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ARTICLE

Estimating the Discard Mortality of Atlantic Cod in the Southern Gulf of Maine Commercial Lobster Fishery

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Abstract

The Gulf of Maine (GOM) commercial lobster fishery has approximately 3.5 million actively fished traps and captures several nontargeted groundfish species, including Atlantic Cod *Gadus morhua*, as bycatch, yet there has been limited research on the incidental mortality of groundfish in this fishery. Although the mortality of Atlantic Cod has been estimated in other GOM commercial fisheries, unaccounted discard mortality in the lobster fishery may impair recovery efforts for this stock. To help meet research needs, we assessed the discard mortality rate of Atlantic Cod captured in the Maine Lobster Management Zone G commercial lobster fishery using acoustic transmitters and observations of viability. From 2016 to 2017, 111 Atlantic Cod were captured in 18,853 individual trap hauls and were observed for viability. A subsample of 54 Atlantic Cod was externally tagged with acoustic transmitters and observed after release. The combined at-vessel mortality (9.3%) and model-based long-term discard mortality (17.1%) estimates indicated an overall discard mortality rate of 24.8% for Atlantic Cod captured in commercial lobster gear. Based on this finding and the low bycatch of Atlantic Cod in the lobster fishery, the commercial lobster fishery may not be responsible—to the extent previously assumed—for hindering the GOM Atlantic Cod stock's regrowth.

The Gulf of Maine (GOM) fishery for American lobster *Homarus americanus* is the most lucrative commercial fishery in the northeastern United States, with an ex-vessel landings value of US$563.6 million in 2017 (NMFS 2017). According to the most recent available data, commercial lobster fishermen actively deploy approximately 3.5 million lobster traps within the GOM and an additional 175,000 traps are estimated to be lost in this region annually (ASMFC 2009; GOMLF 2014). Although designed to capture a single species through two funneled openings, the configuration of lobster traps still yields incidental bycatch of several groundfish species (e.g., Atlantic Cod *Gadus morhua*, sculpins, Sea Raven *Hemitripterus americanus*, Cunner *Tautogolabrus adspersus*, etc.; MSC 2013). Although such bycatch events are mitigated with a biodegradable escape panel (measuring at least 9.5×9.5 cm), larger fish that become trapped in the pots via the much larger funneled opening may be unable to escape.

Of particular concern, it has been suggested that the GOM Atlantic Cod population may be negatively impacted by bycatch in the commercial lobster fishery. This stock has reached historically low biomass levels despite the implementation of strict management plans (Serchuk and Wigley 1992; Leavenworth 2008; Nenadovic et al. 2012; NEFSC 2013, 2017; Pershing et al. 2013). While past research has suggested overfishing (Jackson et al. 2001; Kleiven et al. 2016), climate change (Pershing et al. 2015; Palmer et al. 2016; Swain et al. 2016), and predation (Collie et al. 2013) as reasons for the observed declines, the mortality of individuals captured and discarded within the lobster fishery may be contributing to the low stock biomass (MSC 2013). However, the only existing information on the interaction between Atlantic Cod and lobster gear is based on limited observer data collected in the Maine (state and federal waters) fishery (MSC 2013). Here, bycatch statistics extrapolated by the Marine Stewardship Council estimated that approximately 177,247 Atlantic Cod were captured in the lobster fishery during 2008 (MSC 2013). Although this estimate was provided as evidence to support a ban on lobster gear in known Atlantic Cod spawning grounds (Bell 2014a), industry stakeholders and the Maine Department of Marine Resources fought this measure due to the absence of a dedicated study of Atlantic Cod bycatch in the fishery and concerns about the validity of the data in the Marine Stewardship Council's report (MEDMR 2012; Keliher 2014; Bell 2014b). While this bycatch estimate has raised concerns for the Atlantic Cod stock (Keliher 2014; Bell 2014), understanding whether these fish survive after capture and handling is necessary to document the true impact of the GOM commercial lobster fishery on Atlantic Cod (MEDMR 2012; Boenish and Chen 2017, 2020).

Acoustic telemetry has emerged as an effective tool for assessing the fate of discarded fish under natural conditions (e.g., Curtis et al. 2015; Capizzano et al. 2016; Ferter et al. 2017; Hayes et al. 2019) and can be especially powerful for cases in which the species and/or size-class remains active within a limited spatial range (Capizzano et al. 2016). In addition, acoustic telemetry enables the determination of specific times when an animal dies or was last observed alive (i.e., longitudinal data); such data can then be analyzed with specific survival models that are capable of quantifying and explaining survival parameters (e.g., Benoît et al. 2015).

Given the potential impact of the commercial lobster industry on an already depleted Atlantic Cod stock (Pershing et al. 2015; Palmer 2017), the primary objective of this study was to use acoustic telemetry in tandem with a suite of health indicators and environmental factors to estimate the discard mortality (DM) of Atlantic Cod within the Maine Lobster Management Zone (LMZ) G commercial lobster fishery. In addition, the study evaluated the influence of several covariates (soak time, air temperature, and surface and bottom water temperatures) on at-vessel mortality (AVM; also referred to as immediate mortality) in order to recommend best fishing practices (Capizzano et al. 2016) for increasing the survival rates of Atlantic Cod that are discarded in the commercial lobster fishery.

METHODS

Acoustic array.— The acoustic receiver array, constructed off the coast of southern Maine (43°21′30′′N, 070°22′25′′W) in a location suspected to support year-round presence of Atlantic Cod (Ames 2004), was composed of 30 VEMCO VR2W 69-kHz receivers (VEMCO Division, Amirix Systems, Inc., Bedford, Nova Scotia), resulting in a detection area of roughly 30 km^2 (Figure 1). Each receiver station configuration consisted of a single, 22.7-kg mushroom weight secured to a bullet buoy that was attached to 35 m of sink line and 15 m of float line. 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 that time period.

Gear configuration.— Atlantic Cod were collected from commercial lobster traps (122 × 53 × 34 cm) designed according to the state management regulations of Maine LMZ G, ranging from Cape Elizabeth to Kittery, Maine (Figure 1). Gear configurations within the southern Maine lobster fishery may vary between fishermen; however, all gear within LMZ G must meet regulation standards to legally capture lobsters within this region. Explicitly for this study, traps deployed inside the acoustic array (IA) consisted of 10 strings, each comprising 10 two-trap trawls for a total of 200 individual traps. Atlantic Cod were also collected from hauls of 600 traps, constructed of three-trap and five-trap trawls, outside of the acoustic array (OA; ≥0.5 km) in order to increase the probability of capturing individuals that would be tagged with acoustic transmitters. Moreover, the observation of hauls from IA and OA increased the number of traps fished over a larger area, which more accurately represented the Atlantic Cod CPUE per day within the southern Maine commercial lobster fishery. The placement of fishing gear varied by both depth and bottom type (e.g., gravel, sand, and mud), consistent with the standard practices of a commercial lobster vessel within this region.

This study examined Atlantic Cod that were caught as bycatch during lobster fishing activities between May 2016 and 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*, and cowhide lobster bait; Worcester's Lobster and Crab Bait, Prospect, Maine) and were hauled every 4–6 d, emulating practices within the southern Maine region. Fishing was conducted aboard the F/V *Christina Mae II* (Captain Ed Hutchins; 11.6 m). Data collected upon landing Atlantic Cod included soak time (i.e., days from trap deployment to retrieval), handling and air exposure times (i.e.,

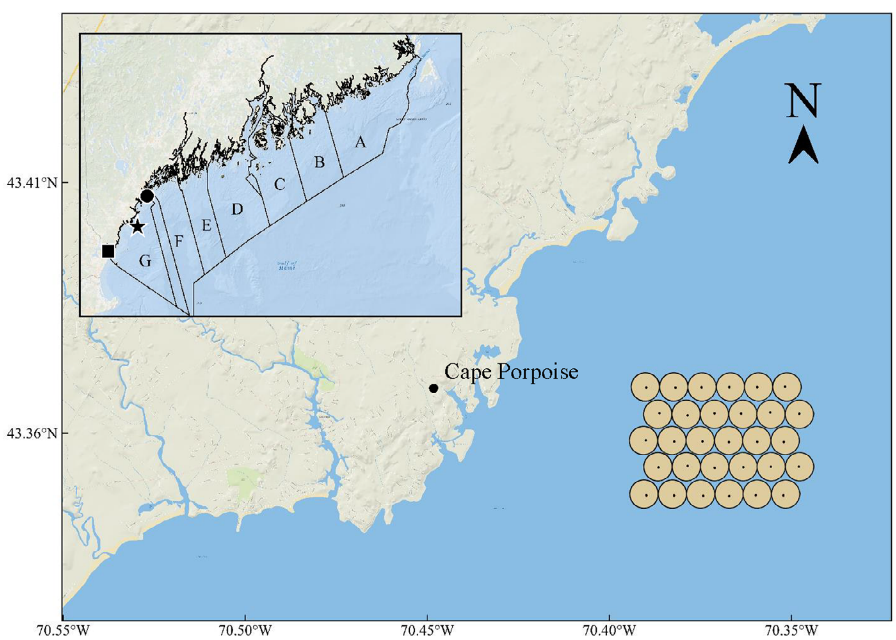

FIGURE 1. The study site and acoustic receiver array, located approximately 5 km off the coast of Cape Porpoise, Maine. Receivers are indicated by black dots and surrounded by their theoretical 600-m-diameter detection range, which provided continuous area coverage of 30 km^2. The inset map displays Maine Lobster Management Zones A–G; the star indicates the general location of the acoustic array, the circle indicates the location of Cape Elisabeth, and the square indicates the location of Kittery, Maine.

stopwatch recording the time from removal from the trap until release), capture depth, bottom type, air temperature, and surface and bottom water temperatures. We recorded air temperature with a Ben Meadows Traceable Waterproof Mini Thermometer (Forestry Suppliers, Jackson, Mississippi), surface water temperature with a YSI Model 30M (YSI, Yellow Springs, Ohio), bottom water temperature with a HOBO Water Temperature Pro v2 data logger (Onset Computer, Bourne, Massachusetts), and depth and bottom type with a Raymarine Digital Sounder Module 300 (dual 50 and 200 kHz, 1,580 pulses/min at 15 m; FLIR Maritime, Nashua, New Hampshire). Individual Atlantic Cod were measured for TL to the nearest centimeter and were assessed for injury using a modified four-level ordinal index designed previously for Atlantic Cod by Capizzano et al. (2016; Table 1). Individuals classified as injury level 4 were assumed either dead or moribund and were considered to have experienced AVM.

Tagging procedure.— Prior to field tagging, a preliminary in-lab attachment test following the protocol for external field application ensured the retention and survival rate of four individuals tagged with acoustic transmitters and two individuals tagged with T-bar anchor tags over the course of 30 d (100% survival rate). These Atlantic Cod were captured through hook-and-line fishing near the acoustic array, transported to the University of New England within a live well, and placed into a holding tank. Observations occurred twice daily to monitor liveliness and degree of injury in addition to detailed examination of the attachment site for disturbances (i.e., cohesion loss and skin necrosis). Although the tagging protocol applied in the field was identical to the in-lab tagging procedure, it was assumed for analysis purposes that the absence of mortality from tagging would be observed in Atlantic Cod tagged in the field. However, due to the unpredictable nature of field work and the variability between the two systems (e.g., controlled environment, presence or lack of predation events), there may be unobserved discrepancies that lie outside the confines of this study.

TABLE 1. Four-tiered injury scale (modified from Capizzano et al. 2016) used to score the degree of physical trauma present in Atlantic Cod captured within commercial lobster traps.

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)

Due to size limitations of the acoustic array, individuals that were 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 compared mortality rates between these individuals and those captured within the array to ensure that transportation was not an additional covariate influencing mortality. Tagged fish were chosen opportunistically, without restrictions on size and injury status, to remove the possibility for selection bias due to the low CPUE of Atlantic Cod (0.006 fish/trap) in commercial lobster gear in this region. All captured individuals received a Floy T-bar tag; however, only Atlantic Cod that were limited to the confines of the array (including the 0.5-km adjacent area) received acoustic transmitters.

After individual Atlantic Cod were sampled, a modified external attachment tagging method from Capizzano et al. (2016) was used to minimize air exposure duration and handling time. To secure the location of the acoustic transmitter, a dart tag applicator (3.40-mm outer diameter) pierced the dorsal musculature below the rear base of the primary dorsal fin (Figure 2). A small segment of ultra-thin Floy spaghetti tag (Model FT-4; Floy Tag and Manufacturing, Seattle) was passed through the opening and tied into a knot to secure the attachment of the transmitter (Model ADT-MP-9-SHORT; 9×28 mm, 3.7 g in air, 2.2 g in water, pressure sensor maximum depth = 86 m [resolution = 0.01 m, accuracy = $\pm$0.5 m], minimum temperature sensor = 0°C [resolutio = $\pm$5°C]; Lotek Wireless, Thelma Biotel, Trondheim, Norway). Additionally, a droplet of Loctite adhesive (Henkel Corporation, Westlake, Ohio) was applied to the knot to prevent detachment. A 22.5-kg monofilament loop fastened the acoustic transmitter to the attachment site using electrical tape (3M Scotch, 1.905 cm [0.75 in]) and Loctite Ultra Gel, reinforced with shrink wrap (HS515-1.22M; Heatshrink, 12 mm). After tagging, the animals were released. Acoustic transmitters tracked Atlantic Cod by using a random ping schedule wherein pings were generated every 30–90 s until the cessation of battery life, estimated to be 8 months by the manufacturer. Additionally, individuals that were captured OA within commercial lobster gear were subject to the aforementioned sampling protocol (i.e., measured, assessed for injury, etc.) and tagged with Floy T-bar tags (Model FD-94).

Data analysis.— In acoustic tagging studies, mortality of an individual is typically inferred from an absence of depth variation over an extended period of time. However, the bathymetry in the study area is highly irregular and some depth variation could be generated from the

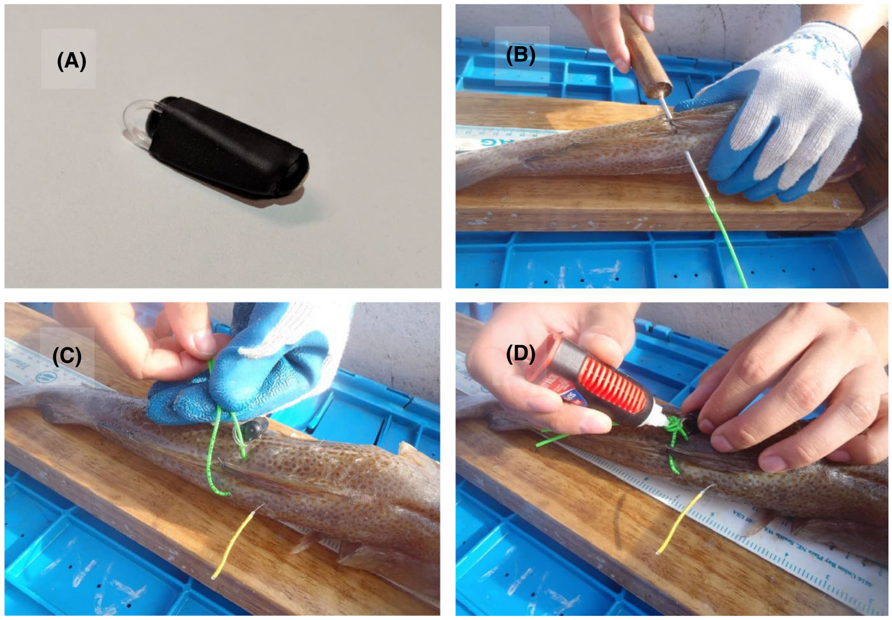

FIGURE 2. The tag application process used to attach **(A)** the Lotek acoustic transmitter (ADT-MP-9-SHORT). **(B)** A dart tag applicator was used to minimize injury and allow for the rapid and efficient application of the transmitter. **(C)** The transmitter was secured to the body through the use of an ultra-thin spaghetti tag looped through the dorsal musculature. **(D)** Finally, the spaghetti tag was tied and secured with a sufficient application of Loctite Ultra Gel. [Color figure can be viewed at afsjournals.org.]

passive drift of a dead Atlantic Cod along the seafloor. To overcome this problem, we adopted the approach of Capizzano et al. (2016). A subset of individuals euthanized via pithing was acoustically tagged and released in the array to identify depth signatures of passive drifting Atlantic Cod and therefore served as negative controls. Detection data were downloaded from acoustic receivers using VEMCO's User Environment (VUE version 2.3.0) software. Differences in depth variation over time between negative controls and Atlantic Cod released alive with acoustic transmitters were used to classify dead individuals (e.g., postrelease mortality, predation) by using a semi-quantitative test that combined methods from Capizzano et al. (2016) and qualitative review (Figure 3). The test, applied to each successive postrelease time bin for each Atlantic Cod with an acoustic transmitter, identified the mortality event and determined a time of death. To ensure greater test accuracy, the tidal cycle from the study site was removed from each individual Atlantic Cod's vertical depth time series using the R package "oce" version 0.9-19 (Kelley and Richards 2016).

To estimate the total DM of Atlantic Cod within the commercial lobster fishery, the estimates of AVM and long-term DM were added together. At-vessel mortality was estimated from Atlantic Cod captured in commercial lobster traps. A binomial generalized linear model (logistic regression with logit link) was used to model AVM as a function of capture-related predictors, including fishing depth, TL, soak time, air temperature, surface and bottom water temperatures, and the water temperature gradient (Zhang and Chen 2015). Here, covariate inclusion was determined by forward selection through minimization of Akaike's information criterion corrected for small sample sizes (AIC_c). In the event that the inclusion of multiple covariates provided the best model fit, correlation among them was assessed to ensure that collinearity was not influencing the interpretation of the results. To estimate the long-term DM rates within the fishery, survival data from Atlantic Cod tagged with acoustic transmitters were fitted with a mixture distribution parametric model that accounted for fish that left the array before suffering mortality (i.e., right-censored individuals) following the methods of Benoît et al. (2012, 2015). Briefly, the parametric model is defined as

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

where $S(t)$ is survivorship to time t, α and γ are parameters of a Weibull survival function that describes the attrition of fish that will die after release due to the capture-and-release event, and π is the DM rate. Survivorship $S(t)$ reaches an asymptotic value of $1 - \pi$ once all mortality associated with the capture-and-release process (including delayed mortality) has occurred. This model can be modified to also account for natural mortality (Benoît et al. 2015); however, this was not implemented because sample sizes were small and an asymptote in $S(t)$ was rapidly achieved, suggesting that natural mortality was negligible

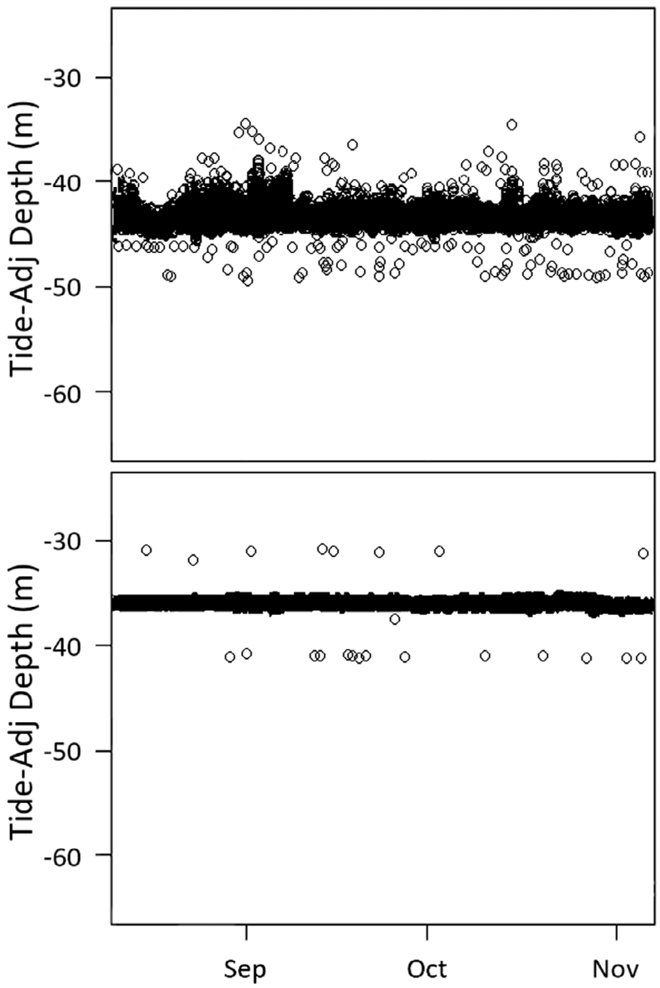

FIGURE 3. Depth detections (with tidal influence removed; tide-adjusted [adj] depth) between a live Atlantic Cod (top panel) and a negative control (bottom panel) over the course of approximately 3 months in 2016. A significant difference in the vertical variance between these individuals allowed for quantitative comparisons in determining postrelease mortality of Atlantic Cod tagged with acoustic transmitters.

during the short time span of the acoustic tag monitoring period; we also assumed that all mortality resulting from discarding was expressed during the monitoring period. The model in equation (1) was fitted to event time data (mortality times, or time of last observation prior to leaving the array) via minimization of the AIC_c and maximum likelihood estimation. All analyses were performed in R version 3.5.0 (R Core Team 2016).

RESULTS

Observations of Total Length, Injury Condition, and Movement Data

The acoustic array was active for a total of 369 d throughout the sampling period (June 6–November 11, 2016; and April 12–November 10, 2017), accumulating over 731,658 individual detections and 4,759.4 d of movement data. In total, 111 Atlantic Cod ranging in TL from 23.5 to 64.5 cm (mean ± SD = 47.0 ± 11.5 cm) were captured over 105 fishing trips (consisting of 18,853 individual lobster trap hauls) at depths from 37.8 to 64.6 m (mean ± SD = 50.13 ± 7.53 m) (Supplementary Materials available in the online version of this article). The number of captured Atlantic Cod was similar for the 2016 and 2017 fishing years: 59 and 52 individuals, respectively. There was no significant difference (two-sample *t*-test: $P = 0.88$) between the lengths of Atlantic Cod tagged from IA (acoustic transmitters, $n = 54$; mean ± SD = 47.3 ± 5.5 cm) and those tagged from OA (T-bar anchors, $n = 57$; mean ± SD = 46.7 ± 13.9 cm). Out of the 111 captured Atlantic Cod, 11 fish suffered AVM, 5 fish were recaptured once, and 1 fish was recaptured twice, for a total of 118 individual capture events. The 118 individual capture events consisted of 66 individuals with an injury score of 1 (56.0%), 38 fish with an injury score of 2 (32.2%), 3 fish with an injury score of 3 (2.5%), and 11 fish with an injury score of 4 (9.3%; considered to have succumbed to AVM). With the inclusion of recapture events ($n = 6$), observed injuries of Atlantic Cod with acoustic transmitters consisted of 37 individuals with an injury score of 1 (59.7%), 22 fish with an injury score of 2 (35.5%), and 3 fish with injury score of 3 (4.8%). Injuries observed from T-bar-tagged individuals with the inclusion of recapture events ($n = 56$) were composed of 27 fish with an injury score of 1 (48.2%), 18 fish with an injury score of 2 (32.1%), and 11 fish with an injury score of 4 (19.7%).

Severity of injury scores increased over time for the six tagged fish that were recaptured over the course of the study, with one individual classified as AVM upon recapture. The mean time at liberty for the five recaptures that survived was 24.8 d, while the individual that suffered AVM had an observed 252 d at liberty. Among the 54 Atlantic Cod that were tagged with acoustic transmitters, 9 (16.4%) were inferred to have died. These individuals ranged in TL from 41.5 to 54.0 cm (mean ± SD = 47.1 ± 4.3 cm) and had the following prerelease injury scores: two fish (both 44.0 cm) had an injury score of 1, six fish (range = 49.0–54.0 cm) had an injury score of 2, and one fish (54.0 cm) had an injury score of 3. The residence time within the acoustic array ranged between 0.2 and 187.4 d (mean ± SD = 86.5 ± 56.8 d). Eleven Atlantic Cod in 2016 and eight fish in 2017 were detected within the confines of the study area up to the removal of the acoustic array. Additionally, 18 acoustically tagged Atlantic Cod in each of the 2016 and 2017 fishing years were inferred to be alive right up until the time when the individuals migrated outside the detection range of the array. The vertical movement patterns of these individuals were analyzed and found to be similar to those of the individuals that were recaptured alive, therefore indicating that the fish exhibited vertical movement patterns of known survivorship. In a similar fashion, to address the possibility that individuals tagged with transmitters remained undetected within the acoustic array (i.e., between receiver detectability radii), horizontal movement patterns were compared against the movements of Atlantic Cod serving as negative controls.

Five individuals that were captured near the edge of the acoustic array's detection area (within ~0.5 km) were tagged with acoustic transmitters, transported, and released within the core of the acoustic array. The results from Fisher's exact test ($P = 0.1782$) suggested that transportation did not increase mortality compared to individuals that were captured, tagged, and released within the array. Data for acoustically tagged individuals that were captured IA and OA were therefore combined.

Estimating Bycatch Mortality

A logistic regression including all IA and OA observations indicated that fishing depth, individual TL, soak time duration (continuous variable), air temperature, surface and bottom water temperatures, and water temperature gradient were not significant predictors of AVM (Table 2). For individuals fitted with acoustic transmitters, the mixture distribution parametric model estimated a long-term DM rate of 17.1% (95% CI = 9.1–29.7%; Figure 4). Additionally, this model estimated that the mortality rate reached an asymptote after 26.0 d (95% CI = 9.30–88.3 d), confirming that the study was of sufficient duration to properly estimate DM (Benoît et al. 2015). To estimate the overall total mortality observed within this fishery, the long-term DM rates were applied to the group of individuals that survived (90.7%) the capture and handling process. The results of the combined estimates of AVM (9.3%) and the long-term DM from the model-based estimates (17.1%) resulted in an overall total DM rate of 24.8% in the Maine LMZ G commercial lobster fishery.

TABLE 2. Results of the forward selection procedure used to determine covariate inclusion in the logistic regression model of Atlantic Cod at-vessel mortality (AIC_c = Akaike's information criterion corrected for small sample sizes). These results incorporate individuals that were captured inside the acoustic array and outside of the acoustic array (i.e., the two groups were pooled). The logistic regression fit was not improved by including any of the predictors monitored in this study.

Model	AIC_c
Intercept	37.15
TL	37.73
Water temperature gradient	38.07
Depth	38.11
Surface temperature	38.42
Air temperature	38.46
Bottom temperature	39.34
Soak time	39.92

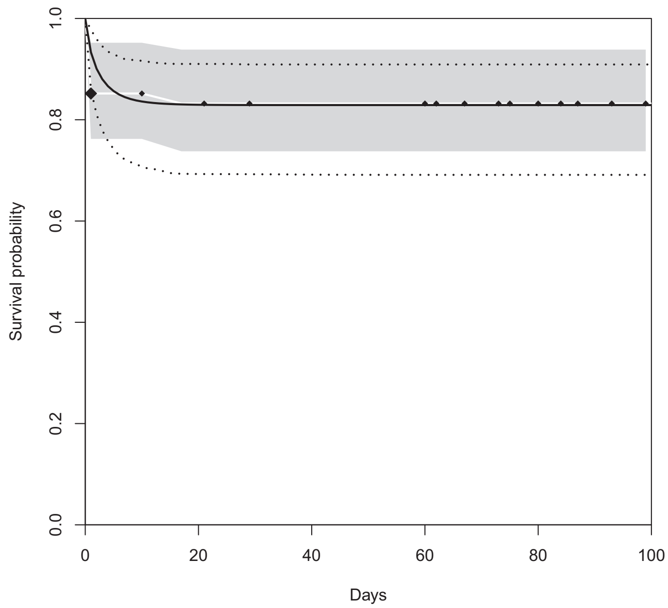

FIGURE 4. Estimate of long-term discard mortality for acoustically tagged Atlantic Cod. The black line represents the overall long-term discard mortality, and the dotted lines signify the 95% CI. The gray band and white line are the maximum likelihood estimate and the 95% CI, respectively, for the Kaplan–Meier survivorship estimate, which provides a model-free summary of the survival data. The black diamonds on the Kaplan–Meier curve indicate right-censored observations (i.e., an individual that left the array while still alive).

DISCUSSION

Estimated Discard Mortality

This study provides the first estimate of DM for Atlantic Cod captured in a GOM commercial lobster fishery, which is essential information for understanding the recovery potential of the GOM Atlantic Cod stock and for managing one of the largest and most valuable commercial fisheries in the northeastern United States (MEDMR 2017). Collectively, the observed AVM (9.3%) and model-based long-term DM (17.1%) rates indicate an overall mortality rate of 24.8% for Atlantic Cod captured in the Maine LMZ G commercial lobster fishery, and this mortality rate can also be applied to LMZs E and F, which share similar fishing depth and fishing gear configurations (Table 3). Maine LMZs E, F, and G are adjacent in space and do not share as many distinctive features with the more northerly LMZs, which is further reflected in the difference in substrate type (soft and hard bottom, respectively). Examining the DM rates that have been estimated for Atlantic Cod in other fisheries, including recreational (11.2%: Weltersbach and Strehlow 2013; 16.5%:

TABLE 3. Summary of inshore lobster trap configurations (as described by McCarron and Tetreault 2012) between the individual lobster management zones in the Gulf of Maine. 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. Landings percentages in this table were taken from the 2010 fishing year.

Zone	Fishing depth (m)	Landings (%)	Tidal change (m)	Habitat type	Fishing season	Soak time (d)	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

Capizzano et al. 2016), handline (43.0%: Pálsson et al. 2003), pelagic longline (69.0%: Milliken et al. 1999), and demersal longline (31–100%: Milliken et al. 2009) fisheries, demonstrates the gear-specific nature of fishing mortality for this species. Based on comparisons between gear types, Atlantic Cod may be more resilient to capture in commercial lobster gear compared to most gears used in other fisheries. Moreover, Atlantic Cod CPUE in commercial lobster gear is relatively low. Models that were produced using observer data indicated that the probability of capturing Atlantic Cod as bycatch in a commercial lobster trap was less than 0.1% in LMZ G from 2006 to 2013, with approximately 40,000–50,000 Atlantic Cod discarded per year (Boenish and Chen 2017). To estimate the weight of Atlantic Cod discards from 2006 to 2013, it was assumed that individuals observed in this study reflected the length distribution of Atlantic Cod bycatch within the commercial lobster fishery. The weight of each Atlantic Cod captured throughout this study was calculated by using a length–weight relationship ($W = 0.000005132 \cdot L^{3.1625}$, where W is weight [kg] and L is length [cm]; NEFSC 2013), and the total mean weight was determined from these values. Applying our DM rate to these discard estimates and estimating the mean weight of captured Atlantic Cod to be 1.041 kg, we can estimate that around 9,920–12,400 individuals or 10.3–12.9 metric tons of Atlantic Cod per year experienced DM within the commercial lobster fishery from 2006 to 2013. These discard estimates provide further insight into the controversial impact of commercial lobster gear on Atlantic Cod, which was initially suggested by the Marine Stewardship Council (MSC 2013). In comparison, the observed discards of Atlantic Cod from the bottom trawl commercial groundfish fishery in 2009 equaled 752 metric tons (Palmer 2017). However, as landings decreased in subsequent years, Atlantic Cod discards were reduced to 52 metric tons in 2013 and continued to decline to 8 metric tons in 2016. Given the relatively low DM estimate and bycatch CPUE, our study suggests that the GOM commercial lobster fishery may not be responsible—to the extent previously assumed—for hindering the GOM Atlantic Cod stock's regrowth.

Factors Influencing Mortality

A total of 5.4% of the Atlantic Cod collected throughout the current study were recaptured, similar to recapture rates reported in 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 (4.8%: Howell et al. 2008) fisheries. The majority of recaptured individuals exhibited an increase in the severity of injury with repeated capture and handling events. This finding was unsurprising, as multiple capture events are expected to increase the probability of mortality, commonly referred to as the cumulative mortality risk (Musick 1999; Burns 2002; Bartholomew 2005). Even for instances in which fish do not succumb to AVM, repetitive capture and handling events can subject individuals to cumulative injuries and increased predation risk, especially for long-lived species and populations subject to intense fishing pressure (Bartholomew and Bohnsack 2005). For example, a model by Bartholomew and Bohnsack (2005) estimated the postrelease mortality of Red Grouper *Epinephelus morio* at 12%, yet cumulative mortality increased to 72% after 10 capture-and-release events. Given that approximately 3.5 million lobster traps are actively hauled 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 an unknown impact on the long-term vitality of Atlantic Cod within this region (Ames 2004).

Barotrauma is often observed in finfish captured with nets or traps deployed at depth, and species with physoclistous swim bladders (i.e., Atlantic Cod) are particularly susceptible to rapid changes in pressure (Korsøen et al. 2010; Lancaster et al. 2017; Rankin et al. 2017). When Atlantic Cod are rapidly hauled from depth, internal gases expand at an accelerated rate, which inflates and potentially ruptures the gas bladder, causes a loss of equilibrium, and increases the probability of mortality due to postrelease predation events (Raby et al. 2014; Humborstad et al. 2016). Our study observed a low rate of external barotrauma symptoms, comparable to previous observations for Atlantic Cod captured in other gear types. For example, discarded individuals in the present study were noted to "float" (5.5%; $n = 3$) if unable to submerge soon after release, similar to observations in the recreational rod-and-reel fisheries (2.2%: Ferter et al. 2015; 5.2%: Capizzano et al. 2016). In contrast, Atlantic Cod captured in commercial fisheries at depths beyond those observed in this study exhibited the lethal effects of barotrauma (Stewart 2008; Milliken et al. 2009; Ovegård et al. 2011). Individuals captured at depths of 50 m or greater with angling gear, for instance, demonstrated a mortality rate exceeding 40%, indicating that the probability of mortality may be significantly impacted by capture depth (Ferter et al. 2015). Within LMZs B and E, where fishing occurs at depths of 70 m or greater, the probability of barotrauma increases, whereby floating individuals that are unable to quickly submerge on their own may be subject to avian predation, solar radiation, and unfavorable water temperatures and could experience mortality rates as high as 79% (Midling et al. 2012). However, the Maine–New Hampshire inshore trawl survey observed the highest capture rates of Atlantic Cod at shallow depths ($\leq$37 m) during the fall season (Peters et al. 2018). Due to the lower probability of capturing Atlantic Cod in deeper waters, the impact of DM as a direct result of barotrauma may not be significantly different between LMZs.

Linking specific factors related to capture and handling (i.e., air exposure duration, fish size, temperature, etc.) to the mortality of a species can be used to recommend best fishing practices within a given fishery. For example, previous research regarding best practices for gadoids in the recreational rod-and-reel fishery offered suggestions to avoid fishing grounds with smaller individuals (Capizzano et al. 2019) and to minimize handling times (Capizzano et al. 2016) so as to reduce injury and mortality. Interestingly, the current study found no significant predictors of AVM. However, the lack of significant relationships between fishing factors and AVM may be attributed, in part, to the uncontrolled nature of this fishery-dependent study. For example, soak time may not accurately reflect the amount of time individuals were confined in lobster traps, as fish have been observed to enter and exit trap gears at will (i.e., Jury et al. 2001; Cole et al. 2004). It is also important to consider the likelihood of additional stressors that were unaccounted for in our survival model (i.e., air exposure duration, fish size, and catch biomass) and that have been found to be related to mortality in other species (i.e., Capizzano et al. 2016, 2019). Given these uncertainties, further research into the specific factors contributing to the mortality of Atlantic Cod captured in the GOM commercial lobster fishery is needed in order to provide recommendations for best fishing practices.

Conclusions

Having gear-specific information on the DM of a bycatch species is critical for accurate stock assessments and effective fishery management plans. Our study provides an initial assessment of the mortality associated with the incidental capture and release of Atlantic Cod within the southern Maine commercial lobster fishery, which should be incorporated into future stock assessments and fishery management plans. Collectively, our results suggest that capture in commercial lobster gear may not be negatively impacting the GOM Atlantic Cod stock to the extent that was previously assumed. The results presented herein can fill data gaps in management plans and stock assessments, provide information on the impact of the southern Maine commercial lobster fishery on the GOM Atlantic Cod stock, and better inform stakeholders about the condition of this economically and ecologically important species.

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SUPPORTING INFORMATION

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