similar method for size selection is also employed in the Queensland Australia fishery for saucer scallop *Ylisstrium balloti*, with high levels of survival (>95%) after one trawl, although repeated capture and handling events were found to reduce scallop survival (Campbell et al. 2010).

While sea scallops are harvested worldwide, individual fisheries often operate over broad spatial and temporal scales, and given the potential range in both biotic and abiotic factors that animals encounter, understanding factors that might influence discard mortality is important. The U.S. sea scallop fishery operates year-round, and the resource areas encompass two zoogeographic regions that are subject to extremes in both water and air temperature (Bigelow 1933). Stewart and Arnold (1994) report a lethal water temperature for sea scallops at 21°C. During the summer months, surface water and air temperatures on the deck of vessels can routinely exceed this threshold. Dredge gear is typically retrieved quickly through the water column; however, extended periods of air exposure on deck can subject animals to high temperatures and desiccation. The present study did not identify air temperature as a significant factor in the discard mortality process, and the model that included the interaction between air temperature and exposure time did not converge. Given the effect of exposure time and the reported threshold of thermal tolerance for the species, these two factors may have a synergistic effect on sea scallop survival outside the bounds of the variables measured in the study.

Model output supports exposure time as an important factor in the discard mortality process, and extended time on deck resulted in a negative impact on survival. Exposure time typically leads to a decreased probability of survival across taxa, and this effect has been documented for other marine species ranging from groundfish to crabs (Benoît et al. 2013; Urban 2015; Methling et al. 2017). Sea scallops typically settle in areas of high density that can lead to increased catch volumes due to a breakdown of the selective characteristics of the gear, extending sorting times on deck (Yochum and DuPaul 2000; Roman and Rudders 2019). This extended time on deck can result in higher discard mortality due to longer exposure time. Discarding in this scenario has been implicated as the contributing factor to the mortality of 10 billion juvenile sea scallops from a spatially managed area along the Mid-Atlantic Bight (Stokesbury et al. 2011). Hart and Shank (2011) dispute the finding that discarding was the major causative factor in the reduction of sea scallop abundance in the area as the scale and characteristics of the loss were neither consistent with the selective characteristics of the commercial dredge gear nor corroborated by observer data (that suggested 319 million sea scallops were discarded). The all-time high of observed discards (2,504 metric tons) and the discard mortality rate describe in the current work also do not fully support that discarding alone was responsible for the disappearance of 10 billion juvenile sea scallops.

The ability to monitor the fate of discarded sea scallops for up to 7 d permitted the characterization of short-term mortality. This duration allowed us to reach an asymptote for survival of the sea scallops retained in the deck tank system. While this duration of retention was sufficient for the stabilization of mortality associated with the catch and handling process, additional sources of mortality may exist that were outside of the scope of this study. Increased predation rates by multiple taxa on discarded sea scallops have been observed (Veale et al. 2000; Jenkins et al. 2004). This may be potentially important for sea scallops as predators are attracted to fishing activities in general, which may be intensified in sea scallop fisheries due to hand shucking procedures at sea where only the adductor muscle is retained and the shell and viscera are returned to settle to the seafloor. Hart and Shank (2011) suggest that the loss of 10 billion sea scallops during the reopening of a spatial management area that received high levels of fishing (i.e., in the Mid-Atlantic Bight) was due to an increase of natural mortality due to this predation. In addition to predation, the effect of multiple capture events was not explicitly examined in this study. In areas with commercial quantities of sea scallops, typical fishing practices may consist of multiple vessels operating in small areas for extended durations. This implies that sea scallops may experience multiple capture events over a relatively short time period. While our experiment only examined a single catch and handling process event, the possibility exists that the cumulative impact of multiple catch and handling process events could result in higher mortality rates (Maguire et al. 2002; Campbell et al. 2010). Given these additional sources of potential mortality, the estimates provided should be viewed as a minimum. Future quantification of these components of the discard process would provide a more comprehensive assessment of the full impact that the fishery has on discarded sea scallops.

In this study, we attempted to construct a composite index of sea scallop vitality that consisted of semiqualitative measures of both overt physical trauma (i.e., shell damage) and response to stimuli. Ultimately, the simple shell damage score provided a rapidly assessed metric that correlated to survival. While the scoring system used to delineate likely response to stimuli was predicated during prior laboratory experiments, our results from the field study did not support its use as a reliable predictor of sea scallop mortality. In some cases, the responses that we hypothesized would be correlated with increasing levels of mortality did not produce mortality rates as expected. Given this outcome we relied solely on shell damage as the assessment metric to correlate to survival.

Central to the construction of our response index, sea scallops have evolved an escape response to evade predators wherein many swim through the water column when encountering potential predators (Guderley and Tremblay 2013). We hypothesized that the absence of this response as well as similar physiological manifestations tied to exhaustion would be indicative of an animal that would have a lower probability of survival. Pérez et al. (2008) described the energy utilization of the sea scallop's adductor muscle (i.e., the muscle used during the escape behavior) in response to handling stress and found that while the number and force of contractions were reduced as a result of exhaustion, individuals were ultimately able to recover within hours. This exhaustion did result in a higher vulnerability to predation, but mortality as a function of exhaustion was not materially increased (Maguire et al. 2002). This recovery from exhaustion but not a concomitant increase in mortality may be reflected in the difficulty of our constructed index to accurately predict mortality. Guderley et al. (2008) also found that both the thermal history as well as spawning state were significant factors that impacted the contraction rate and force exerted by sea scallops, which could suggest a seasonality to the ability to recover and subsequently avoid predation after discarding.

In an attempt to capture the current operational and spatiotemporal characteristics of the fishery, we stratified our sampling cruises both seasonally and geographically. The evaluation of over 16,000 sea scallops for condition, with a subset monitored for up to 7 d to characterize mortality, allowed for the inclusion of factors that discarded sea scallops might encounter. While this was representative of current conditions in the fishery, this could change in the future. The use of an index based upon shell damage represents a robust means to assess future discard mortality should changes occur in the fishery. Assuming that the correlation between condition and mortality is conservative across time, this index should represent an easily implementable means to assess mortality whether in the context of a resource assessment survey or via fishery observers to capture a realistic representation of morality across the extent of the fishery. The scalability of this approach has been demonstrated by the utilization of fisheries observers to collect data to inform or estimate discard mortality on the U.S. West Coast for Pacific Halibut *Hippoglossus stenolepis* and has been suggested by the National Marine Fisheries Service in the USA and the International Council for the Exploration of the Sea's Expert Group on Methods for Estimating Discard Survival as a method to improve discard mortality estimates in commercial fisheries (Jannot et al. 2014; Benaka et al. 2016; ICES 2016). In addition to the utility of the index, the important covariates identified by the survival mixture models can be informative for managers and direct both best management practices as well as possible refinements to estimates of spatiotemporally explicit estimates of discard mortality.

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DATA AVAILABILITY STATEMENT

The data underlying this article will be shared on reasonable request to the corresponding author.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.