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Original Article

Estimating and mitigating the discard mortality of Atlantic cod (*Gadus morhua*) in the Gulf of Maine recreational rod-and-reel fishery

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In recent years, the recreational contribution to the total catch of Atlantic cod (*Gadus morhua*) in the Gulf of Maine (GOM) has increased with recreational discards outnumbering recreational landings by 2:1. However, the discard mortality (DM) rate of cod released in the recreational fishery remains poorly understood, thus contributing to the uncertainty in stock assessments and fishery management plans. The current study examined the capture-related factors most detrimental to cod DM in the GOM recreational rod-and-reel fishery. Atlantic cod ($n = 640$; 26.0 – 72.0 cm) were angled from June – October 2013 on southern Jeffreys Ledge in the western GOM using fishing gear representative of the local recreational fishery. A subset ($n = 136$) was also tagged with pressure-sensing acoustic transmitters before being released into an acoustic receiver array ($n = 31$) deployed to monitor survival up to 94 days. To properly model DM up to the fishery-wide level, all cod were visually assessed for capture-related injuries according to a four-level injury score index. Mean tackle-specific DM rates of 15.4 and 21.2% were estimated for bait- and jig-captured cod, respectively, with an overall 16.5% mean DM rate for the 2013 GOM recreational cod fishery. Twenty-nine cod tagged with acoustic transmitters were identified as dead, where the majority (~90%) died within 16 h post-capture. Upon evaluation with a specifically adapted parametric survival analysis, greater incidence of mortality was attributed to the capture and handling process (rather than release) for moderately and severely injured cod. Based on the capture-related factors associated with the highest injury rates, we recommend minimizing fight and handling times, avoiding areas with small cod, educating inexperienced anglers, and favouring bait over jigs to mitigate mortality. Results will continue to inform the development of fishery management plans and enhance survival through dissemination of "best practice" techniques to fishery stakeholders.

Keywords: acoustic telemetry, Atlantic cod, discard mortality, *Gadus morhua*, Gulf of Maine, parametric survival analysis, recreational fishing.

Introduction

Marine recreational fishing is a popular activity (Pawson *et al.*, 2008; Mora *et al.*, 2009; Figueira and Coleman, 2010) that can account for a significant portion of total fishery removals in some stocks (Ihde *et al.*, 2011). In addition, the frequency with which fish are discarded by recreational anglers is increasing due to more strict regulatory controls (e.g. possession and size limits) and increased conservation ethics among the angling community (Bartholomew and Bohnsack, 2005; Ferter *et al.*, 2013). However, the efficacy of management techniques such as catch-and-release angling for reducing fishing mortality rates relies on the premise that discarded fish will survive the capture and handling process (Wydoski, 1977; Cooke and Schramm, 2007). While released fish may appear healthy and destined to survive at the time of release, various factors such as physiological stress (Wood *et al.*, 1983) and mechanical stress/injury (Davis, 2002) can later lead to unaccounted mortality (e.g. Davis, 2002; Cooke and Wilde, 2007). Therefore, understanding and estimating the discard mortality (DM) rate of captured and released fish is essential to identifying practices to reduce dead discards and accurately estimate total fishery removals for inclusion in stock assessments and fishery management plans.

Atlantic cod (*Gadus morhua*) have been a principal target species in New England's groundfish fishery since the 17th century (Serchuk and Wigley, 1992). In recent decades, the Gulf of Maine (GOM) cod stock has experienced considerable declines in abundance and is currently estimated to be at historically low biomass levels (NEFSC, 2015). Further, despite the current zero possession limit for cod captured in the GOM recreational fishery (Department of Commerce, 2015), cod remain a key species for the management of both the recreational and commercial fisheries in the GOM. While the commercial fishery has been historically responsible for the majority of landings, the recreational fishery has accounted for 20–42% of the total GOM cod catch by weight since 2003 (Palmer, 2014). Moreover, dead recreational discards of primarily sublegal cod outnumbered recreational landings by more than two times from 2006 to 2011, assuming a conservative DM rate of 100% (Palmer, 2014). Given that there is not an experimentally derived estimate of the cod DM rate for this fishery, the actual contribution of recreational discards to the total fishing mortality remains uncertain. Consequently, the relative value of catch-and-release and associated management measures (e.g. minimum sizes, possession limits) as effective management tools are also uncertain.

Whereas several studies have estimated cod DM rates in commercial fishing gears across various regions under representative fishing operations (e.g. Milliken *et al.*, 1999, 2009; Pálsson *et al.*, 2003; Suuronen *et al.*, 2005; Ingólfsson *et al.*, 2007; Humborstad *et al.*, 2016), only one has addressed recreational fisheries (11% overall DM in the Baltic Sea; Weltersbach and Strehlow, 2013). Although not primarily focused on providing representative DM rate estimates, other recreational cod DM studies have been essential in understanding sublethal factors associated with capture-and-release events (Ferter *et al.*, 2015a, b). Despite the increasing frequency of such studies, DM of recreationally captured cod in the GOM has never been examined. As such, when recreational discards were first accounted for in GOM management in 2011, a conservative 100% DM estimate was instituted (NEFSC, 2012). To mitigate the increase in cod mortality that would occur based on this speculative assumption, fishery managers responded by reducing the minimum retention size (24–19 inches [in.]; 60.96–48.26 cm) and possession limit (10–9 cod per angler) so that anglers would theoretically discard fewer cod (Department of Commerce, 2012). To comply with calls for a more realistic recreational cod DM rate estimate, a revised 30% figure was non-experimentally derived in a multistakeholder forum (Singer and Meredith, 2012), and incorporated into the stock assessments (NEFSC, 2013, 2015; Palmer, 2014). Given the reduced DM expectation (Department of Commerce, 2014), increased discard numbers were encouraged, and the minimum size limit was consequently increased (19–21 in.; 48.26–53.34 cm). In light of the 30% DM rate being speculative (NEFSC, 2013), and the 2014–2015 GOM cod emergency action and zero possession recreational bag limit, a more comprehensive study estimating GOM cod recreational DM is required to inform management strategy, especially because this stock is managed using a bioeconomic model that is sensitive to DM rates (Department of Commerce, 2015).

Through the use of passive acoustic telemetry and fishery observations, the current study sought to estimate Atlantic cod DM in the GOM recreational rod-and-reel fishery. In addition, a suite of capture-related factors were examined for their influence on DM to generate "best practice" catch-and-release methods that could be disseminated to GOM recreational fishery stakeholders to increase the survival of discarded cod and promote fishery sustainability.

Methods

Study site and fishing

Cod were captured from June–October 2013 on the southern portion of Jeffreys Ledge in the western GOM (Figure 1), which is an area known to be frequently fished by recreational anglers. Fishing was concentrated during summer to coincide with the season with the greatest level of recreational fishing effort, the period of warmest sea surface temperatures, and the greatest temperature differential between bottom water and air temperature. Elevated water temperatures can have a negative impact on survival (Robinson *et al.*, 1993; Milliken *et al.*, 2009), thus fishing during this period was anticipated to provide a "worst-case scenario" for estimating DM and maximize its applicability for fishery management. Given the plausibility that size or possession limits would be adjusted in the future, the study included cod that were above and below the minimum retention size limit during the fishing year of which the study was conducted (19 in.; 48.26 cm).

Before conducting fieldwork, the fishing gear and terminal tackle most commonly used by anglers targeting cod in the GOM were selected based on directed questions in the Marine Recreational Information Program (MRIP) survey (Table 1) conducted by the Massachusetts Division of Marine Fisheries (MA DMF), as well as input from the project's collaborators. The gear configuration and tackle choices of recreational anglers were recorded from trips that either reported catching cod or were designated groundfish (e.g. cod) trips in the GOM (596 interviews over 47 trips). These trips originated from a variety of Massachusetts ports, but were dominated by the ports of Gloucester and Newburyport. The standardized gear consisted of a Shakespeare Ugly Stik rod (model BWB 1120–2.4 m), a Penn Senator reel (model 4/0 113H) equipped with braided mainline (29.5 kg test), a monofilament "top-shot" (15 m, 22.7 kg test), and a monofilament leader (1.25 m, 36.3 kg test). Additionally, two different terminal tackle types were used: (i) a Solvkroken stainless steel cod jig (i.e. "pilk"; 400–500 g) equipped with a Mustad treble-hook (size 10/0, model 3551) and teaser (size 6/0, model 34091, equipped with synthetic hair) fastened 30–40 cm above the jig and (ii) a lead-weighted, sea clam-baited "high-low" rig with two Mustad J-hooks (size 6/0, model 92642) attached using ∼10 cm dropper loops tied into the leader (Figure 2). Given the tackle configuration preferences documented by MRIP data for the GOM, this study considered jig and teaser in combination rather than as individual components. The jig size and lead weight size (on bait rigs) were adjusted when necessary to ensure that anglers were able to keep their tackle near the seabed, which was impacted by weather and ocean conditions.

Fishing trips occurred on-board two different vessels: *F/V* Too Far (8 m) and MA DMF *RV* Alosa (9.5 m). Before fishing commenced, all volunteer anglers completed a questionnaire specifically designed to evaluate their angling experience level in the recreational groundfish industry (Appendix I). Volunteer anglers of various

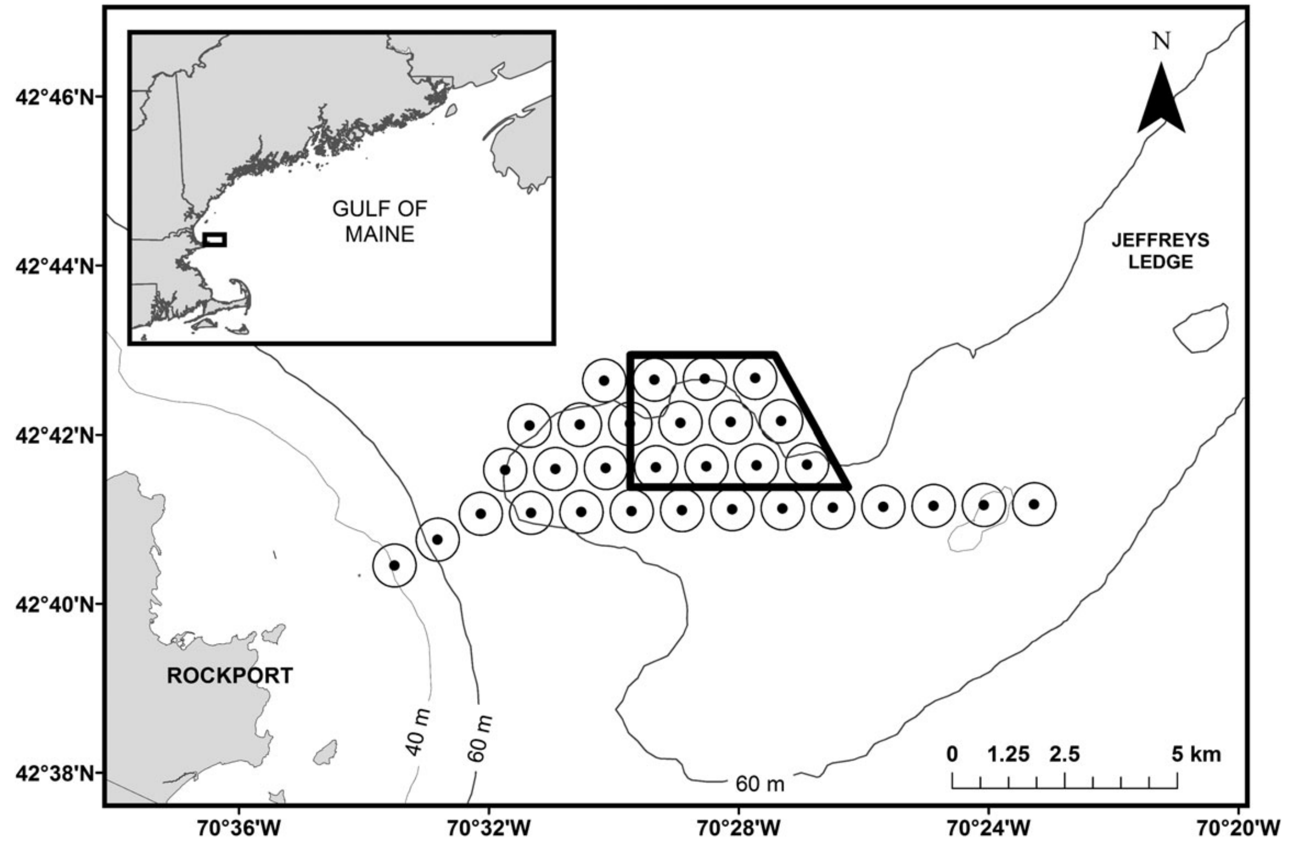

Figure 1. Map of the study area on southern Jeffreys Ledge in the western GOM (USA). All fishing was performed inside the passive acoustic receiver array ($n = 31$; indicated by black dots [•]), which monitored a detection area of $\sim$35.1 km^2 over 94 days. Circles surrounding each receiver indicate the predicted 470 m detection radius according to 50% mean detection from the range test. Bathymetric contour lines represent depths of 40 m (grey) and 60 m (black). The black polygon within the receiver array denotes where most fishing was performed between 26 June and 4 October 2013.

Table 1. Terminal tackle configurations from the 2013 MRIP gear and tackle survey interviews ($n = 596$) for Massachusetts anglers targeting cod.

Terminal tackle type			
(A) Jig **11%**		**(B) Bait** **89%**	
Style		Hook number	
Norwegian	85%	1	52%
Other	15%	2	41%
Size		3	<1%
<350 g	23%	Unknown	6%
350–425 g	44%	Hook style	
450–500 g	23%	J-hook	83%
550–600 g	5%	Circle hook	17%
>600 g	0%	Bait type	
Unknown	5%	Clams	99%
Teaser number		Other	1%
0	5%		
1	75%		
2	17%		
Unknown	3%		

experience levels were allowed to determine how best to fish and to handle and unhook their catch to promote authentic fishing scenarios and remove possible bias (Weltersbach and Strehlow, 2013). Efforts were made to maintain equal tackle-specific fishing effort (i.e. the amount of time anglers used bait vs. jigs) throughout the study to ensure representative samples across tackle types and trips.

A series of technical (i.e. capture time, depth, angler, tackle type, fight time, handling time, hook location, and removal method) and biological (i.e. total length, physical injury, and release behaviour) variables were recorded upon the capture of each cod. Cod total length was recorded to the nearest half centimetre. Fight time was defined as the time from hooking the fish to landing it on deck, and handling time as the time from landing the fish on deck to its release back into the water. Anatomical hooking location was recorded for each capture event and categorized into one of the following classes: mouth, head, gills, dorsal surface, ventral surface, and tail (modified from Kneebone *et al.*, 2013; Weltersbach and Strehlow, 2013; see subsequent results). Mouth-hooking events were further designated into shallow (e.g. lip, jaw), medium (e.g. vomer, tongue), and deep (e.g. esophagus, gills) designations, while foul-hooking events were characterized as any hooking location occurring outside of the mouth. Physical injury was assessed visually (<10 s procedure) according to a four-level ordinal scoring index (Table 2). Additional environmental parameters including air temperature and surface and bottom water temperatures (°C) were assigned to each capture event using data from the nearest meteorological buoy (NOAA Station 44029, Massachusetts Bay/Stellwagen Bank, http://www.neracoos.org) and depth-temperature archival tags (model DST milli-L, Star-Oddi Ltd., Iceland) deployed in the study area.

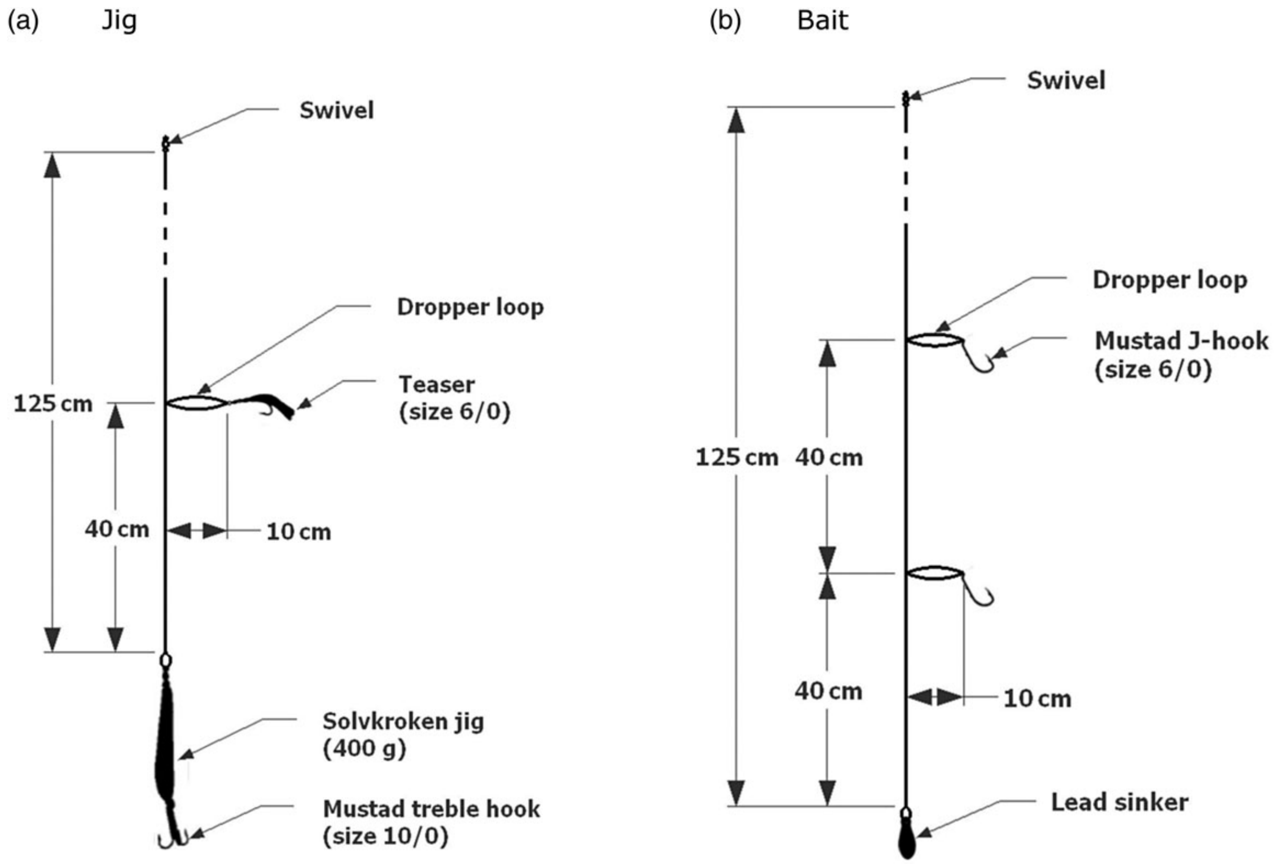

Figure 2. Terminal tackle types configured on the rod-and-reel's monofilament leader (black line; thickness not to scale) during fishing trips: (a) a Solvkroken stainless steel jig (400 g pictured) with a Mustad treble-hook (size 10/0) and teaser (size 6/0, synthetic hair) fastened above the jig via a ~10 cm dropper loop tied into the leader and (b) a lead weighted, sea clam-baited "high-low" rig with two Mustad J-hooks (size 6/0) attached via ~10 cm dropper loops. The dotted line along the monofilament leader on both tackle types represents a break so crucial elements to each configuration could be seen more easily.

Table 2. The ordinal scoring index used to assess the physical injury of captured cod after hook removal (modified from Kaimmer and Trumble, 1998; Benoît *et al.*, 2010; Kneebone *et al.*, 2013).

Score	Injury category	Definition
1	None	Hooking injury limited to hook entry/exit hole; no visible barotrauma symptoms
2	Minor	Hooking injury <1 cm in diameter; minor barotrauma symptoms (e.g. swimbladder expansion)
3	Moderate	Hooking injury >1 cm in diameter; moderate barotrauma symptoms (e.g. exophthalmia)
4	Severe	Putatively dead upon release due to significant hooking injuries (e.g. exposed internal organs, damaged gills); severe barotrauma symptoms (e.g. everted stomach)

Tagging

A subsample of the assessed cod was tagged externally in the dorsal musculature with Vemco ultrasonic transmitters (model V9P-1H, 9 × 42 mm, 5.2 g in-air, 2.7 g in-water, pressure sensor max depth 100 m [accuracy ±5 m, resolution 0.44 m]; Vemco Division, AMIRIX Systems Inc., Halifax, Nova Scotia) affixed via end caps to Floy spaghetti tags (model FT-4, Floy Tag & Mfg, Inc., Seattle, WA, USA). Cod were selected for acoustic transmitters based on the need to proportionally distribute injury class (see below) across tackle configurations and multiple trips. Before fishing, a lab-based transmitter retention study confirmed the aforementioned tagging process was most optimal due to its rapid application (<30 s procedure), high transmitter retention rate (100% over 18 days), minimal stress and health impacts, and 100% survival rate. All remaining cod not selected for the acoustic transmitter subsample were tagged in a similar location (~5 s procedure) with two conventional Floy T-bar anchor tags (model FT-94). While applying acoustic transmitters to equal numbers of cod across the four injury classes was optimal for the survival analysis and extrapolation scheme, fish were chosen opportunistically due to the low occurrence of moderate and severe injuries. All cod that did not suffer immediate (i.e. at-vessel) mortality were released.

Post-release survival monitoring

To assess short- (i.e. <3 days) and long-term (i.e. ≥3 days) survival of cod tagged with acoustic transmitters, fine-scale vertical movements were monitored using an array of Vemco acoustic receivers ($n = 31$; model VR2W-69 kHz) that were strategically deployed to maximize the likelihood of transmitter detection (Figure 1). Preliminary detection range testing in the study area concluded that acoustic coverage did not continually overlap. In an effort to balance the competing needs of high-resolution data and prolonged battery life, while at the same time minimizing the potential for concurrent transmissions (i.e. detection "collisions"), acoustic transmitters were programmed with the following ping schedule: every 2 min for first 7 d, every 5 min for the next 23 d, and every 15 min until transmission terminated at 365 d. In some instances, the fate of cod tagged with acoustic transmitters that emigrated from the study site during or following the 94-d monitoring period (1 July–3 October 2013) was opportunistically assessed by detection data received from other acoustic receiver arrays in the GOM region or by fisheries-dependent recapture. Acoustic monitoring concluded on 3 October 2013 to mitigate receiver loss in response to the opening of the commercial midwater trawl fishery on common fishing grounds. Additionally, a subset of cod that were intentionally sacrificed ($n = 5$) were affixed with transmitters and released into the array to serve as negative controls (i.e. known dead fish) by which to distinguish mortalities among the cod tagged with acoustic transmitters.

Analysis

All transmitter detection data were evaluated for false detections using Vemco User Environment software (VUE, version 2.06) with specific filter criteria (i.e. receiver/transmitter detection count <2 and receiver/transmitter detection separation >29 min) and identifying irrational depth sensor data indicative of transmitter failure (e.g. depths greater than study area). Relationships between capture-related, categorical variables (e.g. tackle type and angler experience level), and measured parameters (e.g. fish total length, fight time, and handling time) were examined using Mann–Whitney–Wilcoxon (MWW) tests to preliminarily identify potential capture relationships (e.g. size selectivity, handling differences between tackle types) that may require additional investigation. A Fisher's exact test was employed to examine differences in hooking location by tackle type (i.e. bait, jig). A Pearson's χ^2 test and subsequent *post hoc*, pairwise comparisons with Bonferroni corrections to adjust for significance value inflation were performed to examine the relationship between injury score and tackle type and release behaviour. Statistical significance was accepted at a level of $p < 0.05$.

Mortality assessment

Given that passive acoustic telemetry only confirms an animal is present within the detection area of a particular receiver (Kessel *et al.*, 2014) and that seabed depth varies considerably within the study area, it was not possible to identify mortality by a lack of difference between transmitter depth and seabed depth. Therefore, mortality was assessed by comparing the variance in the depth observations from each tagged cod to that of the negative controls using a one-tailed t-test of the absolute difference from the median (modified Browne–Forsythe–Levene test for homogeneity of population variance; Lyman Ott and Longnecker, 2010); from now on referred to as the depth-variance survival test (Figure 3). The variability in depth associated with the study area's tidal cycle was removed from each depth recording using the statistical computing software R (version 3.2.3; R Core Team, 2015) and the associated package "oce" (version 0.9-18; Kelley and Richards, 2016). Tide-adjusted depth data of negative controls were assumed to be representative of dead cod in the study area since they interacted with area's bathymetric features over time. When a tagged cod's depth-variance was not significantly different ($p > 0.05$) from the negative controls through its last recorded detection, a mortality event was deduced and time of death was recorded. Due to the phased ping schedule and sensitivity of the depth-variance survival test to detection sample size, depth data of cod tagged with acoustic transmitters were binned into time intervals that maintained a consistent number of expected detections per interval (i.e. time bins increased in size with ping delay), and therefore a consistent ability to detect differences. Since the depth-variance survival test did not possess a temporal component, the test was consequently applied to each post-release detection bin of each cod tagged with an acoustic transmitter to identify a time of death. Significance values were corrected for multiple comparisons using false discovery rate procedures (Benjamini and Hochberg, 1995). If available, fisheries-dependent recaptures and acoustic receiver detections outside of the study area were used to confirm survival.

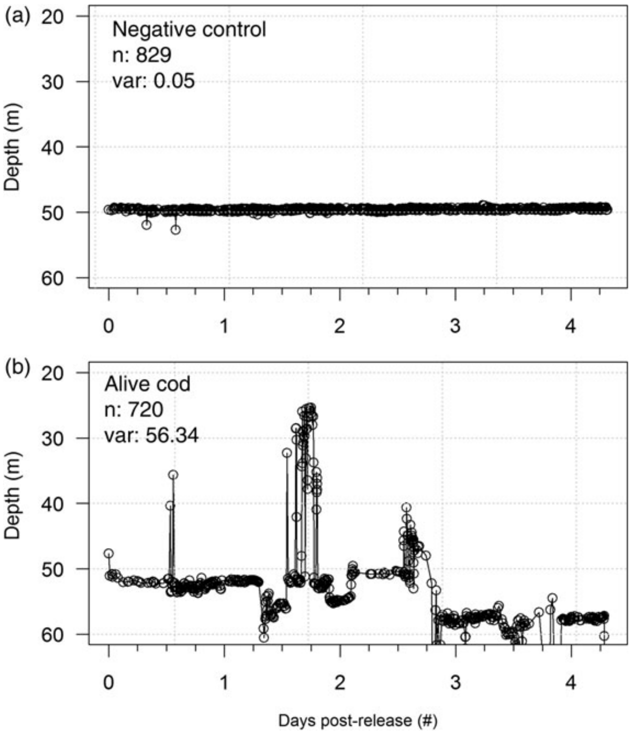

Figure 3. Tide-adjusted depth data examples for (a) a negative control (i.e. known dead cod) and (b) a living cod (possessed minor injury, shallow mouth hooking) over a 4-day post-release period. Depth data sample size (n) and overall variance (var) are displayed to demonstrate the inherent variance differences between these two datasets.

Analysis of survival data

The cod survival data were evaluated with specifically adapted analyses that can assist with quantifying and interpreting various survival parameters (e.g. the effect of capture-related covariates on survivorship, sources of mortality, the temporal extent of capture-related mortality). These survival data consist of records for each fish tagged with an acoustic transmitter and are made up of an event time, an injury score, and values for a series of covariates (i.e. capture-related variables) that might affect survival. Event times were assigned according to the fate of each released fish, where cod either died after release, died during capture, handling, or immediately after release (treated as left-censored observations), or were last seen alive (right-censored observations) (see Benoît *et al.*, 2015 for details). Since ongoing, passive acoustic telemetry was used to obtain the (event) times at which cod tagged with acoustic transmitters either died or were last observed alive (i.e. longitudinal survival data), survival data were evaluated using a specifically adapted parametric survival analysis modelling approach described by Benoît *et al.* (2015).

Survival data were initially analysed using the non-parametric Kaplan–Meier (KM) estimator of the survival function (cumulative probability of survivorship over time) by injury category (Cox and Oakes, 1984) to evaluate whether survival was injury dependent and if each injury category produced distinct survival functions. The KM estimator is a function of only the survival data and, in the absence of censored values, follows the proportion of individuals alive as a function of time. In addition, log-rank tests and contingency tables were utilized to confirm if the observed injury categories displayed distinct survival functions (injury-specific survival functions). These preliminary analyses suggested that cod survival was injury-dependent and that cod with no and minor injuries had nearly identical survival functions. A log-rank test failed to reject the null hypothesis of no difference in survivorship between those two injury classes ($\chi^2 = 0.9, d.f. = 1, p = 0.343$). This result was independently corroborated by a contingency table analysis of the mark-recapture data for the conventionally tagged cod in the study, which also failed to reject the null hypothesis (uninjured: 21 of 311 recaptured; minor injuries: 5 of 113; $\chi^2 = 0.366$, $d.f. = 1$, $p = 0.545$). Consequently, the two injury classes were combined into a "none/minor" injury class for all subsequent survival analyses.

The objective of the analysis was to estimate key quantities for the captured and released cod, namely the capture and handling mortality, the post-release mortality, and their sum (i.e. total DM). However, because the fish were released into their natural environment and monitored over a prolonged period, other natural sources of mortality (e.g. predation) needed to be accounted for to avoid inflating the estimates of fishing-related mortality. We used the model of Benoît *et al.* (2015) since it is particularly well suited for this context. At its core, the model is founded on a basic mixture distribution of released individuals that have been adversely affected by the capture-and-release process and will die as a result, and unaffected released individuals that will otherwise survive (see Equation (3), Benoît *et al.*, 2015). This model was further generalized by the authors to include distinct capture-handling and post-release mortality rates, as well as a natural mortality rate that applies to all released fish. The survival function for this model ($S(t)$; probability of surviving to time t) is expressed as:

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

where τ is the probability of surviving capture and handling, π controls the probability that an individual was adversely affected by the fishing event, α and γ are, respectively, the scale and shape parameters of an underlying Weibull distribution that determines the mortality patterns over time for the adversely affected individuals, and M is the instantaneous rate of natural mortality (details in Benoît *et al.*, 2015). From Equation (1), it is clear that at $t = 0$, $S(t) = \tau$. Assuming $M = 0$ for illustrative purposes, one can see that as $t \to \infty$, the term $\tau \cdot \pi \cdot \exp[-(\alpha \cdot t)^{\gamma}] \to 0$ (i.e. the affected fish will all die) and $S(t) \to \tau(1 - \pi)$. Thus, $\tau \cdot \pi$ is the conditional post-release mortality rate (i.e. the mortality rate for individuals that were alive when released but subsequently died as a direct result of capture and release), and $1 - \tau + \tau \cdot \pi$ is the total DM probability. Unlike traditional survival analysis models applied to DM data (e.g. Neilson *et al.*, 1989), the DM probability is time independent. This is a key property because generally one would expect that the consequences of the discarding event should be manifested over a finite interval, that is, at some point the sample of discarded fish will be comprised exclusively of fish that will die only of other causes.

In Equation (1), the natural mortality rate M is assumed to act equally on affected and unaffected groups of fish. Any differences in natural mortality between these groups are subsumed in the Weibull survival function for affected fish. Such a difference might result, for example, from increased predation risk associated with decreased predator avoidance abilities for affected fish (e.g. Raby *et al.*, 2014). Because this increased risk constitutes an indirect effect of the fishing event, it makes sense that it be accounted for in the survival function for affected fish, at least in the baseline model.

A small number of model variants of Equation (1) were fit to identify one or more models that best fit the cod survival data (described briefly below and in Table 3). Models were fit using maximum likelihood (see Benoît *et al.*, 2015 for details) and then compared using Akaike's information criterion corrected for small sample sizes (AICc; Burnham and Anderson, 2002). Survival functions predicted by each model were also plotted along with the non-parametric survival functions estimated with the KM estimator to gauge model fit. Preliminary analyses using the KM estimator suggested injury-dependent survival functions, consequently models with injury-dependent π parameters were deemed most appropriate. This effect was modelled as:

$$\pi = [1 + \exp(-X'\beta_1)]^{-1},$$

where X is the design matrix for the covariates (injury score) and β_1 is a vector of parameters for the effect of the covariates. The logit transformation was used to ensure that π is bounded in the interval [0,1]. The KM estimator also suggested that injury-dependent τ parameters might be relevant. Therefore, five variants of Equation (1) were compared, all of which included injury-dependent π's (Table 3). Note that in variant 3 the exponential function was used to ensure that M's were positive and in variants 4 and 5 the

Table 3. Assumptions for capture and handling (CH; τ) and natural mortality (M) parameters of Equation (1) used to define the five competing model variants (with injury-dependent π parameters) for cod survival analysis.

Model	T	M	Description	ΔAICc
1	1	0	No CH mortality, no natural mortality	6.05
2	1	Estimated	No CH mortality, estimated overall natural mortality rate	5.99
3	1	$\exp(X'\beta_2)$	No CH mortality, injury-dependent natural mortality	10.10
4	$[1 + \exp(-X'\beta_3)]^{-1}$	0	Injury-dependent CH mortality, no natural mortality	8.72
5*	$[1 + \exp(-X'\beta_4)]^{-1}$	Estimated	Injury-dependent CH mortality, estimated overall natural mortality rate	–

The preferred and final model is denoted with an asterisk. Differences in AICc score between the model variants and the final, preferred model are also displayed (ΔAICc).

logit transformation was used to bound the τ parameters in the interval [0,1]. There were difficulties in fitting variant 3 due to sensitivity to the initial parameter values used in fitting, possibly due to no observed mortalities for cod in two of the injury classes (see below). Consequently, a sixth variant with injury-dependent τ's and M's was not attempted.

Once a preferred model was identified, the role of sensible covariates possibly affecting survivorship under that model was examined. Specifically, the effects of tackle type, angler experience level, capture depth, fish total length, fight time, handling time, and sea temperature differential (between the surface and bottom) were examined. Covariate effects were included on τ (i.e. an effect on mortality occurring during capture and handling) or on π (i.e. an effect on conditional post-release mortality). A stepwise forward selection process using AICc was used and only variables that produced a reduction in AICc of two or more were retained.

Analysis of injury data

A second objective of this study was to better understand the factors that affect injury in captured cod to formulate "best practice" techniques to reduce such injury, given the apparent relationship between injury and survival. Therefore, a proportional-odds multinomial linear model based on cumulative logits was used since this type of model is well suited for modelling the effect of covariates on ordinal categorical responses, and has been applied in the context of fishery discards (see Equation (1), Benoît *et al.*, 2010). Furthermore, the addition of a trip- or observer-level random effect (random intercept) can account for both subjectivity in the assignment of individuals to injury categories and within trip (observer) correlations in responses (see Equation (2), Benoît *et al.*, 2010). Injury data were analysed using the "ordinal" package in R (version 2015.6-28; Christensen, 2015) following the procedures and equations detailed in Benoît *et al.* (2010). First, two saturated models with all relevant covariates were fitted to both fixed effects only and mixed effects (random intercept) proportional-odds models. The relevant covariates used to fit these saturated models included depth, tackle type, angler experience, fish total length, fight time, and handling time, while trip ID was treated as the random effect. Model comparisons were performed between both fixed and mixed effects saturated models by a likelihood ratio statistic whose subsequent p-value was corrected for boundary testing given that the variance of the random effect is a positive quantity. If improvements in fit were statistically significant, the mixed effects rather than the fixed effects model was chosen. Subsequently, covariates were selected using a forward selection process and a conservative delta AICc criterion of 3, as per Benoît *et al.* (2010). Select two-way covariate interactions that were deemed *a priori* to be potentially important were then tested in the same fashion. These two-way interactions included tackle type and angler experience level individually coupled against handling time, fight time, and total length.

Estimating a fishery-wide cod DM rate

The DM rate for the 2013 GOM cod recreational fishery was estimated by extrapolating empirically derived DM rates to tackle-specific fishing effort resulting from 2013 MRIP survey data. The uncertainty surrounding this DM rate was estimated via a combined empirical and parametric bootstrap routine that accounted for error in each component, as well as the clustered nature of both the injury score observations and the tackle survey data (e.g. Benoît *et al.*, 2012). Each of the 1000 routine iterations proceeded in two phases. First, a multistage empirical and parametric bootstrap of the injury score data was conducted, fishing trips with replacement and fish within trips with replacement, to estimate tackle-specific frequency distributions of injury scores. Injury-dependent survival rates were then calculated by drawing parameter values for the preferred survival model from a multivariate-normal distribution based on the estimated parameter vector and covariance matrix. The randomly drawn injury scores and model parameters were then used to predict the DM rate by tackle type. Second, the trips in the MRIP survey were resampled to account for variability in the tackle and effort data. Specifically, trips were sampled with replacement and angler responses with respect to the type of tackle used and the fishing effort were sampled with replacement within trips. The proportion of angler-trips using each tackle type by fishing mode (i.e. for-hire or private vessels) was calculated as well as the mean number of cod released per trip by tackle and mode (Table 4). The total number of trips in the fishery that caught or released cod under each fishing mode was randomly drawn from a normal distribution based on the MRIP survey estimates (and standard error; SE) for the GOM in 2013. The estimated total number of recreational angler-trips (SE) that caught or released cod during 2013 in the GOM were 58075 (4239) trips for party/charter (i.e. for-hire) vessels and 100574 (16192) trips for private vessels (National Marine Fisheries Service Fisheries Statistics Division, pers. comm.).

Table 4. Summary of the 2013 MRIP gear and tackle survey interviews for the Massachusetts recreational cod fishery ($n = 596$).

Mode	Trips	Tackle	Interviews	Releases/ angler-trip	% using tackle
Party/charter	37	Bait	517	1.32 (0.16)	0.90 (0.02)
		Jig	56	2.53 (0.41)	0.10 (0.02)
Private	10	Bait	14	7.45 (4.86)	0.60 (0.18)
		Jig	9	2.12 (0.70)	0.40 (0.18)

Values in parentheses are bootstrapped standard errors.

To calculate the fishery-wide DM rate, the tackle and effort data obtained from phase two of the bootstrap routine were first combined to estimate the total number of cod released by tackle type as follows:

$$\mathrm{Releases}_{\mathrm{tackle}} = \sum_{\mathrm{mode}} (\mathrm{Trips}_{\mathrm{mode}})(P_{\mathrm{tackle,mode}})(RPT_{\mathrm{tackle,mode}}), \quad (2)$$

where $\mathrm{Trips}_{\mathrm{mode}}$ is the total estimated number of trips by mode (for-hire vs. private vessels) from the MRIP survey; $P_{\mathrm{tackle,mode}}$ is the proportion of anglers using each tackle type (bait vs. jigs) by mode; and $\mathrm{RPT}_{\mathrm{tackle,mode}}$ is the mean number of cod released per trip by tackle and mode. Second, the total numbers of cod released by tackle type were then used as weights in an average of the tackle-specific DM rates that were calculated at the start of the iterations. Finally, the distribution of bootstrap iterations provided the fishery-wide DM rate mean, as well as the 2.5th and 97.5th quantiles as approximate confidence intervals for the mean (Efron and Tibshirani, 1993). Preliminary bootstrap routines indicated that 1000 iterations were sufficient to properly and consistently characterize the quantiles.

Results

Characteristics of capture

In total, 640 Atlantic cod ranging in total length from 26.0–72.0 cm (mean ± SD: 46.0 ± 8.0 cm) were captured at depths ranging from 44.5 to 82.9 m over fourteen fishing trips with the assistance of 17 different anglers (Table 5). Roughly equal amounts of cod were captured via baited hooks (52.5%) and jigs with teasers (47.8%; from now on grouped together as "jig"). There were 504 cod tagged with T-bar anchor tags (mean ± SD: 45.5 ± 8.5 cm total length), while 136 were externally tagged with pressure-sensing acoustic transmitters (mean ± SD: 47.0 ± 8.0 cm total length). Furthermore, of the 640 tagged fish that were successfully released back into the study area ($n = 619$), 58 (9.4%) were confirmed alive through 59 recapture events via either opportunistic fisheries-dependent recapture ($n = 37$, 6.0%) or detections on acoustic receiver arrays outside the study area ($n = 21$, 3.4%); one cod was confirmed alive through both recapture and acoustic detection on other arrays.

The type of tackle used did not influence the size of captured cod (MWW; $W = 52\,497$, $p = 0.208$) or differences in fight time (MWW; $W = 44\,460$, $p = 0.245$); however, average handling times for cod captured by bait (mean ± SD: 110 ± 64 s) exceeded those captured by jig (mean ± SD: 91 ± 54 s) (MWW; $W = 52\,548.5$, $p = \leq 0.001$). Handling times varied according to angler experience level (MWW; $W = 25\,916.5$, $p = \leq 0.001$), with less experienced anglers taking longer to handle their fish (mean ± SD: 119 ± 56 sec) compared with more experienced anglers (mean ± SD: 93 ± 60 s). Anatomical hooking locations of captured cod primarily consisted of shallow- and medium-hooking in the mouth (77.2%), while the occurrence of deep- (0.5%) or foul-hooking (22.3%) made up the remainder (Figure 4). The majority (87.3%) of assessed fish incurred no or minor injury and the remainder suffered moderate-to-severe injuries (12.7%). Fish captured by jig were 11.8 times more likely to be foul-hooked compared with bait-captured cod (Fisher's exact test; $p \leq 0.001$), resulting in a greater degree of injury in jig-captured cod (Pearson's χ^2 test; $\chi^2 = 39.61$, $d.f. = 3$, $p \leq 0.001$).

Post-release behaviour and mortality assessment

Of the cod that were successfully released and had their release behaviour observed ($n = 602$), the vast majority swam straight down ($n = 542$; 90.0%), while the remaining fish either floated ($n = 31$; 5.2%), sank without response ($n = 27$; 4.5%), or swam erratically ($n = 2$; 0.3%). Of the floating individuals, 29.0% ($n = 9$) experienced immediate (i.e. <5 min) mortality due to seabird predation. Cod with no and minor injury were able to submerge at a higher rate than those with moderate and severe injuries (Pearson's χ^2 test; $\chi^2 = 78.80$, $d.f. = 3$, $p \leq 0.001$).

Using the depth-variance survival test, 104 and 32 cod in the acoustic subsample were identified as alive and dead, respectively. One transmitter was identified to experience failure upon which data were truncated as recommended by the manufacturer. Three cod that were considered dead were recaptured and/or detected by receivers outside the study area, indicating that there were classification errors using the depth-variance survival test, resulting in a final estimate of 107 alive and 29 dead cod. Of the cod determined to be alive, 65.4% ($n = 70$) were not detected on the last day of the monitoring period, either due to emigration from the study area or detection transmission failure. Moreover, surviving fish exhibited moderate short-term residency (i.e. presence) over the 94-day observation period (mean ± SD: 50.9 ± 33.3 days). Of the cod identified as dead, 20.7% ($n = 6$) and 69.0% ($n = 20$) experienced immediate and short-term mortality, respectively, while the remaining three cod (10.3%) experienced long-term mortality (Max delay: 75.3 days). Most deceased cod (89.7%, $n = 26$) died within 16 h of release (mean ± SD: 1.1 ± 3.9 h).

Analysis of survival data

Model 5 was found to produce the best fit to the cod survival data and included only injury-dependent parameters on both the capture-handling (τ) and post-release mortality (π) parameters (Table 3). This model matched the KM non-parametric survival functions well (Figure 5) and suggests that almost all mortality related to the fishing event was ascribable to the capture and handling process, rather than random events (i.e. natural mortality) during the post-release period (Table 6). The estimated capture and handling mortality was essentially the same for moderately and severely injured cod and was higher than that of less injured fish. Estimated post-release mortality was low for moderately injured cod and ~15% for severely injured fish, though there was considerable uncertainty in these estimates given the low sample sizes. Overall, an instantaneous natural mortality rate of 0.16 was estimated, which is of a similar scale to values used in the assessment of this stock (0.2 or 0.4, depending on the model; NEFSC, 2013). However, this estimate was derived from data collected over a finite size range and season; seasonal differences in natural mortality could explain some of the discrepancy between our estimate and assessment values, which are meant to be generally relevant to all seasons.

Analysis of injury data

Given that the mixed effects proportional-odds model did not provide a statistically significant improvement in fit ($p = 0.097$), a fixed effects proportional-odds model was selected. Handling time, tackle type, fish total length, fight time, and angler experience level were all retained in the preferred proportional-odds model; depth and the selected two-way interactions were not (Table 7). More severe injury was associated with smaller individuals,

Table 5. Capture-related covariate characteristics of entire sample ($n = 640$), including data mined from the nearest NOAA meteorological buoy (NMB) and data storage tags deployed in the study area (DST) between 26 June and 4 October 2013.

	N	Range	Median	Mean	SD	SE
Capture depth (m)	633	44.5 – 82.9	57.3	57.8	6.0	0.2
Fish total length (cm)	631	26.0 – 72.0	45.0	46.0	8.3	0.3
Fight time (s)	614	41 – 413	90	95	35	1
Handling time (s)	601	0 – 400	88	101	61	2
Air temperature (NMB) (°C)	640	15.3 – 25.6	19.6	20.4	2.5	0.1
Surface temperature (DST) (°C)	586	14.8 – 21.2	18.5	18.2	1.6	0.1
Bottom temperature (DST) (°C)	586	6.1 – 8.5	7.3	7.4	0.6	0.0
Temperature differential (DST) (°C)	586	8.3 – 13.9	10.8	10.8	1.3	0.0

Descriptive values exist for each variable and include sample size (n), range, median, mean, standard deviation (SD), and standard error (SE). Sample sizes for each capture-related covariate varied based on data availability.

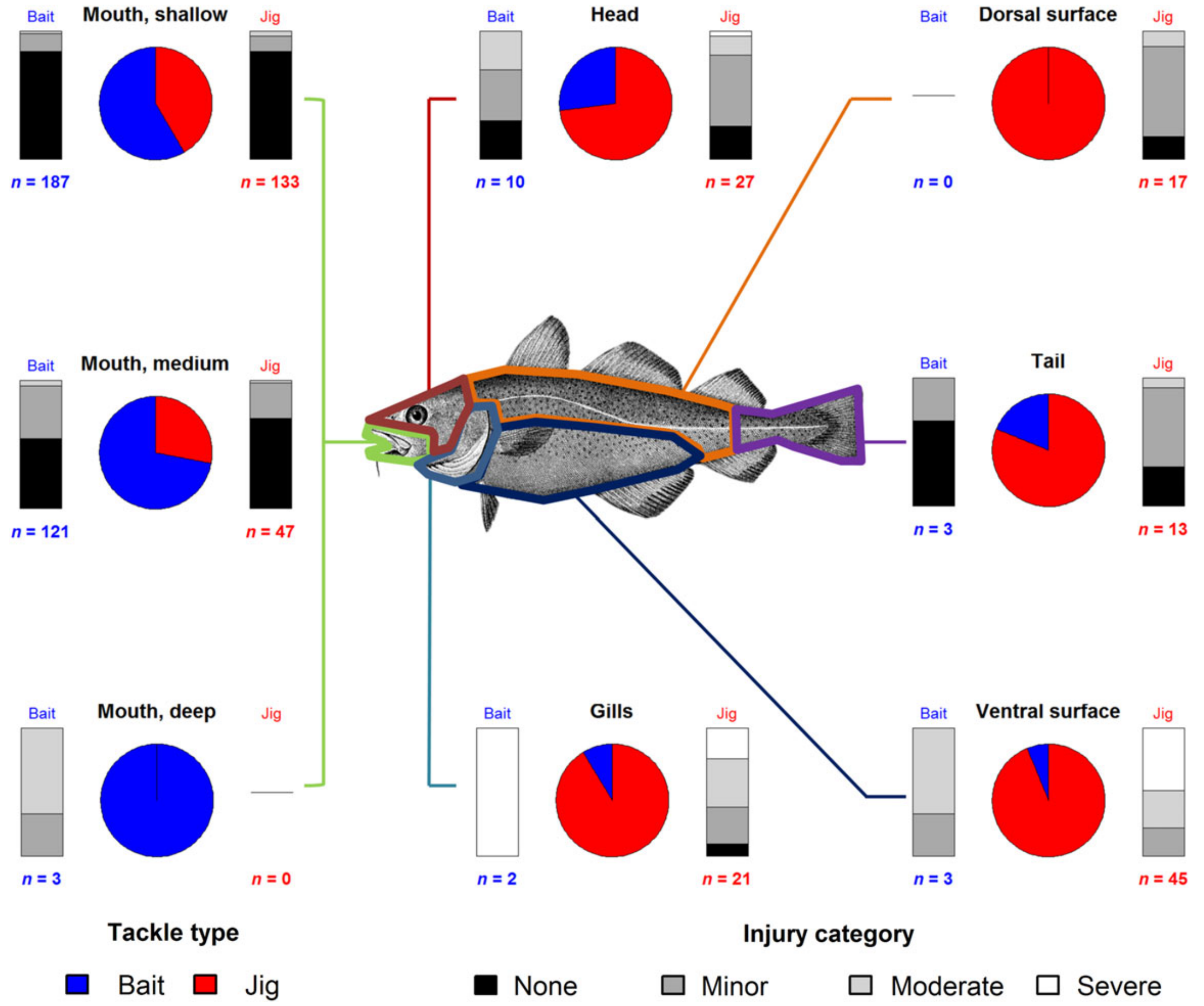

Figure 4. Hooking location frequency distributions for all assessed cod ($n = 632$) by tackle type (pie charts) and injury category (bar plots; bait = left, jig = right). Sample sizes for each hooking location are located at the base of each bar plot. Mouth-hooking events were further divided into shallow, medium, and deep hooking locations (see Weltersbach and Strehlow, 2013).

extended fight, and handling times, and with capture by jig or by less experienced anglers (Table 8).

Estimating a fishery-wide cod DM rate

Mean DM rates were estimated at 15.4% (95% CI: 8.1%, 39.8%) for bait-captured cod and 21.2% (95% CI: 13.2%, 44.1%) for jig-captured cod. This resulted in an overall mean DM rate estimate for the 2013 GOM recreational cod fishery of 16.5% (95% CI: 9.9%, 35.1%).

Discussion

Estimated DM rate

The present study sought to derive a broad-scale DM rate estimate for cod caught in the GOM recreational rod-and-reel fishery that could be confidently incorporated into stock assessments and fishery management plans. The 16.5% mean DM rate estimate suggests that the highly conservative 100% DM rate used in 2011 (NEFSC, 2012) and the 30% DM rate currently used (Palmer, 2014; NEFSC, 2015) were both overly conservative. In addition, our results are similar to those reported for recreationally caught cod in the Baltic Sea (mean DM: 11.2%, range: 0–27.3%; Weltersbach and Strehlow, 2013), the only other study to estimate cod DM with recreational fishing equipment and tackle.

Under the present study, ∼90% of fatalities occurred before or within 16 h of release, which is consistent with observations in other cod DM studies that utilized enclosures to monitor mortality (85–95% over 24 h, Pálsson *et al.*, 2003; Weltersbach and Strehlow, 2013). Given the clustering of fatalities in the initial hours post-capture, the modelling framework employed (which accounted for natural mortality losses), and the low likelihood of transmitter shedding relative to the mortality window observed, the vast majority of cod mortality can confidently be ascribed to the capture and handling process, as opposed to longer term sources of post-release mortality. Based upon the transmitter retention window observed in the lab-based study (100% over 18 d), we are confident mortality events within that initial period following release were not attributable to transmitter shedding; however, we cannot rule out the

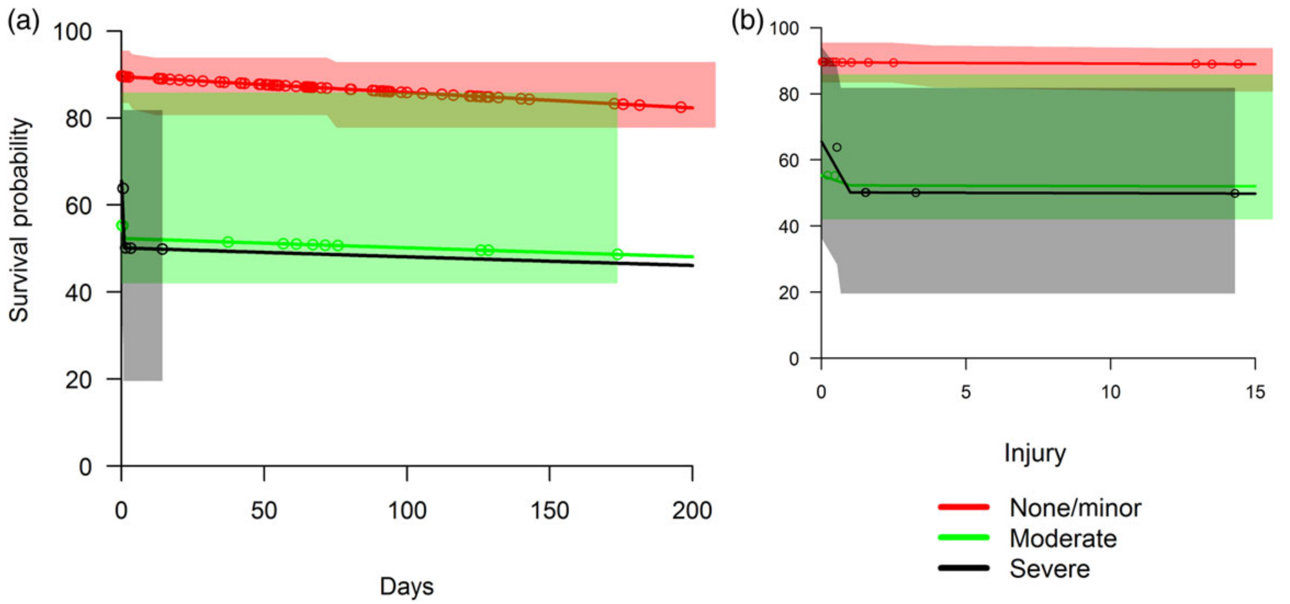

Figure 5. Non-parametric and model-based estimates of injury-class specific survival functions for cod in the acoustic subsample that were captured in the study and deemed dead before or following release. The shaded areas are the 95% confidence band for the KM survivor function estimates, the solid lines are estimates from the preferred survival model, and the circles indicate the occurrence of censored observations. The injury-specific survival function plot in (a) principally highlights the influence of natural mortality over a 200-d period. (b) A subset of (a) that displays the rapid onset and asymptotic nature of mortality during the first 15 days after release.

Table 6. Sample sizes and estimates of key parameters for the analysis of the survival data.

	Injury category		
	None/minor injury	**Moderate injury**	**Severe injury**
Numbers			
Dead	4	0	2
Left-censored	10	8	5
Right-censored	88	12	5
Mortality			
Capture-handling	0.103 (0.058, 0.171)	0.447 (0.249, 0.660)	0.344 (0.144, 0.638)
Post-release	0.001 (0.001, 0.269)	0.030 (0.002, 0.241)	0.154 (0.029, 0.446)
Total DM	0.105 (0.062, 0.395)	0.477 (0.289, 0.763)	0.499 (0.265, 0.816)
Natural	–	0.157 (0.051, 0.419)	–

The number of fish that died upon release (dead), that died during capture and handling or immediately after release (left-censored), and that were last seen alive (right-censored) are presented by injury class. Estimates (95% confidence intervals) of the capture and handling mortality rate ($1 - \tau$), the conditional post-release mortality rate ($\tau \cdot \pi$), and the total DM rate associated with the fishing event (i.e. capture, handling, and release; $1 - \tau + \tau \cdot \pi$) are presented by injury category, while the estimated natural mortality rate (M) applies to all injury classes.

Table 7. Forward selection process for the fixed effects proportional-odds multinomial model based on cumulative logits relating injury score to selected covariates.

Run	Covariates	AICc	ΔAICc
1	~1	1122.81	–
2	~handling time	1106.23	16.58
3	~handling time + gear type	1083.51	22.71
4	~handling time + gear type + total length	1071.06	12.46
5	~handling time + gear type + total length + fight time	1065.87	5.18
6*	~handling time + gear type + total length + fight time + angler experience	1062.82	3.06
7	~handling time + gear type + total length + fight time + angler experience + depth	1062.86	0.04

Covariates that produced a conservative AICc reduction of three or more were retained (see ΔAICc). The final model is denoted with an asterisk.

possibility that the small number of mortality observations beyond the 18-d period may have included cases of transmitter shedding incorrectly interpreted as mortality. This possible confounding event would affect the estimate of natural mortality and not DM (Benoît *et al.*, 2015), and we feel that our estimates of DM are therefore robust with respect to transmitter shedding.

Factors influencing mortality

The preferred mixture distribution model (i.e. Model 5) only included injury-dependent parameters, suggesting that physical trauma was the best predictor and predominant driver of cod DM. Among the cod that died, roughly 52.7% displayed moderate or severe physical injury. Injury from capture has been known to increase DM among cod captured in commercial and recreational hook fisheries (Milliken *et al.*, 1999, 2009; Pálsson *et al.*, 2003; Weltersbach and Strehlow, 2013). The degree of physical trauma

Table 8. Regression output coefficient table of the final fixed effects proportional-odds multinomial model based on cumulative logits (model run 6, Table 7) used for analysing injury data.

	Coef.	SE	*z*-value	*p*-value	OR
Handling time	0.0076	0.0015	5.0071	5.526e − 07	1.008
Tackle type: jig	0.9795	0.1902	5.1499	2.606e − 07	2.663
Total length	− 0.0534	0.0118	− 4.5087	6.522e − 06	0.948
Fight time	0.0067	0.0023	2.9028	3.70e − 03	1.007
Angler experience: inexperienced	0.4597	0.2033	2.2613	2.374e − 02	1.584

Parameter estimates for each covariate are listed and include log coefficient estimate (Coef.), standard error (SE), Wald test (z-value), *p*-value, and odds ratio (OR).

appeared to be heavily influenced by hooking location, where damage to vital organs or profuse bleeding can directly and indirectly (e.g. heightened predation risk) increase mortality (Pálsson *et al.*, 2003; Weltersbach and Strehlow, 2013). Despite the expected decrease in mortality with lower degrees of injury, cod in the current study within the "none/minor" injury class still displayed 10% mortality after release, which is higher than estimates from other studies of mouth-hooked, non-bleeding cod (0%, Ferter *et al.*, 2015b). It should be noted, however, that this injury class incorporates two levels of injury and could cause variations in mortality. In addition, the mortality rate for each injury class does not account for any physiological consequences of extended fight or handling times (Wood *et al.*, 1983) that cannot manifest as physical injury.

Not surprisingly, the physical injury severity of cod in the present study was associated with certain aspects of the capture experience. For example, more severe injuries were found in fish captured by jig, those with extended fight and handling times, and fish that were caught and handled by less experienced anglers. In addition, within the size range examined, smaller cod suffered more severe physical trauma, with fish in the 26–39 cm range being nearly twice as likely to suffer severe injuries compared with larger fish (52–72 cm range). Interestingly, the majority (79%) of the cod observed with moderate-to-severe injury were foul-hooked by treble-hook-jigs. These findings contradict past studies where treble hooks and artificial lures produced lower or equal mortality rates when compared with single hook and bait, respectively (Arlinghaus *et al.*, 2007; Cooke and Wilde, 2007). The severity and incidence of injury from foul-hooking among jig-captured cod could be influenced by the active fishing technique (i.e. as the jig is bounced on the seabed in repeated and rapid vertical movements) associated with groundfish jigging, or the use of jigs with treble hooks that are larger than those hooks typically used to target other GOM groundfish. More work is needed to better understand the effects of treble-hook- vs. single hook-jigs, including the effect of hook size on foul-hooking, injury, and ultimately mortality in cod.

In contrast to jigs, baited hooks were mainly associated with shallow mouth-hooking, leading to far fewer foul-hooking events and associated injuries. Mouth-hooking represented 94% of all bait-caught cod where only three individuals (∼1%) were hooked deeply (i.e. hooking of esophagus, gills, or stomach). The leader's relatively short dropper loop (∼10 cm) and sinker weight combination commonly used in this fishery may limit contact of the hook with the innermost portions of the mouth, thereby reducing the incidence of deep hooking (Beckwith and Rand, 2005; Arlinghaus *et al.*, 2007). However, without comparing other dropper loop lengths and sinker weights, accurate conclusions cannot be made. Shallow hooking of cod could be attributable to feeding morphology and/or aspects of fishing (e.g. gear and tackle configuration, angler behaviour, drifting vessel while actively holding rod), but such possible influences require further investigation.

In the present study, angler inexperience was associated with prolonged handling times and higher injury rates for cod. Previous studies on other species also reported a negative relationship between angler experience and hooking injuries/mortality (Diodati and Richards, 1996; Meka, 2004). Although the relationship between angler experience and handling time was not found via the proportional-odds model, such significant conclusions were surmised indirectly from other analyses (i.e. MWW). The effect of angler experience, while not often studied directly, likely influences other aspects of capture and handling with direct bearing on injury and mortality, such as the tactics to remove embedded hooks and associated effects on handling times (Diodati and Richards, 1996; Meka, 2004). The concept that novice anglers inflict increased tissue damage through more aggressive hook removal methods was the probable basis for the significant (yet indirect) positive relationship between handling time and injury; however, method of hook removal is difficult to quantify, and for the purposes of the present analyses, was considered subsumed by the broader angler experience category. Nevertheless, it seems sensible, where possible, for novice anglers to seek assistance from more experienced anglers or crew when handling fish and removing hooks to reduce the probability of injury and mortality.

Tackle type may also influence hook removal and handling times. For example, handling times in the present work were longer for cod caught by bait vs. jigs. This could be due to the Mustad J-hooks being smaller and more difficult to manipulate than the treble hooks, especially when considering the higher proportion of mouth-hooked cod caught by bait, vs. foul-hooked cod caught on jigs. Barbless hooks may reduce handling time and injury in cod as they have in several studies in other species (Arlinghaus *et al.*, 2007; Cooke and Wilde, 2007), yet direct comparisons are likely inappropriate given that barbless hooks were not used. As such, future investigation into the differential effects of these tackle choices is warranted.

The sea temperature differential between surface and bottom waters was not a significant predictor of cod DM. Both temperature differential (Brattey and Cadigan, 2004; Diamond and Campbell, 2009; Campbell *et al.*, 2010) and high sea surface water temperature (Arlinghaus *et al.*, 2007; Cooke and Wilde, 2007) have been shown to induce physiological disturbance and increase mortality in several species, including cod (Milliken *et al.*, 2009; Weltersbach and Strehlow, 2013). However, maximum surface temperatures during the study (21.2°C) never exceeded the thermal tolerance maximum of Atlantic cod (24°C) and fell within the range that juvenile cod can tolerate during brief exposure (Pérez-Casanova *et al.*, 2008), which could possibly explain the lack of negative effect on mortality. The lack of influence may also be attributable to the relatively small gradient in bottom vs. surface seawater differentials in the study area (see Table 5), or the short exposure period to warm surface water during capture and release.

Depth also had no effect on cod DM despite its known deleterious effect on the survival of physoclistous fish (Arlinghaus *et al.*, 2007), including cod (Pálsson *et al.*, 2003). Lack of a depth effect was also observed in the Baltic Sea's recreational cod fishery, yet in that study fishing was limited to depths <20 m (Weltersbach and Strehlow, 2013). It is important to note, however, that the lack of depth effect in the current study pertains only to the capture of cod at 45–83 m (Table 5) and does not suggest that depth would have no effect on DM at capture depths exceeding 83 m. Although typical barotrauma events influence buoyancy control and potentially post-release predation events (Raby *et al.*, 2014), only 5.2% ($n = 31$) of all cod initially floated at the surface upon release in the current study, which is comparable with other studies where cod were released with no to minimal injury (2.2%, Ferter *et al.*, 2015b). Based on the presence of intraperitoneal gas bubbles and ability to re-submerge in the current study, it is possible that the majority of cod suffered swimbladder ruptures before handling (Humborstad and Mangor-Jensen, 2013). However, such trauma is considered minor and not a large contributor to mortality (Midling *et al.*, 2012; Ferter *et al.*, 2015a, b), suggesting that catch-and-release events did not increase depth-related injury and mortality.

Analytical considerations

Although this study was conducted in a small area off the Massachusetts coast using standardized gear and tackle, we are confident that our analytical approach produced a robust DM rate estimate that is representative of the greater recreational GOM cod fishery. For example, although the estimated 2013 GOM cod recreational DM rate was derived solely from 2013 Massachusetts MRIP gear and tackle survey data, we feel the tackle configuration and effort data of Massachusetts anglers are representative of the entire GOM recreational fishery given that roughly 70% of all directed GOM cod trips originated from Massachusetts fishing ports in 2013 (National Marine Fisheries Service Fisheries Statistics Division, pers. comm.). Further, while the relative proportion of effort by jig or bait could vary across time, previous or subsequent annual fishery-wide DM rate estimates would still be bounded by the two tackle-specific rates, all else being equal (bait: 15.4%; jig: 21.2%). Specific tackle configurations used in this study were also established based on the survey of anglers before the zero possession limit and therefore are not representative of the hooking injury and/or mortality of alternative tackle (e.g. barbless hooks, circle hooks). The broad range of cod size classes examined (26–72 cm total length) was also chosen to ensure that our DM rate estimate would remain relevant in the event of future changes to the minimum possession size limit. This was not predicated, however, on the possibility that cod landings would be prohibited in general, as they currently are in the GOM recreational fishery (Department of Commerce, 2015). With an expected increase in regulatory discards resulting from the current zero possession limit, the DM rate of larger cod size classes (e.g. >72 cm) holds increased importance, and requires further study.

The external application of acoustic transmitters was a practical approach for estimating cod DM. For instance, the external transmitter application decreased handling intervals and degree of invasiveness associated with the tagging process (Bridger and Booth, 2003). While transmitter retention is presumed to have been high based on our lab study and recaptures, there is no means to confirm that transmitter attachment did not contribute to cod fatalities. The cod used in the lab study were composed of both cultured and wild-caught individuals, all of which were subjected to various anthropogenic stressors (e.g. multiple handling events, sustained confinement). Unlike these individuals that might have been desensitized to stress, the cumulative stressors from fishing and tagging on the acoustic subsample could have increased mortality via either sublethal effects (Bridger and Booth, 2003) or predation (e.g. Stansbury *et al.*, 2015).

The use of transmitter depth data also aided in the conclusion of mortality events. Negative controls (i.e. known dead cod) were crucial to the success of the technique as they defined mortality via depth data and thus increased confidence in mortality determinations. Binning post-release detections in time intervals congruent with the programmed transmitter ping schedule ensured an equal number of observations per bin, and thus equal power in the depth-variance test for mortality. Shorter time bins in the first few days post-release also provided more accurate morality times during the period when most DM occurred. Nevertheless, there were some logistical shortcomings and uncertainties with the approach. Most notably, various physical and biological interactions could have influenced the recorded depth of tagged individuals and thus cause DM classification errors. Spatial heterogeneity in tidal height, post-release predation events (e.g. Gibson *et al.*, 2015), or transmitter failure (as witnessed in the given study), for instance, could have artificially increased depth variance, resulting in false negatives (i.e. dead fish are considered alive). Conversely, depth variance could have been decreased due to unexpected cod behaviour in the study area or long-term transmitter shedding that lead to false positives (i.e. alive fish considered dead).

Our DM estimate may have been biased by the incorrect classification of fish with respect to their post-release fate. However, currently there is insufficient information to quantify the direction and magnitude of a possible bias and to correctly estimate a classification error rate. Nevertheless, a number of strategies could be employed to better quantify classification error, which in turn could then be incorporated in DM rate estimates. For instance, the use of more advanced technologies (e.g. transmitters with tri-axial accelerometers and/or fine-scale acoustic positioning systems) could further resolve mortality determination, but are costly and likely would not eliminate all classification error. Quantifying such error by releasing and recapturing alive cod with acoustic transmitters is another alternative, yet results would be dependent upon high recapture rates of released fish and could be skewed if some control specimens died (due to various fishing and post-release conditions). More detailed investigations on the acoustic patterns of negative controls (i.e. known dead cod), possibly through enhanced receiver arrays or mobile surveys outside the study area, are preferred since they would certainly improve the quantification of classification error and possible bias.

Conclusions

The results of the current study suggest a lower overall DM rate for cod in the GOM recreational fishery than previously assumed. Physical injury appears to be the most telling predictor of and likely contributor to cod mortality in this fishery, with tackle type, fish size, angler experience, and fight and handling times influencing injury severity. Therefore, to mitigate injury and mortality associated with recreational discards of Atlantic cod in the GOM, it is recommended that anglers favour the use of bait over jigs, reel cod to the surface at a slow-to-moderate pace (as to reduce fight time but not elevate potential barotrauma), minimize handling times, and avoid fishing areas inhabited by small cod. Since anglers are more likely to rely on state and federal natural resource programmes for current regulations and "best practice" techniques rather than scientific literature (Pelletier *et al.*, 2007; Ferter *et al.*, 2013), it is also recommended to promote the accessibility and accuracy of angler education programmes. Finally, while in the midst of the present cod crisis and associated zero bag possession regulations for the recreational fishery (Department of Commerce, 2015), anglers should attempt to avoid areas where cod aggregate during fishing trips that are targeting other groundfish species.

Given the relative contribution of the recreational fishery to total cod discards in the GOM, the DM rate estimate presented herein has the potential to fill a valuable data-gap for a variety of management purposes. Furthermore, the dissemination and hopeful adoption of improved catch-and-release practices for recreational anglers that capture cod in the size classes examined can ultimately reduce incidental mortality of this economically and ecologically important species in the GOM.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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