Abstract

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Evaluating the Condition and Discard Mortality of Winter Skate, *Leucoraja ocellata*, Following Capture and Handling in the Atlantic Monkfish (*Lophius americanus*) Sink Gillnet Fishery.

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Abstract

Discard mortality (DM) estimates are vitally important to fisheries management. Commercial fishery DM estimates, for example, can help calculate total fishing mortality and biologically acceptable catch limits. The winter skate, *Leucoraja ocellata*, is the only species within the US portion of the western North Atlantic that is targeted in the skate wing fishery. However, due primarily to fishery regulations, this species is also routinely discarded at sea when daily quotas are reached. While already examined in mobile fishing gears (i.e. bottom otter trawls), DM has not been addressed in western North Atlantic skate species captured in sink gillnet fisheries, and a conservative 50% DM is therefore used in management processes. Given this uncertainty, we estimated the DM of winter skate in sink gillnets under standard commercial fishing conditions. The study methods we employed addressed the issue of cryptic mortality (drop out of dead skates from the gear and depredation prior to retrieval), which can bias DM estimates low for bycatch in passive gear. The degree of injury sustained during capture and handling was found to be a statistically significant predictor of mortality. Overall mean DM rates reached an asymptote within 170 hrs of captivity, with estimates of 11% and 17% for females and males, respectively. Based on these results, the species appears more resilient to sink gillnet capture and release than previously thought. However, cryptic fishing mortality appeared to be high for extended soak times and likely represents an important focus of future research and management actions.

Key words: discard mortality; post-release mortality, cryptic mortality

1. Introduction

When accounting for harvest, baseline (i.e. under present industry practices) discard mortality (DM) estimates are an integral component of the fisheries management process, including the calculation of total fishing mortality and biologically acceptable catch limits (Alverson, 1999; Davis, 2002). Discard mortality rates are typically estimated in experiments that simulate authentic fishery conditions, followed by observation of the fate of individuals. These observations typically come from containment of experimental subjects (i.e net pens and deck tanks) or result from traditional (tag and recapture) or electronic tagging (acoustic or satellite). When predictors of DM, such as injury and/or vitality indices at the point of capture, are validated from the aforementioned observations, DM rates can quantified at the scale of the fishery (Depestele et al., 2014; Benoît et al. 2012, 2015; Capizzano et al., 2016).

One of seven species managed by the New England Fishery Management Council, the winter skate, *Leucoraja ocellata*, (hereafter referred to as skate) is subject to a directed fishery for its wings in the North Atlantic US waters (hereafter referred to as the skate wing fishery). This species is managed by the use of annual catch limits (ACLs) and accountability measures (e.g., management triggers such as curtailing permissible effort if ACLs for incidentally caught species are exceeded) consistent with the requirements of the reauthorized Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act) (NEFMC 2011). In addition, target species must also be discarded after daily quotas have been satisfied, and when captured incidentally in fisheries targeting other species. On the continental shelf waters adjacent to New England and the mid-Atlantic, sink gillnets are used to target skates, monkfish (*Lophius americanus*), and other species. Skate landings from sink gillnets are second only to those from otter trawl fisheries (https://www.st.nmfs.noaa.gov/commercial-fisheries/index). Although the estimated short-term (72 h) DM of skate captured in otter trawl fisheries appears low (~9%; Mandelman et al., 2013), DM has not yet been examined in sink gillnet fisheries,and a conservative rate of 50% is currently assumed (NEFMC 2003). Given this uncertainty, the objectives of the current study were to quantify the DM rate for skates discarded in the monkfish sink gillnet fishery.

2. Methods

2.1 Study location and design

The study sites were located approximately 32km due south of Newport, Rhode Island in collaboration with a commercial fisherman (Fishing Vessel; *F/V Gertrude*) (Figure 1). The vast majority of reported skate landings originate from the study area, which is easily accessed during single day fishing trips. This area is quite homogeneous with respect to depth, which varies from 105-128 m. Research trips were conducted between the peak commercial fishing seasons of mid-July and mid-October in both 2014 and in 2015. The gillnet gear used in the study was standard monkfish gear consisting of twelve, 91m panels of 30cm mesh netting, strung together, with gillnet height restricted by "tiedowns" (twine looped from the floatline to the leadline and back) resulting in a nominal fishing height of 48 in (122 cm). The gear is fitted with 85 lb (39 kg) lead line, 3/8 inch (10 mm) diameter polypropylene float line, and floats at every 8 ft. (2.4 m) interval. Gillnet floatlines included breakaway links intended to promote the escapement of entangled whales. Gillnet soak times were varied to approximate soak times typical of the monkfish fishery (2 to 5 days), as well as longer soak times that may occur when foul weather prevents net retrieval (up to 14 days) (Fig. 2). A total of 28 fishing trips were conducted over the course of the study.

For each haul, skates were placed in a large onboard container, continuously supplied with fresh seawater. At this time, sea surface (SST) and air temperatures were measured. Individual skates were measured, sexed, tagged with an identifying marker (Floy spaghetti tag) and assigned an injury/vitality score per standards outlined in Mandelman et al. (2013). For example, a skate placed in Category 1 (excellent) will show no signs of apparent morbidity and no overt physical trauma, while a skate placed in Category 3 (overt physical trauma, listless, or moribund) will have already succumbed or be predicted to suffer mortality from the sink gillnet capture. Two motor reflexes were also assessed as possible predictors of DM (e.g. Davis, 2010): a gag reflex (following the insertion of a small probe in the skate's mouth) and back fly reflex (skate were held by the tail in the air and assessed for wing beats). These reflexes have previously been shown to be appropriate predictors of DM in skates captured incidentally in scallop dredges (Knotek et al., 2015). Skates were selected for captivity trials in a generally random manner, though skates in injury category 3 were disproportionately selected to ensure sufficient sample size.

Skates were then transferred from the deck tanks into partially submerged net pens which were then slowly lowered to the seafloor (exclusively on mud substrate to reduce the likelihood of amphipod/isopod (i.e., "sand fleas") infestation) for periods of captivity that varied between 72 and 285 hrs. To maximize surface area on the seafloor and reduce the likelihood of dislodgement, circular net pens (diameter of bottom ring = ~1.8 m; diameter of upper ring = ~1.2 m; height = ~0.9 m) were utilized, based on a modified crab pot design (Burkes Custom Metal Works, PEI, CA). Each pen was also outfitted with a special mesh bottom designed to further reduce potential for sand flea infestation. Fifteen individuals were held in each pen during each trial. When the pens had reached biomass capacity, additional skates captured in a given haul were assigned an injury/vitality score, tagged and released back to the ocean. Following the captive period, net pens were retrieved to evaluate the mortality outcome of individual skates (alive/dead), then all surviving animals were released.

2.2 Analysis

2.2.1 Winter skate bycatch numbers

Our first objective was to estimate bycatch per unit effort ((BPUE); numbers per gill net panel per haul) of skate caught in gear associated with the monkfish fishery. Of particular importance was to assess how soak time affects BPUE because of the possibility of drop out losses of dead skate at longer soak times. Such drop outs occur as scavengers or detritivores consume dead individuals to the point of diminishing their retention in the net (Uhlmann and Broadhurst, 2015; Gilman et al., 2013). Losses of dead skate from gillnets prior to retrieval will result in an underestimation of incidental fishing mortality and must be taken into account in the mortality analyses described later. Thus, in our analyses, we considered not only the impacts of fishing conditions (e.g. season, depth, seawater and air temperature), but also the impacts of the demographic characteristics (e.g., size, sex) of captured skates.

A Poisson generalized linear mixed model (GLMM) was used to model skate catches in each gillnet panel of each unique haul. The full (saturated) model was of the form:

$$C_{ij} \sim Poisson(\mu_j) \qquad (1)$$

$$\mathrm{E}\left[C_{ij}\right] = \mu_j \quad \text{and} \quad \mathrm{var}\left[C_{ij}\right] = \mu_j \qquad (2)$$

$$\mu_j = \exp\left(\alpha + soak_j + depth_j + SST_j + a_j\right) \text{ where } a_j \sim N(0, \sigma^2_{Haul}) \qquad (3)$$

where C_{ij} is the number of skate caught in panel i of gillnet haul j, α is an intercept term, $soak_j$ is a factor for soak time, $depth_j$ and SST_j are the effects of depth (m) and SST(^{o}C) both treated as covariates, and a_j is a random effect for haul which has a variance σ^2_{Haul}. Because the nets are fished on the bottom, the water column depth is the fishing depth. Note that SST and air temperatures were unsurprisingly highly correlated (r=0.71), and only SST was used in the analyses. The random effect accounts for the effect on BPUE of factors not included in the model, such as differences between hauls in the local density of skate and their catchability to the gear. Soak time (integer days) was included as a factor in the model because its effect on BPUE was expected to be non-linear given that it reflects a balance between likely time-varying capture and loss rates of skate to the gear. Given the small range of values for SST and depth, no interactions between variables were included in the saturated model.

Prior to the analysis, the explanatory variables of the saturated model were examined for extreme values that may cause leverage effects, collinearity and potential non-linear relationships with mortality. No issues were identified. Beginning with a random-effect only model, forward selection using Akaike's Information Criterion for small sample size (AICc; Burnham and Anderson, 2002) was used to select the most parsimonious model(s). The number of hauls was used as the sample size in calculating AICc as the covariates were measured at the haul level. Models with the same number of parameters that were within 2 AICc units of each other were viewed as having equal support in the data. Additional covariates were only retained if they reduced AICc by 2. Pearson residuals from the selected models were used to check for possible overdispersion in the data and to assess model fit following Zurr et al. (2009).

2.2.2 Winter skate bycatch mortality

Initial checks of potential explanatory variables for the DM analysis were undertaken as described above for the analysis of BPUE. A small cluster of skate with outlying lengths (<35 cm; Fig. 3) were removed from the analysis to avoid possible leverage effects. Based on the results of the analyses of skate bycatch numbers, skates from hauls with a soak duration exceeding 6 days were also removed from the analysis to minimize introducing bias to the mortality estimates due to the drop-out of dead skates. With these modifications, there were 280 skates for which mortality outcomes were known.

An examination of the relationship between mortality and the duration of skate captivity for mortality assessment is important because, all else being equal, an asymptote in survivorship should be observed to ensure full accounting of DM (Davis 2002; Benoît et al. 2015). The duration of captivity was treated as a three-level factor given that captivity times were clustered around 3 sets of values 72-96 hrs (mean 75 hrs), 170 hrs and 285 hrs. Also, data for captivity times between 92-96 hrs were grouped with those with times of around 72 hrs because there were no observed mortalities in the former group, which prevented estimating a unique parameter in the model described below.

There was little evidence for collinearity among covariates; all variance inflation factor values were <1.3. All continuous covariates were standardized to zero mean and unit variance to improve model convergence and to facilitate interpretation of effect sizes.

The basic response variable was the mortality outcome of individual skate (alive/dead) following the captive holding period. This motivated the use of a Bernoulli GLMM to analyze that outcome as a function of environmental, experimental and biological factors, and as a function of the health indicators. The saturated model was of the form:

$$Y_{jkl} \sim Bernoulli(\pi_{jkl}) \quad (4)$$

$$\mathrm{E}\left[Y_{jkl}\right] = \pi_{jkl} \text{ and } \quad \mathrm{var}\left[Y_{jl}\right] = \pi_{jkl}(1 - \pi_{jkl}) \quad (5)$$

$$\mathrm{logit}\left(\pi_{jkl}\right) = \alpha + soak_j + depth_j + SST_j + Sex_{jkl} + TL_{jkl} + CT_{jl} + Inj_{jkl} + Back_{jkl} + Gag_{jkl} + a_j + b_{l|j} \text{ with } a_j \sim N(0, \sigma^2_{Haul}) \text{ and } b_{l|j} \sim N(0, \sigma^2_{pen|Haul}) \; (6)$$

where Y_{jkl} is the mortality outcome for individual skate k in haul j and held in pen l which is nested in haul j. The terms α, $soak_j$, $depth_j$ and SST_j are as described above., Sex_{jkl} ,TL_{jkl}, Inj_{jkl}, $Back_{jk}$, Gag_{jk}, and CT_{jl} are respectively the effects of sex, total length (cm), injury ($Inj_{jk} \in (1,2,3)$), reflex responses for the back-fly and gag tests, and captive time (hrs) for skate k in haul j and pen l. As in the analysis of catch numbers, a_j is a random effect for haul, and in addition there was also a random effect, $b_{l|j}$, for the pen used to contain skates from a particular haul

Forward selection based on AICc was used to select the most parsimonious model. The number of pen holdings within hauls was used as the sample size in calculating AICc. Pearson residuals from the selected models were examined for overdispersion in the data and to assess model fit.

Skates held captive for mortality assessment were selected to best represent the different values or levels of plausible mortality covariates and were not necessarily representative of the survivorship of all skates in the experiment. An overall DM rate was therefore estimated as a weighted average of health-dependent mortality rates (which were found to be a significant predictor of mortality in this study, see Results) and the frequency distribution of the health indicators in all skates captured during the experiment in hauls with soak times of 6 days or less (e.g., Benoît et al. 2012). Following Benoît et al. (2012), this was implemented as part of a

Monte Carlo simulation based on bootstrapping from which uncertainty in the overall DM rate was estimated. Each Monte Carlo iteration, m, proceeded as follows:

i) Individual fishing hauls, x_s, were sampled with replacement from the population, F, of the 15 experimental hauls for which soak times were 6 days or less:

$$x_s \overset{i.i.d.}{\sim} F \text{ for } s=1, 2,\ldots, 21.$$

This step contributed to characterizing among-haul variability.

ii) For each randomly selected haul, x_s, individual skate, y_{ks}, were sampled with replacement from the population, O_{sm}, of n_s observed fish:

$$y_{k,s} \overset{i.i.d.}{\sim} O_s \text{ for } k=1, 2,\ldots, n_s.$$

This step contributed to characterizing within-haul variability. The total number of skate in each unique health class h out of a total of H classes for iteration m, $n_{hm} \in (n_{1m}, n_{2m}, \ldots n_{Hm})$, was then obtained by summing over individuals in each class from across all random individuals and hauls.

iii) A vector of random parameter values for the GLMM, $\dot{\boldsymbol{\psi}}_m$, was drawn from a multivariate normal distribution:

$$\dot{\boldsymbol{\psi}}_m \overset{i.i.d.}{\sim} N(\hat{\boldsymbol{\psi}}, \hat{\boldsymbol{\Sigma}}_{\psi})$$

where $\hat{\boldsymbol{\psi}}$ and $\hat{\boldsymbol{\Sigma}}_{\psi}$ are respectively the estimated vector of parameters and parameter covariance matrix for the most parsimonious GLMM. The random parameters $\dot{\boldsymbol{\psi}}_m$ were then inserted into eq. 7 and the inverse-logit transformation was applied to estimate health-status dependent DM rate, *D(h)*$_m$, for each unique health status class *h*. This step contributed to characterizing uncertainty in estimated health-dependent DM from the GLMM.

v) The overall mean DM rate for iteration *m* was estimated as:

$$\bar{D}_m = \frac{\sum_{h=1}^{H} n_{hm} \cdot D(h)_m}{\sum_{h=1}^{H} n_{hm}}$$

Steps i-v were repeated 5000 times to generate a population of $\bar{D}_m$ values. The mean and the 2.5th and 97.5th quantiles for this population were taken respectively as the average DM rate and its associated lower and upper confidence intervals.

To complement the estimation of the average DM rate, analyses were also undertaken to examine the effect of covariates on health indicator scores for experimental hauls for which soak times were 6 days or less. Because injury score was the only health indicator that was found to be a significant predictor of mortality in the GLMM analysis (see Results), the analysis was limited to this health indicator. A cumulative logits link mixed model for multinomial data was used as this type of model has previously been shown to be appropriate for such data (Benoît et al. 2010). The basic form of the model is:

$$\operatorname{logit}\,[P(I_{jk} \le v \mid \mathbf{X_{jk}}, u_j)] = \alpha_v + \mathbf{X}'_{\mathbf{jk}}\boldsymbol{\beta} + u_j\,, \quad \text{where } u_j \sim N(0, \sigma^2_{Haul}) \qquad (7)$$

I_{jk} is the observed injury score for skate *k* captured in fishing haul *j*, *v* is the injury class level from among *V* possible levels (three in this case), α_v is an intercept specific to *v*, $\mathbf{X_{jk}}$ is the design matrix of covariates, $\boldsymbol{\beta}$ is a vector of fixed covariate parameter values and u_j is the random effect specific to haul *j*. $P(I_{jk} \le v \mid \mathbf{X_{jk}}, u_j)$ is the probability that an individual observed injury score is less than or equal to injury class *v*, conditional on the covariates and the random effect. In this model, there are only V-1 uniquely defined probabilities because $P(I_{jk} \leq V)$ must equal one, resulting in V-1 values of α_v to estimate. The intercepts, α_v, increase with v since $P(I_{jk} \leq v \mid \mathbf{X_{jk}}, u_j)$ also increases in v for fixed values of $\mathbf{X_{jk}}$. We tested the effect of three covariates that could sensibly affect injuries: sex, total length and soak time, which could be related to injury as a result of periods of attempted escape. We did not consider covariates that weren`t expected to affect injury, such as SST. As with the previous analyses, we used a forward section approach to model building using AICc.

3. Results

3. 1 Winter skate bycatch numbers

A total of 616 skates were captured during the experiment, 391 of which were individually tagged and held in net pens to assess delayed mortality. No at-vessel mortality was observed at the immediate point of capture in the sampled skates. The duration of captivity was varied such that approximately 56% of individuals were held for around 72 hrs, 18% held for 95 hrs and for 170 hrs, and 8% for 285 hrs. The range in SST values for the study was small 19.2-23.4C^{o}

Soak time was the only variable found to significantly affect BPUE. The relationship between soak time and BPUE was non-linear (Fig. 4), with a predicted value of 1.6 skate per panel after 1 day of soaking, peaking at 8.2 after four days, before dropping off (Table 1). Predicted BPUE values, however, do not differ statistically for soak times from 4 to 7 days and the exact timing of peak BPUE is somewhat uncertain. Nonetheless, this result suggests that the drop-out rate for dead skate begins exceeding the rate of capture some time after 4-7 days of soak time. However, the time at which dead skate begin dropping out cannot be determined from these data. For the purposes of the mortality analyses, we assumed that drop-out losses were minimal up to 6 days of soaking and we included a factor for soak time in the models to estimate any differences in mortality due to soak time that may still exist.

3.2 Winter skate Discard Mortality

The most parsimonious model for DM outcome included fixed effects for captivity time and injury class, in addition to the random effects for haul and holding pen (Table 2). The next best model, which included the fixed effects of injury class and the back reflex, was associated with an AICc value that was 3.3 units higher and was therefore not retained. In the preferred model, the estimated probability of mortality evaluated after 170 hr of captivity was statistically more robust than for 75 hrs of monitoring (i.e., the intercept; Table 2), suggesting that some delayed mortality was expressed sometime in the intervening period. The maximum likelihood estimate for the effect at 285 hrs of captivity was very similar in value to that at 170 hrs, indicating that there was no additional mortality between these periods and suggesting that the DM had reached an asymptote by 170 hrs. However, the parameter for the 285 hr category was marginally not significantly different from that at 75 hrs of captivity, likely as a result of the smaller number of skates held for that longest period. Given these results, we combined the 170 and 285 captive time categories into a single one (170+ hrs) and re-fit the model. The estimate of the captive time parameter remained significant and at a value that was very similar to the previous version of the model (Table 2). The estimates for all other model parameters were nearly identical between the two model versions. As would be expected, there was a monotonic relationship between the probability of mortality and the degree of injury, with at the extremes, low mortality for uninjured skate (4.8%) and high mortality for badly injured skate (71.5%; Fig. 5). Using the final model, we also tested for an interaction between captive time and injury. That model resulted in a 4.0 unit increase in AICc and was therefore not retained. The effects of captive time and injury therefore appeared to be additive.

Sex was the only variable found to affect the distribution of injury score across injury classes in the cumulative logits link mixed modelling and its effect was highly significant (*P*=6.26e-5). The next best model included effects of sex and total length and was associated with an AICc value that was 2.6 units higher and was therefore not retained. Compared to males, female skate tended to be less severely injured (Table 3). Nonetheless most individuals of both sexes were uninjured and few were severely injured. Overall mean DM rates following 170+ hr of captivity were estimated separately for males and females in the bootstrap given the sex-related differences in injuries. The estimated discard mortality probability for females and males were 0.11 and 0.17, respectively (Table 3).

4. Discussion

Based on the lack of at-vessel mortality and overall low (11% for females and 17% for males) DM rates observed in the current study, skates were found to be more resilient to the rigors of gillnetcapture and post-capture handling than previously thought (NEFMC 2003). For instance, while DM presented herein are slightly higher than Mandelman et al., (2013) for mobile gear (~9%), they are much lower than the assumed rate of 50% currently used in the skate management plan (NEFMC, 2003). Furthermore, results from this study can be applied to gillnet fisheries in other geographic areas, such as in Canadian waters, where there is a paucity of DM information in static fishing gears for winter skate and other skate species of conservation concern (e.g., Benoît, 2013).

While skates were routinely captured by gillnets in this study, catch rates were a function of the soak duration of the gear, with more than a fourfold increase in catch rates when soak times were extended from 24 h to 4 d. However, for soaks exceeding 5-6 days, catch rates declined, presumably ascribable to dropout and depredation losses from the gear (Uhlmann and Broadhurst, 2015; Gilman et al., 2013) combined with possible temporary local depletion of skates. Drop outs or removals of dead skate by scavengers confound the ability to account for fishing-induced loss for species incidentally captured in gillnet fisheries that involve extended soak times. Here, we estimated DM rates while attempting to minimize biases due to this possible cryptic mortality, which is potentially important for all discard mortality studies using fixed fishing gear. We found that DM rates for winter skate captured in this fishery are reasonably low and therefore live releases in the fishery are likely to be successful. However, our results suggest that other unaccounted fishing mortality, resulting from drop-outs and depredation, could be very high, particularly for extended soak durations. Clearly there is a need for additional research aimed at quantifying this cryptic mortality. From a management perspective it also suggests that regulating allowable soak times is likely to be an effective way of reducing incidental mortality.

Due to the predictable narrow ranges/gradients characteristic of this fishery, none of the continuous covariates (e.g., size of the skate, fishing depths, temperature, etc.) measured in the study were statistically significant predictors of mortality probability. For example, the sink gillnet fishery is expected to have a restricted modal size-dependent selectivity for skate as a function of a standard mesh sized, and bycatch is expected to be clustered around a small size-range (NEFMC 2003) as was observed in this study. The monkfish fishery is also concentrated over a somewhat narrow range of depths and occurs largely over summer months when SST values are high and variation is restricted relative to the annual temperature cycle. As such, no specific direct recommendations for modifying fishing practices to enhance the success of live release of skate from the sink gillnet fishery are inferred from the results.

Enclosures such as the net pens are often used to hold animals to estimate DM (e.g. Broadhurst et al., 2006; Portz et al. 2006); however, unless accessible onboard a research or fishing vessel (e.g., Knotek et al., 2015), these methods do not ordinarily allow continuous or periodic assessment of the fate of study animals. As such, captive mortality assessments are cross-sectional in nature, in that mortality outcomes are evaluated at a single time point when the enclosure is retrieved. This generally precludes the ability to examine the temporal trend in mortality as time elapses from the initial capture/handling event, and therefore typically prevents determination of whether an asymptote in DM is reached. However, the experimental design employed in this study, in which captivity periods were varied and randomized across other experimental factors such as soak times, allowed for an indirect assessment of evidence for a mortality asymptote during captivity thereby offsetting an important potential bias inherent in cross-sectional studies (Benoit et al., 2015). Though we could not determine exactly when the mortality asymptote was reached, we were able to infer that it occurred during the range of captive times employed and were able to derive DM estimates at the asymptote that can be directly used in the management of the species in US waters.

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5. Literature cited

Alverson, D.L., 1999. Some observations on the science of bycatch. Mar. Technol. Soc. 33, 12–16.

Benoît, H.P. 2013. Twenty years of annual landed and discarded catches of three southern Gulf of St. Lawrence skate species estimated under multiple sources of uncertainty. ICES J. Mar. Sci. 70: 554-563.

Benoît, H.P., Capizzano, C.W., Knotek, R.J., Rudders, R.B., Sulikowski, J.A., Dean, M.J., Hoffman, B., Zemeckis, D.R., and Mandelman, J.W. 2015. A generalized model for longitudinal short- and long-term mortality data for commercial fishery discards and recreational fishery catch-and-releases. ICES J Mar Sci 72:1834-1847.

Benoît, H.P., Hurlbut, T., Chassé, J., and Jonsen, I.D. 2012. Estimating fishery-scale rates of discard mortality using conditional reasoning. Fish. Res. 125-126: 318-330.

Benoît, H.P., Hurlbut, T., and Chassé, J. 2010. Assessing the factors influencing discard mortality of demersal fishes in four fisheries using a semi-quantitative indicator of survival potential. Fish. Res. 106: 436-447.

Broadhurst, M.K., Suuronen, P., Hulme, A., 2006. Estimating collateral mortality from towed fishing gear. Fish Fish. 7, 180–218.

Capizzano, C.W., Mandelman, J.W., Hoffman, W.S., Dean, M.J., Zemeckis, D.R. Benoît, H.P., Kneebone, J., Jones, E., Stettner, M.J., Buchan, N.J., Langan, J.A., and Sulikowski, J.A. 2016.

Estimating and mitigating the discard mortality of Atlantic cod (*Gadus morhua*) in the Gulf of Maine recreational rod-and-reel fishery. ICES J. Mar. Sci. (*in press*)

Davis, M.W., 2002. Key principles for understanding fish bycatch discard mortality. Can. J. Fish. Aquat. Sci. 59: 1834–1843.

Davis, M.W., 2010. Fish stress and mortality can be predicted using reflex impairment. Fish Fish. 11, 1–11.

Depestele, J., Desender, M., Benoît, H. P., Polet, H., Vincx, M., 2014. Short-term survival of discarded target fish and non-target invertebrate species in the “eurocutter” beam trawl fishery of the southern North Sea. Fish. Res. 154: 82–92.

Gilman, E., Suuronen, P., Hall, M. and Kennelly, S. 2013. Causes and methods to estimate cryptic sources of fishing mortality. J Fish Biol, 83: 766–803. doi:10.1111/jfb.12148

Knotek R.J., Rudders D.B., Mandelman J.A., Benoît H.P., Sulikowski J.A. 2015. The survival of rajids discarded in the New England scallop dredge fishery. Master's Thesis. University of New England.

Portz, D.E., Woodley, C.M., Cech, J.J., 2006. Stress-associated impacts of short-term holding on fishes. Rev. Fish. Biol. Fisheries. 16, 125-170.

Mandelman, J.W., Cicia, A.M., Ingram Jr., G.W., Driggers III, W.B., Coutre, K.M., and Sulikowski, J.A. 2013. Short-term post-release mortality of skates (family Rajidae) discarded in a western North Atlantic commercial otter trawl fishery. Fish. Res. 139: 76-84.

New England Fishery Management Council (NEFMC), 2003. Skate Fisheries Management Plan. NEFMC, Newburyport, MA.

New England Fishery Management Council (NEFMC). 2011. 2012-2013 Skate Complex Acceptable Catch Limit Recommendations. Skate Plan Development Team Report, May 2011. NEFMC, Newburyport, Massachusetts. 49 pp. (www.nefmc.org/skates).

New England Fishery Management Council (NEFMC). 2012. Northeast Skate Complex Specifications Environmental Assessment Regulatory Impact Review and Initial Regulatory Flexibility Analysis. NEFMC, Newburyport, Massachusetts. 217 pp

New England Fishery Management Council (NEFMC). 2015. Update on skate stock status based on NEFSC trawl survey data autumn 2014/spring 2015. NEFMC, Newburyport, Massachusetts. 6 pp.

Uhlmann, S.S., and Broadhurst, M.K. 2015. Mitigating unaccounted fishing mortality from gillnets and traps. Fish Fish. 16: 183-229.

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., and Smith, G.M. 2009. Mixed effects models and extensions in ecology with R. New York: Springer

Table 1. Model-based estimates of the bycatch of winter skate per unit effort (numbers per gillnet panel per haul) for different gillnet soak times, with lower (LCI) and upper (UCI) 95% confidence intervals and estimated p-values for differences relative to a 1-day soak. The estimated variance for the haul-level random effect was $\sigma_{Haul}^2 = 0.106$.

Soak time (days)	Estimate	LCI	UCI	P-value
1	1.62	0.67	3.95	-
2	2.62	1.78	3.86	0.332
3	2.36	1.11	5.02	0.528
4	8.22	5.45	12.40	0.001
5	5.66	3.88	8.27	0.011
6	4.81	3.27	7.07	0.028
7	3.32	1.84	5.99	0.188
9	2.18	1.01	4.74	0.622
14	3.44	2.08	5.68	0.149

Table 2. Results for the most parsimonious Bernoulli GLMM for mortality outcome as a function of environmental, experimental and biological factors, as well as health indicators. The best model included a random effects for haul and pen within haul, the three-level injury factor and the three-level factor for captive time (Version 1 in the table). The effects of captive time classes of 170 hrs and 285 hrs were of similar magnitude and the two classes were merged into a 170+ hr class for a more parsimonious model (Version 2).

Parameter	Estimate	SE	z-value	*P*-value
Version 1				
σ^2_{Haul}	0.097			
σ^2_{Haul}	1.506			
α	-4.849	0.857	-5.660	1.51e-8
Inj-2	1.893	0.636	2.974	0.0029
Inj-3	3.898	0.929	4.198	2.70e-5
CT-170hr	1.879	0.914	2.057	0.0397
CT-285hr	1.834	1.071	1.713	0.0687
Version 2				
σ^2_{Haul}	0.109			
σ^2_{Haul}	1.489			
α	-4.849	0.856	-5.661	1.5e-8
Inj-2	1.894	0.635	2.985	0.0028
Inj-3	3.905	0.911	4.285	1.83e-5
CT-170+hr	1.862	0.794	2.345	0.0190

Table 3. Total number of winter skate in the experiment from hauls with soak times of 6 days or less, proportion in each of the three injury classes and estimated total discard mortality probability (*D*; with 95% confidence interval) by sex.

	Males	Females
N	253	195
Injury 1	0.61	0.79
Injury 2	0.33	0.19
Injury 3	0.06	0.02
D (95% CI)	0.166 (0.071, 0.300)	0.111 (0.041, 0.228)

Figure captions

Figure 1. Bathymetric map of sampling area off the coast of southern Rhode Island. Bathymetric contours are denoted in ten meter increments. The area where commercial fishing was concentrated varied from 35-43 m in depth.

Figure 2. Frequency distribution of gillnet soak times in the study.

Figure 3. Frequency distribution of the lengths of winter skate captured during the study, separated into those that were held captive for mortality assessment (black) and not (white).

Figure 4. Box plots of the number of winter skate caught per gillnet panel as a function of soak time. Note that there were no soak times of 8 days or 10-13 days, and consequently these are not shown in the plot.

Figure 5. Estimated discard mortality probability (with 95% confidence interval) as a function of injury class for times of captivity of 170 hrs or more.

Fig 1.

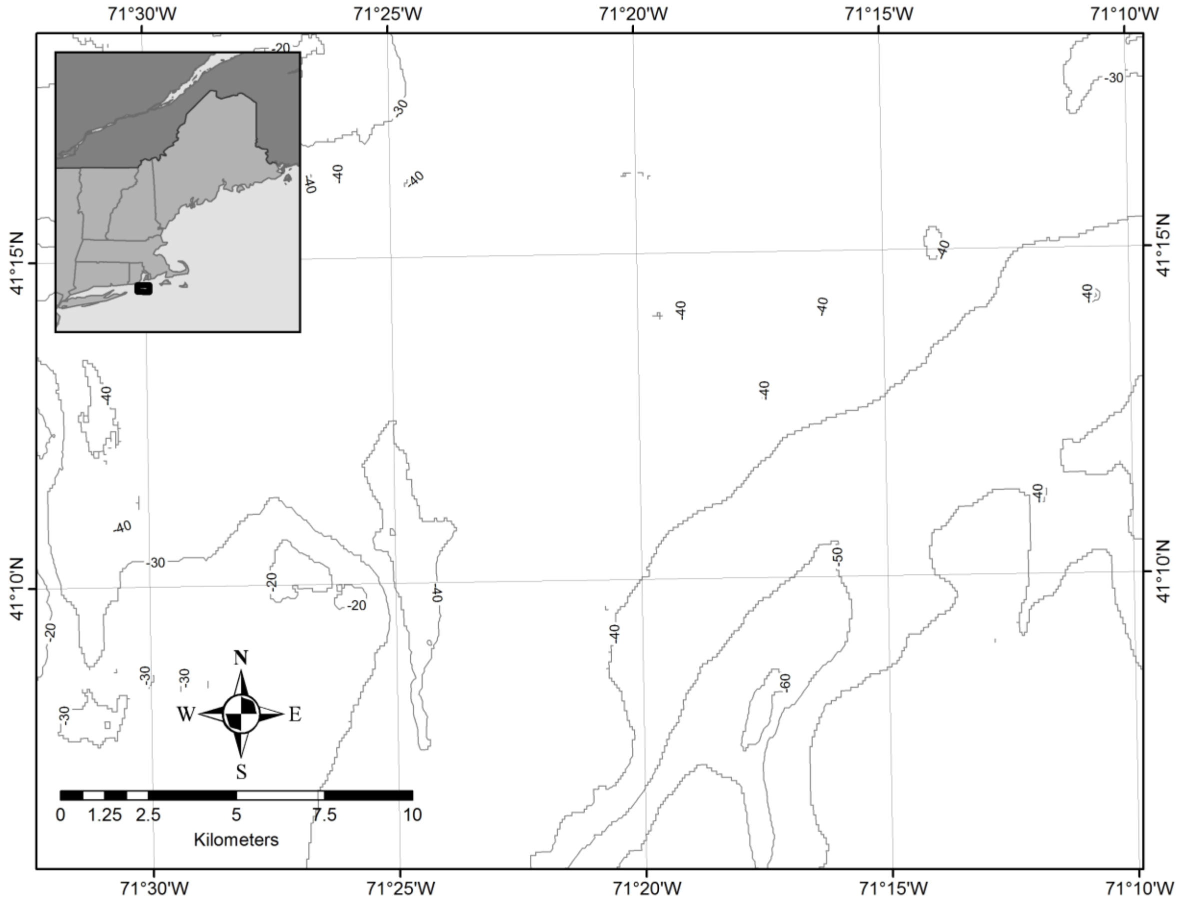
71°30'W
71°25'W
71°20'W
71°15'W
71°10'W
41°15'N
41°10'N
-20
-30
-40
-50
-60
N
W
E
S
0
1.25
2.5
5
7.5
10
Kilometers

Fig. 2

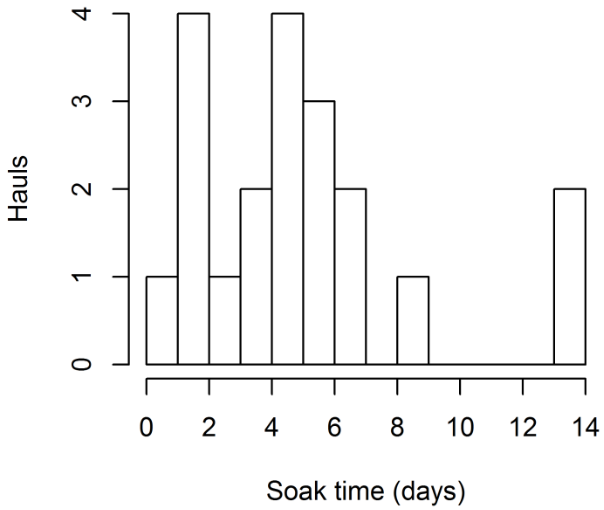
Hauls
0
1
2
3
4
0
2
4
6
8
10
12
14
Soak time (days)

Fig. 3

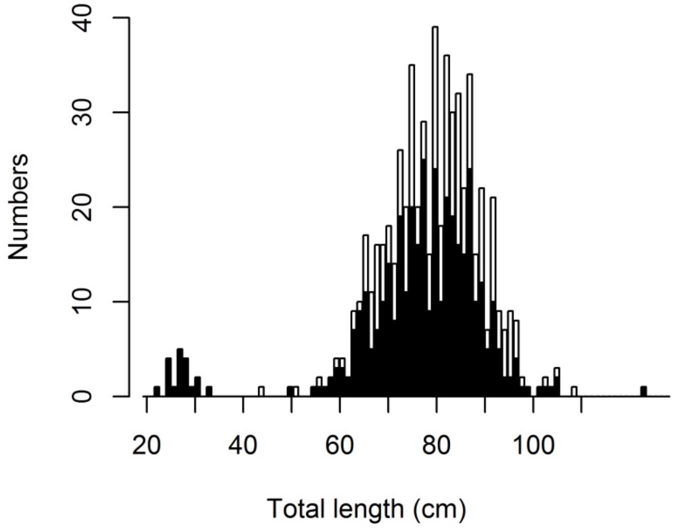
Numbers
0
10
20
30
40
20
40
60
80
100
Total length (cm)

Fig. 4

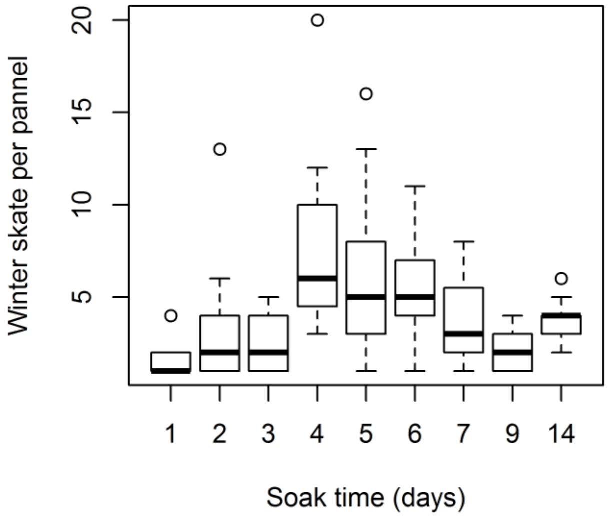
Winter skate per pannel
20
15
10
5
1
2
3
4
5
6
7
9
14
Soak time (days)

Fig.5


Probability of mortality
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
Injury class