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Estimating The Post-Release Mortality Of Atlantic Cod (Gadus Morhua) In The Southern Gulf Of Maine Commercial Lobster Fishery

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Estimating the post-release mortality of Atlantic cod (*Gadus morhua*) in the southern Gulf of Maine commercial lobster fishery

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Dedication

My thesis is dedicated to my wife, Katherine Sweezey, and my parents Richard and Norma Sweezey.

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Atlantic cod, *Gadus morhua*, in the Gulf of Maine has experienced heightened fishing-induced mortality since the 1990s, leading to the lowest population abundances in recorded history. Unaccounted discard mortalities within Gulf of Maine commercial fisheries may be impairing recovery efforts in this and other cod populations. With over 4 million actively fished lobster traps, the Maine commercial lobster fishery has been suggested to be a significant contributor to cod mortality rates within this region. Therefore, the discard mortality rate of Atlantic cod captured by commercial lobster gear was examined to assess its potential influence on recovery efforts using acoustic transmitters and observations of individual viability. In total, 111 cod were captured over 105 fishing trips in 2016-2017, consisting of 18,853 individual trap hauls. A subsample of 54 cod were externally tagged with acoustic transmitters and observed post-release. The observed frequency of injuries following trap hauling included: uninjured (60.0%), slight injured (32.2%), severely injured (2.5%), and deceased (9.3%). Through the use of a mixture-distribution parametric model the discard mortality rate within the southern Maine commercial lobster fishery is estimated to be 24.8%.

CHAPTER 1

ESTIMATING THE POST-RELEASE MORTALITY OF ATLANTIC COD (GADUS MORHUA) IN THE SOUTHERN GULF OF MAINE COMMERCIAL LOBSTER FISHERY

Introduction

The Atlantic cod (*Gadus morhua*) commercial fishery has been a principle contributor to the New England economy since the 17th century; however, landings within the Gulf of Maine (GOM) suggest that this stock has reached historical low biomass levels despite the implementation of strict management plans (Serchuk & Wigley, 1992; Leavenworth, 2008; Nenadovic *et al*., 2012; NEFSC, 2013; Pershing *et al*., 2013). Past research has attributed large declines in commercially-important species to overfishing (Jackson *et al*., 2001); however, other contributing factors, including climate change (Drinkwater, 2005), predation (Collie *et al*., 2013), and fishing pressure from the recreational rod-and-reel fishery (Capizzano *et al*., 2016), cannot be ignored.

A more recent threat, which remains highly controversial, is the impact of cod bycatch in commercial fisheries due to the discard of these animals after capture (NEFSC, 2013). Bycatch, the unintentional catch of non-target organisms, remains a serious issue for fisheries management throughout the world and may contribute to inhibiting the regrowth of the modern GOM Atlantic cod stock (MSC, 2013). The discard mortality rates for many harvested species are rarely known and the methods for estimating these rates are not well established (Cooke and Schramm, 2007). When information regarding the survival rates of non-target species within recreational and commercial fisheries is absent, enforcement by fisheries management may implement conservative mortality estimates (50-100%) or establish closures to alleviate fishing pressure in an attempt to protect a discarded species (Howell *et al*., 2008; Nenadovic *et al*., 2012; Capizzano *et al*., 2016; Knotek *et al*., 2018).

To quantify discard mortality rates, information is acquired through the capture and subsequent monitoring of the individual for a short period of time post release. Past studies have attempted to quantify mortality through a variety of techniques such as holding pens (Milliken *et al*., 2009, Sulikowski *et al*., 2017), on-board tanks (Knotek *et al*., 2018), and conventional mark-and-recapture practices (Hoag, 1975). In general, it is not possible to observe individuals released within the aquatic environment, so accurately estimating the discard mortality after a fishing event can be extremely difficult and is usually laden with caveats (Benoît *et al*., 2010; Mandelman *et al*., 2013). Confinement studies are effective at providing information on the condition of a discarded animal for a short period of time after release (~72 hours) by correlating the vitality of an animal to the probability of survival. However, due to the nature of these studies, mortalities may only be observed at fixed time intervals between the primary and successive observation events so the status of individuals between these time periods is unknown. Therefore, a series of biological, environmental, and technical factors must be accounted for to accurately assess such mortality. In many confinement studies, for instance, complications arise which may artificially increase (e.g., thermal stress, decompression, and crowding) or decrease (e.g., deflecting predators) the actual discard mortality rate (Welterbach & Strehlow, 2013). Additionally, these confinement studies can only account for short term mortality even though casualties are likely to occur after the study period/duration of post-release monitoring (Milliken *et al*., 1999; 2009).

To overcome the caveats observed in confinement studies, an increasing field of research has used acoustic telemetry to estimate the discard mortality in a wide variety of fishes (Yergey *et al*., 2012; Afonso and Hazin, 2014; Curtis *et al*., 2015; Raby *et al*., 2015; Capizzano *et al*., 2016; Ferter *et al*., 2018). Acoustic telemetry allows an observer to determine the movement patterns, home range, and habitat selection of a tagged species, allowing for a greater understanding of how individuals interact within their environment across a range of spatial and temporal scales (Dance *et al*., 2016; Hedger *et al*., 2017). Additionally, studies have used acoustic transmitters to analyze vertical and horizontal movement patterns to provide a clear distinction between live and dead animals (Yergey *et al*., 2012; Capizzano *et al*., 2016). Furthermore, observing the degree of physical injury an animal sustained from capture and handling can be used to estimate the probability of survival once the animal is released (Benoît *et al*., 2015; Capizzano *et al*., 2016; Knotek *et al*., 2018).

The technological advantages provided through the use of acoustic telemetry would allow for a more accurate estimate of the discard mortality rates of cod in one of the largest commercial fisheries in the United States – ex-vessel landings value of $533.1 million in 2016 (MEDMR, 2017). Despite the high level of fishing effort and landings, the impact of commercial lobster gear on the environment remains unknown. According to the most recent available data, there are approximately 3.5 million actively fished lobster traps within the GOM in addition to an estimated 175,000 traps that are lost in this region annually (ASMFC, 2009; GOMLF, 2014). Increasing evidence suggests that the commercial lobster industry may be negatively impacting local groundfish species such as Atlantic cod through unaccounted mortalities that arise from the interaction with commercial lobster gear (MSC, 2013). However, information on this subject remains highly speculative and limited to the state of Maine fishery observer data which was extrapolated by the Marine Stewardship Council. These data observed the capture of 317 cod over 546 sampling trips (representing 123,269 individual trap hauls) and estimated the capture of approximately 177,247 cod within commercial lobster gear during the 2008 fishing year. While these numbers raised a cause for concern, these data were considered controversial due to the absence of a dedicated study evaluating cod discards in the lobster fishery (MEMDR, 2012; Keliher, 2014).

It is imperative to determine accurate discard mortality rates of cod bycatch in the GOM commercial lobster fishery to establish proper management regulations within the commercial lobster fishery. Therefore, upon capture within commercial lobster traps, cod were monitored for vitality condition and movement patterns were observed post release via passive telemetry. In addition, a variety of capture-related covariates were investigated to estimate the influence of capture-and-handling events (CH) upon mortality.

Methods

Atlantic cod were collected from commercial lobster traps (121.92 cm x 53.34 cm x 34.29 cm) following state management regulations of Maine Zone G ranging from Cape Elizabeth to Kittery, ME (Figure 1). Gear modifications within the southern Maine lobster fishery can be variable between lobster fishermen; however, all gear must fall within Zone G parameters to legally capture lobsters within this region (McCarron & Tetreault, 2012). Traps within the acoustic array (IA; see acoustic array details below) consisted of 10 strings comprised of 10 two-trap trawls, totaling 200 individual traps.

Additionally, 500 traps consisting of triples and five traps trawls were hauled outside (OA) of the parameters of the acoustic array. Based on preliminary observations, fishing protocol included hauls from IA and OA to maximize the probability of tagging captured individuals. Moreover, the observation of hauls from IA and OA would more accurately represent the catch per unit effort (CPUE) of cod per day within the southern Maine lobster fishery. The placement of fishing gear varied along both depth (mean ± SD: 50.13 ± 7.53 m) and bottom types (e.g., gravel, sand, and mud) encapsulating the standard practices of a commercial lobster vessel within this region.

Atlantic cod were targeted from May 2016 to November 2017, which encompassed the peak landings of the southern Maine commercial lobster fishery (i.e. April – November) for two individual fishing seasons. Traps were supplied with bait (e.g., Atlantic herring, *Clupea harengus*; Atlantic menhaden, *Brevoortia tyrannus*; cowhide lobster bait; Worcester's Lobster & Crab Bait, Prospect, ME) commonly found within the region and hauled every four to six days aboard the F/V Christina Mae II (Capt. Ed Hutchins; [11.6 m]) to emulate practices within the southern Maine region. Several biological, environmental, and technical (i.e. capture-related) factors were collected upon landing each individual cod, including soak time (i.e. days from trap deployment to trap haul), handling and air exposure (i.e. stopwatch recording removal from trap until release), depth, bottom type, air temperature, and surface and bottom water temperature. Air temperature was recorded using a Traceable® Waterproof Mini Thermometer (Ben Meadows), surface water with a YSI Model 30M (YSI, Yellowsprings, Ohio), bottom water temperature with a HOBO Water Temperature Pro v2 Data Logger (ONSET, Borne, Massachusetts), and depth and bottom type with a

Raymarine DSM300 (Dual 50 kHz and 200 kHz, 1580 pulses per minute at 15 m, Nashua, New Hampshire). Individuals were measured for total length to the nearest millimeter and assessed for vitality using a modified four-level ordinal index previously established by Capizzano *et al*. (2016) (Table 1). Deceased and moribund individuals recovered inside of the traps upon initial haul were categorized with an injury 4 and marked as experiencing at-vessel mortality (AVM).

Tagging Procedure

Cod were tagged using a modified external attachment method from Capizzano *et al*. (2016) to minimize the aerial exposure an individual would experience during the capture and handling process. The tagging process commended after the sampling of an individual was complete. Acoustic transmitters were programmed using a random ping schedule every 30 to 90 seconds, 24 hour/day, 7 days per week. To secure the location of the acoustic tag, a dart tag applicator (3.40 mm outer diameter) was used to pierce the dorsal musculature below the rear base of the primary dorsal fin (Figure 2a). A small segment of ultra-thin spaghetti tag was passed through the opening and tied into a knot to secure the attachment of the transmitter (model ADT-MP-9-SHORT, 9 mm x 28 mm, 3.7 g in-air, 2.2 g in-water, pressure sensor max depth 86 m [resolution 0.01 m, accuracy ± 0.5 m], min temperature sensor 0 C° [resolution ± 5 C°]; Lotek Wireless, ThelmaBiotel, Trondheim, Norway) (Figure 2b). Additionally, a droplet of Loctite was applied to the knot to prevent detachment (Figure 2c). Acoustic transmitters were fitted with an attachment site using a 50lb monofilament loop that was fastened to the transmitter with electrical tape (3M Scotch ¾''), Loctite Ultra Gel (Henkel Corporation, Westlake, Ohio), and reinforced with shrink wrap (HS515-1.22M – Heatshrink, 12 mm) (Figure 3). After tagging the animals were released.

Due to size limitations of the acoustic array (see below for full description), individuals captured within 0.5 km of the outer perimeter of the acoustic array's detection radius were transported and released inside the confines of the array. Fisher's Exact Test was performed to ensure that transportation was not an additional covariate influencing mortality. Previous studies examining acute stress as a result of transportation report that minor periods of handling and transport should result in little to no impact on the stress of an individual (Sulikowski *et al*., 2003). While applying acoustic transmitters to an equal number of individuals across all injury scores and range of values for other capture-related variables was ideal for conducting a parametric analysis (see Benoît *et al*. 2015), many fish were chosen opportunistically due to the low CPUE (1.03 cod/day) of cod within commercial lobster gear in this region. All individuals captured OA were subject to the aforementioned sampling protocol (i.e. measured, assessed vitality, etc.) and were tagged with Floy T-bar tags (model FD-94, Seattle, Washington). Prior to field tagging, a preliminary in-lab attachment test following protocol from Capizzano *et al*., (2016) was conducted to insure the retention and survival rate of individuals tagged with acoustic transmitters and T-bar anchor tags over the course of 30 days (100% survival rate, n = 6).

Acoustic Array

The acoustic receiver array was constructed off the eastern coast of southern Maine (43° 21'30" N, 070° 22'25" W) in a location suspected of the year-round presence of cod (Ames, 2004). The array was composed of 30 VEMCO VR2W-69 kHz receivers

(VEMCO Division, Amirix System Inc, Nova Scotia, Canada), resulting in a detection area of roughly 30 km^2 (Figure 1). Bullet buoys were attached to 35 and 15 m of sink and float line, respectively, and secured to the substrate with a single 22.7 kg mushroom weight. Due to severe weather conditions and the decline in fishing effort during the winter months (i.e. December 2016 – March 2017), the array was removed from the water and sampling did not take place during this time period.

Data Analysis

The handling and analysis of data were performed within the statistical software R (version 3.5.0; R Core Team, Vienna, Austria, 2016). Detection data were downloaded from acoustic receivers using VEMCO'S proprietary software, VEMCO'S User Environment (VUE, version, 2.3.0) following protocols from Capizzano *et al*., (2016) to identify irregular depth sensor data. Due to the nature of the pressure sensors within the transmitters, the use of recorded depth above the seafloor as a mortality indicator was difficult given the variability in seafloor depth in the study area. Therefore, following details outlined by Capizzano *et al*. (2016) a subset of tagged individuals were euthanized and placed within the acoustic receiver array to distinguish mortalities among cod with acoustic transmitters (i.e. negative controls) to overcome this complication. Depth data from these negative controls were used to determine differences in variance between deceased individuals and released cod of unknown condition through the use of a one-tailed t-test of the absolute difference from the median (Brown-Forsythe-Levene test for homogeneity of population variance). To insure greater test accuracy, the tidal cycle from the study site was subtracted from each individual's vertical depth using the R package "oce" (version 0.9-19, Kelley and Richards, 2017). Tide-adjusted profiles of the negative controls were assumed to represent the movement patterns of a deceased cod as they interacted with the seafloor and currents. The one-tailed *t*-test was applied to each post-release time bin for each cod with an acoustic transmitter to determine both mortality events and a time of death.

To estimate the probability of AVM of Atlantic cod captured by commercial lobster traps, a generalized linear model (GLM) was used to model in-trap mortality as a function of capture-related predictors such as soak time and bottom water temperature (Zhang and Chen, 2015). The GLM used a logit link transformation and is expressed as:

$$p(Dead) = \frac{e^{\beta_0+\beta_1 SoakTime+\beta_2 Temp}}{1+e^{\beta_0+\beta_1 SoakTime+\beta_2 Temp}}$$

(Eq. 1)

In an effort to estimate the long-term discard mortality rates of long-term mortality within the fishery, the survivorship data for cod captured and released alive were fitted with a mixture-distribution parametric model following the methods of Benoît *et al*., (2012; 2015). Total mortality was estimated by adding the AVM together with the discard morality rate of the surviving discarded individuals. The discard mortality estimated from this model was applied to the fishing practices within Lobster Management Zone (LMZ) G and extrapolated to regions that shared most similar fishing configurations within the GOM. Comparisons between variations in fishing depth, soak time, seasonality, traps per trawl, and substrate were compared with previous research which identified fishing practices of each LMZ and applied to regions with comparable fishing techniques (Table 2) (McCarron and Tetretault, 2012; Bannister *et al*., 2015). Fishing seasonality, depth, and substrate type within LMZ G were found to be most similar within LMZ E and F as well. Although LMZ D is adjacent to LMZ E, it was excluded from our mortality estimates in addition to the adjacent GOM border state (New Hampshire and Massachusetts) commercial lobster fisheries which vary in seasonality and fishing depth (Bell, 2010; Richaud *et al*., 2016).

Results

A total of 111 cod were captured over 105 fishing trips (consisting of 18,853 individual lobster trap hauls) ranging in total length from 23.5 – 64.5 cm (mean ± SD: 47.0 ± 11.5 cm) and at depths from 37.8 – 64.6 m. The number of captured cod remained relatively consistent between the 2016 and 2017 fishing year (FY2016 and FY2017) at 59 and 52 individuals, respectively. Between the cod tagged between IA (acoustic, n = 54) and OA (T-bar anchors, n = 57), there was no significant difference (p = 0.888 in the TL of cod tagged with acoustic transmitters (mean ± SD: 47.27 ± 5.45 cm) and individuals tagged with T-bar anchors (mean ± SD: 46.65 ± 13.87 cm). Out of the 111 captured cod, 11 suffered AVM and a subset (n = 6) were recaptured with a single individual experiencing a third CH event. With the inclusion of recaptures, a total of 118 individual fishing events were observed, and 100 individuals were successfully released back into the wild.

Due to the close proximity of five individuals that were captured near the edge acoustic array's detection area (within ~0.5 km), these cod were tagged with acoustic transmitters, transported, and released within the parameters of the acoustic array. The results from Fisher's Exact Test (p = 0.1782) displayed that transportation was not an additional covariate to mortality. Since survival status did not depend on IA and OA, they were combined to incorporate accurate survival curves for all captured individuals. However, despite combining capture groups to improve sample sizes, representative Kaplan-Meier survival curves could not be created (Smith *et al*., 2012).

The acoustic array passively monitored the study area for a total of 369 days throughout the sampling period (June 6th – November 11th 2016 and April 12th – November 10th 2017) and accumulated over 731,658 individual detections resulting in 4,759.4 days of movement data. The observed injuries for the 118 individual capture events are composed of 66 injury score 1 (60.0%), 38 injury score 2 (32.2%), 3 injury score 3 (2.5%), and 11 injury score 4 (9.3%). With the inclusion of recapture events (n = 62), observed injuries of individuals with acoustic transmitters consisted of 37 injury 1 (59.7%), 22 injury 2 (35.5%), and three injury score 3 (4.8%). Injuries observed from T-bar tagged individuals with the inclusion of recapture events (n = 56) were composed of 27 injury 1 (48.2%), 18 injury 2 (32.1%), and 11 injury score 4 (19.7%) (Figure 4).

The injuries observed for each recapture event displayed an increase (e.g. injury 1-2, injury 2-3, and injury 1-4) in severity between their primary and secondary as well as secondary and tertiary CH events with one individual being observed to suffer AVM (Table 3). Out of the cod tagged with acoustic transmitters, 9 of the 54 (16.4%) were inferred to die in the subsample. Cod observed to suffer mortality (mean ± SD: 47.1 ± 4.3 cm) ranged in total length from 41.5 to 54.0 cm and were recorded under the following injury scores: two fish were scored as injury 1 (22.2%), six were scored as an injury 2 (66.7%), and one injury score 3 (11.1%). The residence time within the acoustic array ranged from 0.2 – 187.4 days (mean ± SD: 86.5 ± 56.8 days). The number of cod that could be detected within the confines of the study area up to the removal of the acoustic array were 11 and 8 individuals during FY16 and FY17, respectively. The emigration of 36 cod was observed between FY16 and FY17 with both years indicating that 18 acoustically tagged individuals (FY2016: 30.5%; FY2017, 34.6%) left the detection range of the array during both field seasons.

Estimating Bycatch Mortality

The entire sample of captured IA and OA individuals was implemented in the GLM to determine the probability that a trapped cod would suffer AVM. Soak time duration (mean ± SD: 5.69 ± 2.01 days) and bottom temperature were not significant predictors in predicting probability of mortality through the use of the GLM ($p = 0.793$). For individuals with acoustic transmitters, the results of the mixture distribution model estimated a discard mortality rate of 17.1% (9.1 – 29.7 95% CI) which is similar to the Kaplan-Meier estimates for this study (Figure 5; Benoît et al., 2012, Benoît et al., 2015). Additionally, the results from this model demonstrate an asymptote of mortality events after 26.0 days (9.30 – 88.3 95% CI). The estimates of AVM (9.3%) compiled with the mortality of surviving individuals which were discarded (17.1%) result in an overall total mortality of 24.8% in the GOM commercial lobster fishery.

Discussion

Regarded as one of the most commercially important fish in New England, the Atlantic cod stock in the GOM has declined to historically-low biomass levels (NOAA, 2017). Despite the common supposition that directed commercial harvest is to blame for the decline in cod stocks, there is growing evidence that there may be other contributing factors such as climate change (e.g., Drinkwater, 2005; Nye et al., 2009), interspecies competition (e.g., Link and Garrison, 2002), predation (e.g., Collie et al., 2013), and recreational (rod-and-reel) fishing pressure (Weltersbach and Strehlow, 2013; NEFSC, 2013; Capizzano *et al*., 2016). Bycatch within other New England demersal fisheries may also represent an additional threat. For example, the effects of fishing depth, gear type, air exposure duration, water temperature, and presence of injuries and barotrauma have been documented to cause discrepancies among observed discard mortalities (16.4 – 100%) within various commercial and recreational fisheries (e.g. Milliken *et al.,* 1999, 2009; Pálsson *et al*., 2003; Humborstad *et al*., 2009; Ferter *et al*., 2015; Capizzano *et al*., 2016; Kleiven *et al*., 2016). The commercial lobster fishery, in addition to the commercial scallop dredge fishery, is currently one of the most lucrative in the Northeast United States; however, discard mortality rates remain absent from current lobster stock and fishery management plans. In 2013, the MSC report extrapolated 177 metric tons of cod bycatch within the commercial lobster fishery in FY2008. Alternatively, cod landings within other fisheries during this time (otter trawl, hand line, and gillnet) were observed to be approximately 600 metric tons combined (NOAA, 2008). However, the MSC extrapolation did not account for spatiotemporal differences within the GOM and was not considered to be an accurate reflection of cod bycatch within this region. The only study to date to address this issue by Boenish and Chen (2018) extrapolated cod bycatch within the GOM commercial lobster fishery by accounting for nonrandom spatiotemporal patterns between FY2006 – FY2013. The highest levels of Atlantic cod bycatch per unit effort (BCUPE) were observed in the winter and early spring; however, discard rates peaked when BCUPE was at or near the lowest levels of the year during periods of increased fishing effort (summer and fall) (Boenish and Chen, 2018). Additionally, similar to the findings of this project, no significant correlation was found between the BCUPE and trap soak times. Mortality rates were not included in this analysis, but estimates were suggested to be a high priority in future work to evaluate the consequences of cod within commercial lobster gear.

The information presented herein represents the first direct investigation to quantify the discard mortality rate estimate of Atlantic cod within GOM commercial lobster fisheries. Thus, the discard mortality rate estimate from the current study of 24.8%, represents a vital component necessary for both understanding the recovery of cod but also for proactive management for one of the largest and most valuable shellfish fisheries within New England (MEDMR, 2017). Thus, the estimated discard mortality rate presented herein, are representative of the fishery within LMZ G and may be extrapolated to LMZ E and F that share similar depth, bottom composition, and fishing configurations (Table 2) (McCarron and Tetreault, 2012). While it is possible that AVM rates may impact the total mortality of cod captured within commercial lobster gear in the GOM, no significant predictors of AVM could be found; however, the impact of trap mortality should not be ignored. While AVM is highly uncertain, the AVM rate contributes towards approximately 30% of the deceased individuals observed within this study and should be taken into account when estimating discard mortality within the commercial lobster fishery. This discard mortality estimate reflects research of cod discarded within the GOM (16.5% Capizzano *et al*., 2016) where the fishing conditions and region are similar to those observed in our research, albeit within the recreational rod-and-reel fishery. Between LMZs collectively, E, F, and G encompass approximately 30% of the total fished traps within the state of Maine (i.e. 855,087) (GMRI, 2012).

While these LMZs share similar fishing practices such as soak times (McCarron and Tetreault, 2012), the driving factor between cod and lobster gear interactions may be due to the bottom habitat and fishing depths that they both occupy. For example, the habitat conditions that reflect those seen within LMZs E, F, and G are favorable for younger individuals age 2 – 4 (≤ 50 cm), which tend to rely on crypsis and use substrate as protective cover (Gregory and Anderson, 1997). In comparison, adult cod display an affinity for hard bottom and coarse-grain sediments reflective of bottom substrate in LMZs A – D (McCarron and Tetreault, 2012; Siceloff and Howell, 2013). The openings within commercial lobster traps likely provide entrances accessible for immature individuals (< 42 cm, *n* = 12), while deterring larger cod (> 60 cm, *n* = 2) which may bias capture sizes towards smaller individuals within this gear type. The majority of captures in this fishery are suggested to be still immature or approaching maturity (50% length at maturity, 32 – 41 cm) (Mayo, 1995; Boenish and Chen, 2018). Bycatch of younger cod within lobster traps raises cause for concern that immature individuals are removed from the depleted GOM stock before they are able to reproduce (Collie *et al*., 2013).

An interesting finding of the current study was that of the 111 captured individuals (i.e. IA and OA hauls), 5.4% of cod were recaptured within hauled lobster traps. These results reflect similar observations within the recreational rod-and-reel (9.4%, Capizzano *et al*., 2016; 11.7% Kleiven *et al*., 2016), prawn trawl (5.6%, Kleiven *et al.*, 2016), and otter trawl fisheries (4.8%, Howell *et al*., 2008) and has been shown to produce decreases in vitality after multiple CH events (Bartholomew and Bohnsack, 2005). For example, multiple CH events may increase the probability of mortality for species subject to intense fishing pressures, commonly referred to as the cumulative mortality risk (CMR) (Musick, 1999; Burns, 2002; Bartholomew, 2005). Mean CMR (18%) among 274 individual mortality estimates were analyzed by Bartholomew and Bohnsack (2005) and mortality distributions remained similar among salmonids, marine, and freshwater species even though differences existed between taxa and capture environments. Our results observed the majority of recaptured individuals to display a decrease in fitness with repeated CH events. Out of six individuals, one cod suffered AVM (16.6%) which is reflective of the mean CMR reported by Bartholomew and Bohnsack (2005). In addition to AVM, repetitive CH events subject individuals to increased predation, cumulative injuries, and sub-lethal effects on behavior (growth, reproduction, physical condition, and disease and parasite vulnerabilities). With over 4 million actively hauled lobster traps in the GOM, the likelihood of repetitive captures for individuals that display site affinity (e.g. feeding or spawning grounds) over a period of time may have a significant impact on long-term vitality of cod within this region (Ames, 2004).

When cod are hauled from depth, gas within the swim bladder of physoclist species expand at a rapid rate and may inflate various organs such as the eyes (exophthalmia), everted stomach/anus, and cause loss of equilibrium (Humborstad *et al.*, 2016). Barotrauma is another factor observed in commercial fisheries to cause fatal injuries in fishes associated with rapid ascents from depth (i.e. eastern Pacific rockfish species) (Lancaster *et al.*, 2017; Rankin, 2017). The results from our research did not find any direct evidence of external barotrauma and are comparable to previous observations for cod captured in various gear types. For example, discarded individuals were noted “floating” (5.5%, *n* = 3) if unable to submerge soon after release, and similar instances of barotrauma were observed in recreational (rod-and-reel) fisheries as well (2.2%, Ferter *et al*., 2015; 5.2%, Capizzano *et al*., 2016). However, cod captured in commercial fisheries at depths beyond those observed in this study were found to exhibit the effects of barotrauma (Stewart, 2008; Milliken *et al*., 2009; Ovegård *et al*., 2011). For example, individuals captured at depths ≥ 50 m in Norwegian pot gear and recreational fisheries have been observed with compromised buoyancy status (~40%) (Midling *et al*., 2012; Ferter *et al*., 2015; Humborstad *et al*., 2016). Within LMZs (i.e. LMZ B and E) where fishing depths ≥ 70 m, the probability of barotrauma is greater and floating individuals may be subject to avian predation, solar radiation, and unfavorable temperatures experiencing mortality rates as high as 79% (Midling *et al*., 2012; Ferter *et al*., 2015). Alternatively, previous research monitoring discarded individuals from pots had low or zero release mortalities at median fishing depths ranging from 27.5 – 50.6 m, similar to the depths fished within LMZs E, F, and G (Pol and Walsh, 2005; Marcell *et al*., 2016).

The results from our research provide an initial but necessary assessment of the interaction between cod and commercial lobster gear, which should be incorporated into future stock assessment and fishery managements plans. However, regional differences of fishing practices and abiotic variation, such as those observed in northern Maine and the SNE lobster fishery, may alter the discard mortality rates from the estimates found within our study. Future work should be prioritized towards determining the discard mortality of cod within the remaining LMZs (A, B, C, and D). Dedicated research within these areas will be able to account for differences in spatio-temporal accuracy as well as expand upon the effect of abiotic variability on discard mortality (i.e. bottom temperature and fishing depth) which fall outside of the parameters of the current research.

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Tables and figures:

Table 1. Four-tiered injury scale modified from Capizzano *et al*., (2016) to score the degree of physical trauma present in cod captured within commercial lobster traps. Cod with instances of minor barotrauma not visible upon observation were categorized as injury 1.

Injury Score	**Condition**	**Definition**
1	Excellent	Undamaged or injury not observable
2	Good	Minor barotrauma (e.g. swollen stomach) or physical trauma (<1 cm laceration)
3	Poor	Moderate barotrauma (e.g. exophthalmia) or physical trauma (>1 cm laceration)
4	Moribund/ Deceased	At-vessel mortality; Severe barotrauma (e.g. stomach eversion) or physical trauma (e.g. exposed internal organs)

Table 2. Summary of inshore lobster trap configurations as seen in McCarron and Tetreault, (2012) between the individual Lobster Management Zones (LMZs) in the GOM. All information represents mean values per individual zone. Zones E and F were included in our mortality estimate due to the similar habitat and fishing practices. Landing percentages in this table were taken from the FY2010.

Zone	Fishing Depth (m)	Landings	Tidal Change	Habitat	Fishing Season	Soak Time (days)	Trap Limits (trawl)
A	18 – 54	20%	±7.62	Hard and gravel, some mud and sand	Apr. – Dec.	3 – 7	3 – 12
B	18 – 73	13%	±4.57	Mix of hard and mud bottom	Summer – Fall	3	≤ 3
C	9 – 45	24%	±4.57	Hard, some sand and mud	Mar./Apr. – Dec.	3 – 5	≤ 3
D	18 – 73	21%	±4.27	Predominately rock with some sand and mud	Mar./Apr. – Dec./Jan.	3 – 5	≤ 3
E	18 – 73	6%	±3.96	Hard, some sand and mud	Apr. – Dec.	1 – 5	2 – 3
F	27 – 64	12%	±4.57	Mix of mud, sand, gravel, and rock	Apr. – Dec.	2 – 3	1 – 2
G	27 – 64	4%	±3.96	Mix of mud, sand, gravel, and rock	Apr. – Nov.	3 – 6	≤ 3

Table 3. Observed injury scores of all recaptured cod (*n* = 6) totaling seven individual recapture events. Cod IDs with a 1622- prefix indicate acoustically tagged individuals (IA), otherwise a four number serial ID represents a T-bar anchor tag (OA). Severity of observable external injuries increase upon each following recapture event, with the exception of cod 1622031. Days at liberty are representative of the days between the initial and proceeding capture events.

ID	Injury Score	TL (cm)	Capture Date	Days at Liberty
1622031	2	45.6	06/28/17	-
	2		07/05/17	7
	3		08/28/17	54
1622105	1	46.5	07/19/16	-
	4		03/28/17	252
1622119	1	46.6	07/06/16	-
	2		07/29/16	23
1622191	1	51.5	06/21/16	-
	2		07/29/16	38
1622203	1	47.0	07/05/16	-
	2		07/27/16	22
0277	1	48.0	05/19/17	-
	2		05/24/17	5

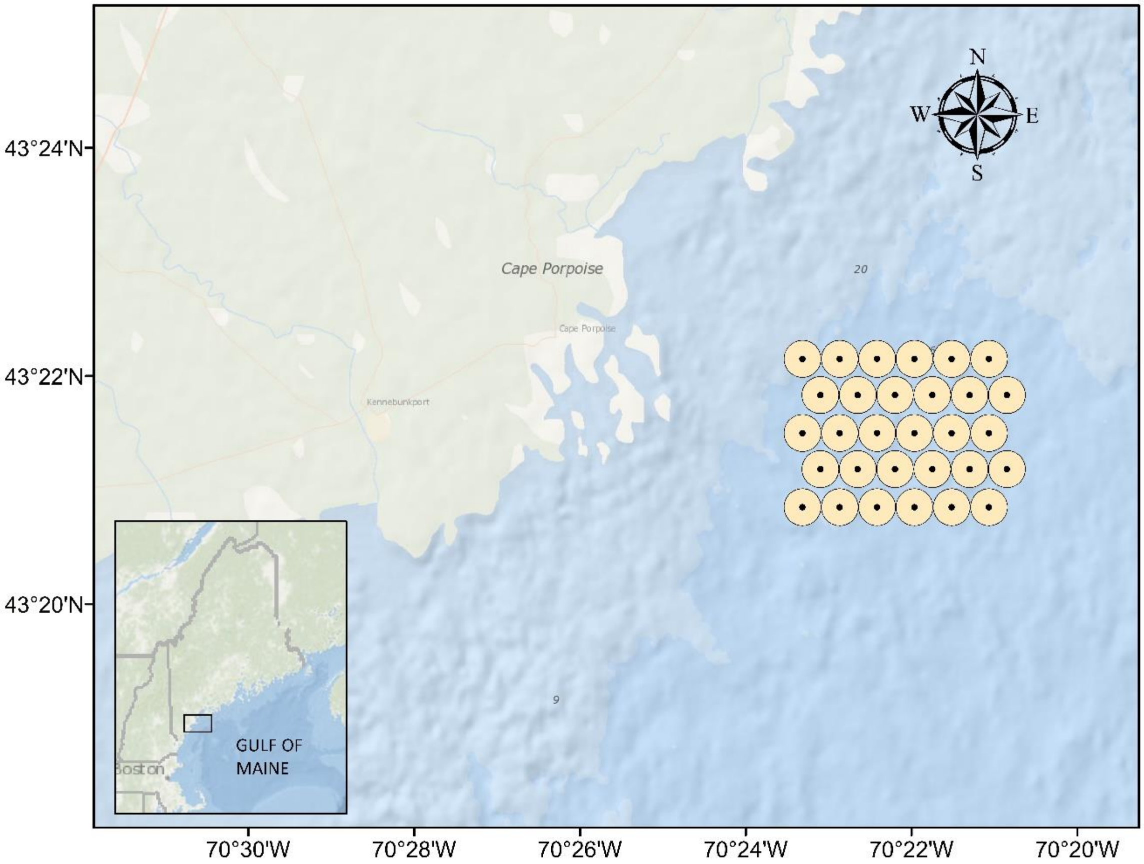

Figure 1. The study site and acoustic receiver (Vemco model VR2W) array located approximately 5 km off the coast of Cape Porpoise, Maine. Receivers are indicated by black dots (•) and surrounded by their theoretical 600 m diameter detection range which provided continuous area coverage of 30 km^2.

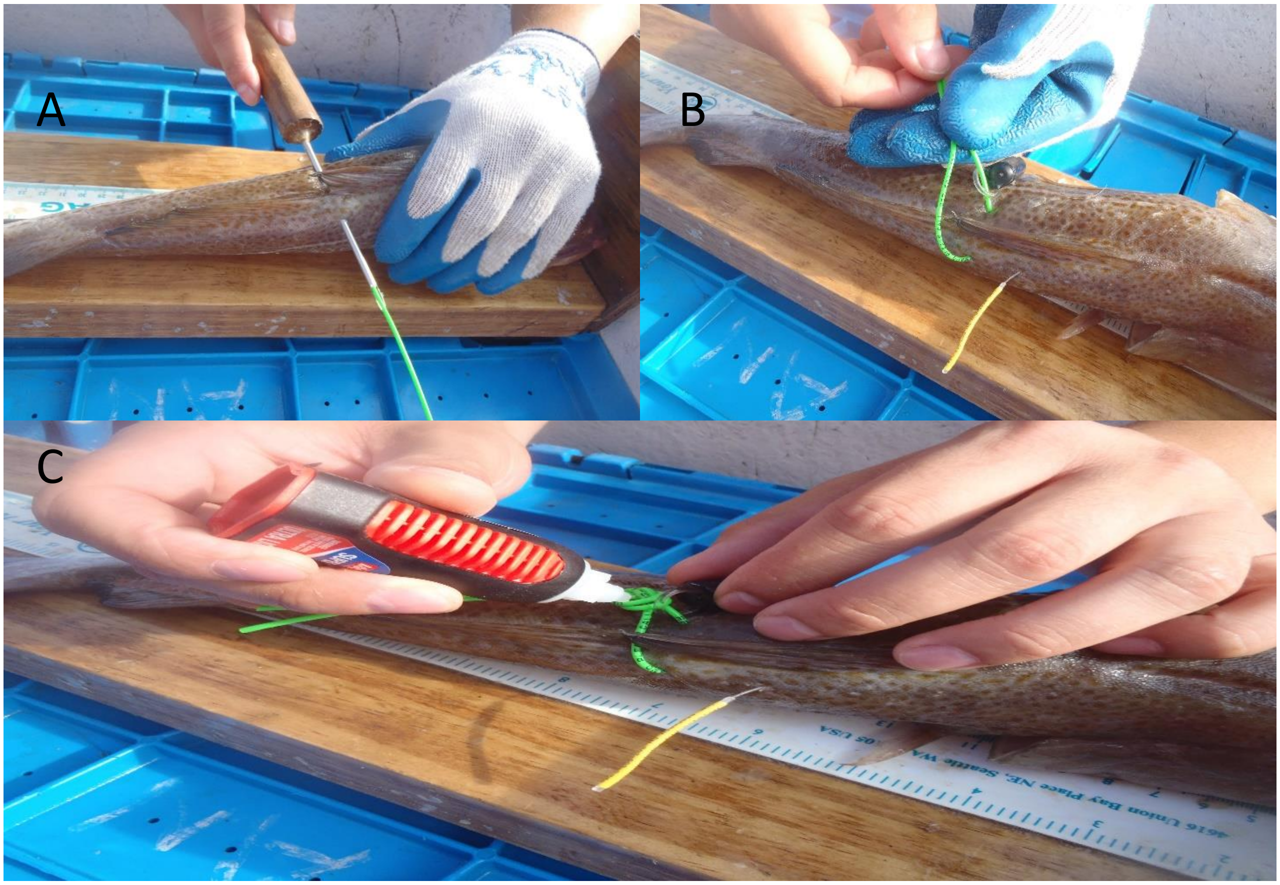

Figure 1. The tag application process used to attach the Lotek acoustic transmitter (ADT-MP-9-SHORT). A dart tag applicator was used to keep the invasive process to a minimum and allowed for the most rapid and efficient method to apply the transmitter (2a). The transmitter was secured to the body through the use of an ultra-thin spaghetti tag looped through the dorsal musculature (2b). Finally, the spaghetti tag was tied and secured with a sufficient application of Loctite Ultra Gel (2c).

Figure 2. Acoustic transmitters were modified with a loop attachment site through the use of 50lb monofilament, electrical tape (3M Scotch ¾''), Loctite Ultra Gel (Henkel Corporation, Westlake, Ohio), and shrink wrap (HS515-1.22M – Heatshrink, 12 mm).

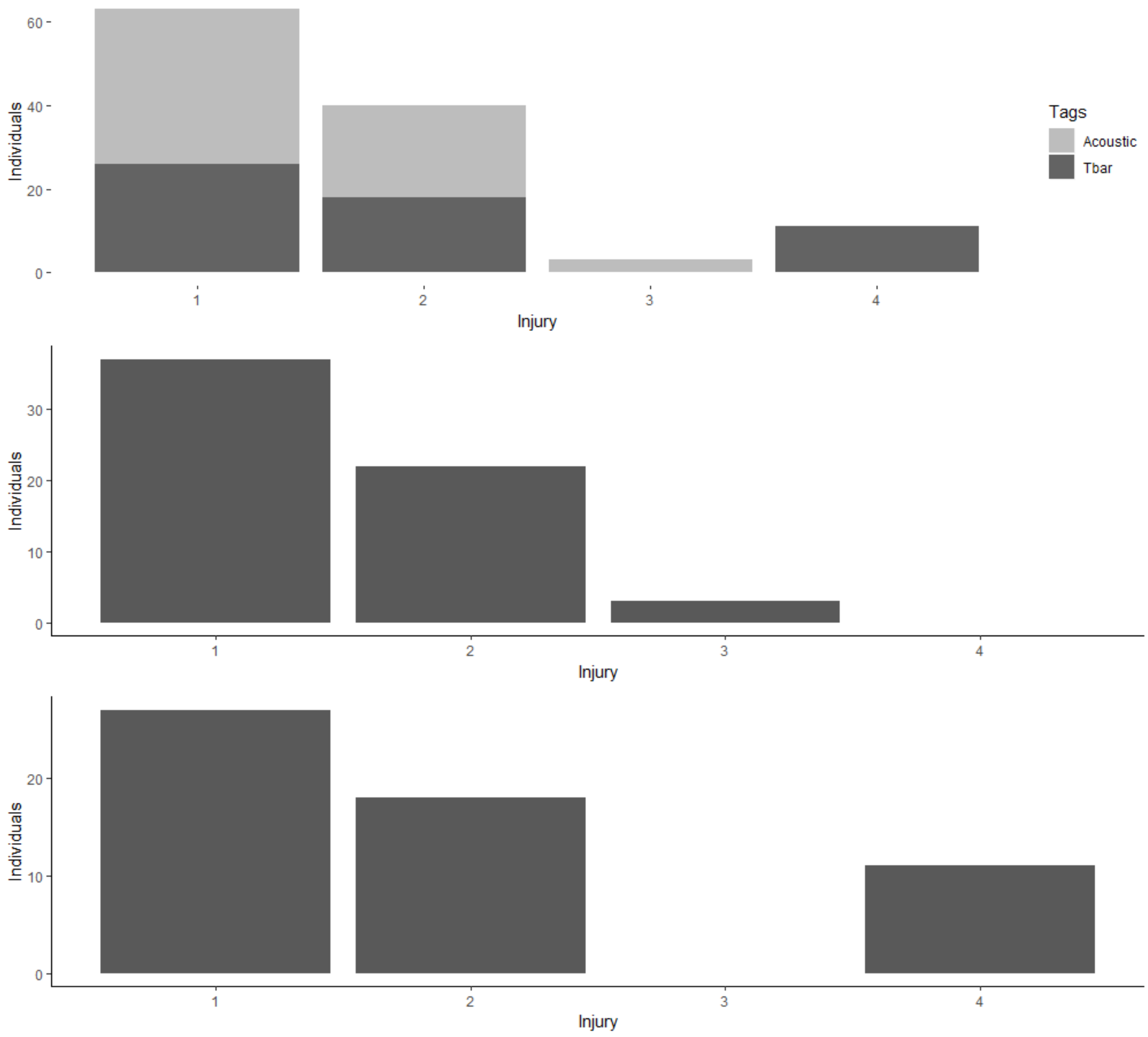

Figure 4. Summary of observed injury condition throughout the duration of the field sampling. A total of 118 capture events were observed between cod tagged with acoustic transmitters and Tbar anchors (4A). The distribution of injuries between tagged cod with acoustic transmitters (4G) and tbar anchors (4C) are skewed towards injury conditions 1 and 2.

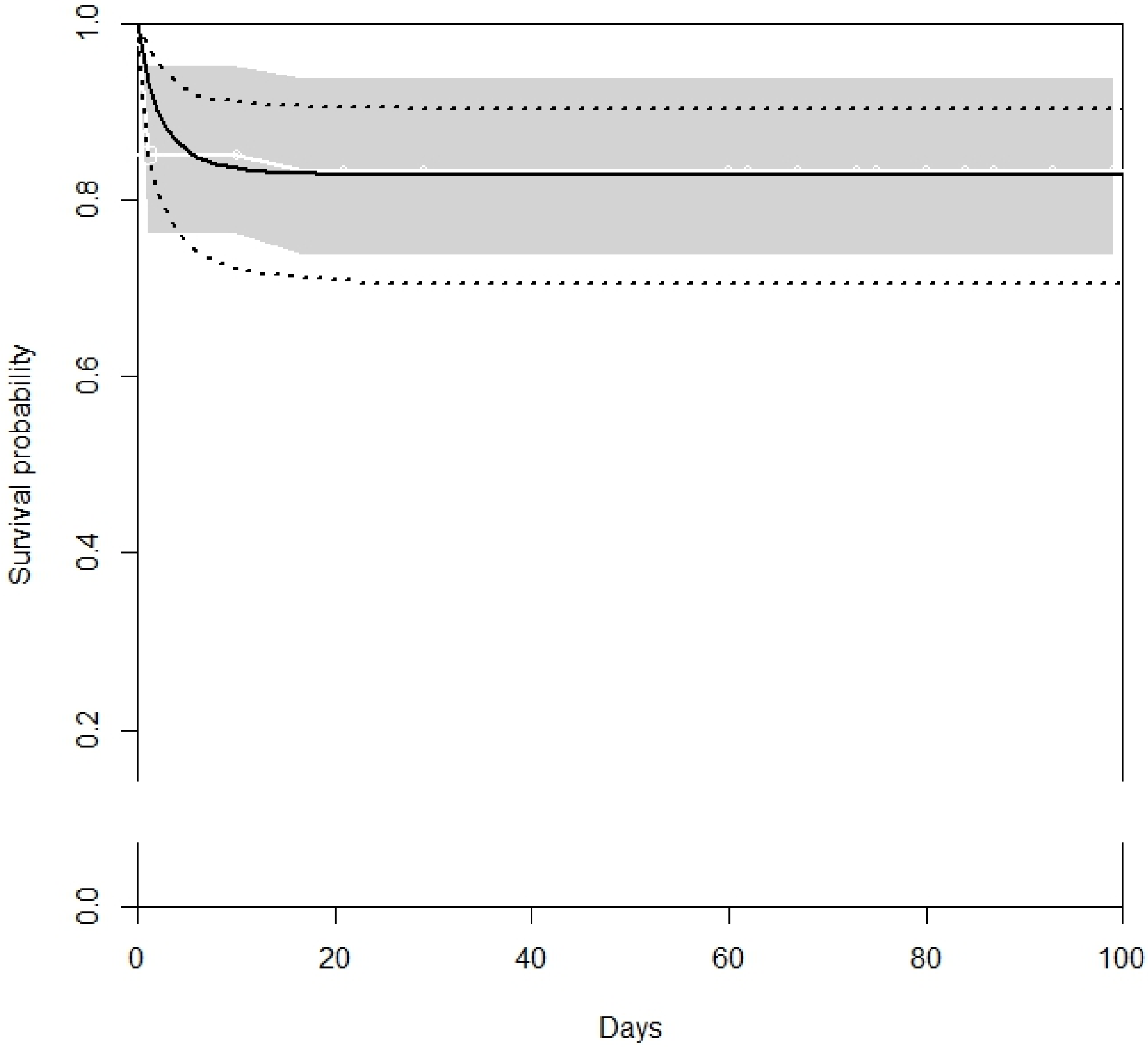

Figure 5. Estimate of long-term mortality for Atlantic cod (*Gadus morhua*) within the commercial lobster fishery. Using the mixture-distribution parametric model (Benoît *et al.*, 2012; Benoît *et al.*, 2015) discard mortality is calculated at 0.171% (0.091 – 0.297 95% CI; dotted black lines). Additionally, this discard mortality is reflected in the Kaplan-Meier estimate (white line and grey band). The mortality asymptote is reached after 26.0 days. The longest period of time a cod was monitored within the acoustic array was 187.4 days.

This thesis has been examined and approved.

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