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Using reflex action mortality predictors (RAMP) to evaluate if trawl gear modifications reduce the unobserved mortality of Tanner crab (*Chionoecetes bairdi*) and snow crab (*C. opilio*)

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Management of Bering Sea crab and groundfish fisheries must account for the delayed (and hence unobserved) mortality of crab that encounter bottom trawls, but are not captured. A new approach to predicting the delayed mortality of crab uses a reflex action mortality predictor (RAMP) model to establish a relationship between mortality and reflex impairments. A 2007 pilot study of 649 crab established RAMP curves for both Tanner crab (*Chionoecetes bairdi*) and snow crab (*C. opilio*). Additional data (1775 crab) collected in 2008 allowed us to update the existing RAMP curves to more fully examine the effect of injury scores on the RAMP models and to determine the best method for estimating overall mortality. Results confirmed that the additional measurements did not significantly alter the original relationship between mortality and reflex impairment score. Additionally, the RAMP curves were used to predict unobserved mortality from observed reflex impairment scores of *Chionoecetes* spp. captured after encounters with different parts of bottom trawl gear (footrope and sweep) and alternative types of footrope and sweep. In addition to estimating mortality rates caused by each gear part, we tested whether the alternative footrope and sweep designs reduced the unobserved mortality rates of crab. Results showed that the alternative footrope (58 cm disk footrope) reduced mortality from 11.4 to 7.2% for Tanner crab and from 9.7 to 5.0% for snow crab. The alternative (off-bottom) sweep reduced mortality from 4.1 to 1.0% for Tanner crab and from 4.9 to 0.0% for snow crab. Thus, the use of the reflex impairment score through the RAMP model is a cost effective way to estimate delayed mortality and to assess the effect of gear types on delayed mortality for management purposes.

Keywords: bycatch, *Chionoecetes*, crab, RAMP, reflex impairment, trawl gear, unobserved mortality.

Introduction

Unobserved, discard, and escape fishing mortalities are components of unaccounted fishing mortality that fishery managers have struggled with for many years. Unobserved fishing mortality can be defined as the mortality imposed on a species by an encounter with fishing gear that does not result in capture; however, both discard (captured and released) and escape (actively escapes capture) fishing mortalities can also considered "unobserved" mortality (Alverson *et al.*, 1994; Cook, 2003). A study group and the workshop convened by the International Council on Exploration of the Sea (ICES, 2005) identify escape and discard mortality as some of the major sources of unaccounted fishing mortality and notes the importance of quantifying unaccounted fishing mortality for improved management. However, there is a lack of tools to estimate unaccounted fishing mortality. The report also specifically states that reducing unaccounted fishing mortality in towed fishing gears is of high importance. The North Pacific Research Board (NPRB, 2007), North Pacific Fisheries Management Council (NPFMC, 1999, 2006), the Alaska Marine Conservation Council (AMCC, 2004), and National Marine Fisheries Service (NMFS, 2004) are a few of the major organizations in Alaska that have underscored the need for additional research on the unobserved/unaccounted fishing mortality of crab from both directed crab fisheries and groundfish trawl fisheries. In the Bering Sea, *Chionoecetes* spp. habitat often overlaps with areas trawled by groundfish fisheries leading to unobserved mortality for crab that encounter the trawl gear. Currently, there are several management measures in place for the sustainable management of *Chionoecetes* spp. in the Bering Sea, area closures and bycatch limits for the groundfish trawl fisheries, and an assumed fixed rate of mortality for discarded crab in both the targeted pot fisheries (20% for Tanner crab and 50% for snow crab) and non-target bycatch in the groundfish trawl fisheries (80% for snow crab; Siddeek, 2003).

Few studies have quantified the full range of mortalities that can occur when fish escape from fishing gears under commercial fishing conditions (Chopin and Arimoto, 1995; ICES, 2000; Suuronen, 2005). One justification for selective fishing gear is that the significant numbers of escaping fish or other animals survive; hence, the quantification of the survival rates of escapees is of fundamental importance when selectivity issues are addressed (ICES, 2005). Some research has been done to quantify discard and escape mortality (Broadhurst *et al.*, 2006, 2008a, b). Broadhurst *et al.* (2008a) suggest that simple modifications to the gear and operation may markedly reduce the mortality of animals encountering but not caught by the gear.

Tanner crab (*Chionoecetes bairdi*) and snow crab (*C. opilio*) are targets of directed fisheries in the Bering Sea. In 2008/2009, the Total Allowable Catch (TAC) for Tanner crab was ~4.3 million pounds (Alaska Department of Fish and Game; ADF&G, 2008); however, only 1.66 million pounds was harvested (Fitch *et al.*, 2012) worth $(US) 2.5 million (Fitch *et al.*, 2012), the TAC for snow crab was ~54.3 million pounds (ADF&G, 2010) and worth $(US) 104 million (Fitch *et al.*, 2012). The Tanner crab fishery in the Bering Sea requires that the stock be above the minimum mature female biomass threshold of 21.0 million pounds for the fishery to be open; since 2009 that threshold has not been met and therefore the fishery has been closed. Snow and Tanner crab are harvested using baited pots. As only males above a certain size can be landed, the discard mortality of sublegal males and females can be a major component of fishing mortality in the pot fishery. Both crab species are also taken as bycatch in the groundfish trawl fishery. Although no retention of crab bycatch is allowed, both discard mortality and unobserved mortality after interactions on the seafloor are significant concerns. The potential for unobserved mortality following the crab/gear interaction was thought to be high by the fishing industry and fishery managers, but there has been no way to quantify this unobserved mortality, given that the crab are not brought on deck. In a companion paper to the present study, based on data from the same research cruise, Rose *et al.* (2013) produced the first estimates for Tanner and snow crab after encounters with conventional trawl footropes and sweeps.

Recently developed reflex action mortality predictors (RAMPs; Davis, 2009) can be used to quantify some types of unaccounted fishing mortality. Reflex impairment imposed on fish and crab from a towed fishing gear has been correlated with stress and mortality outcomes both in the laboratory and field (Davis and Ottmar, 2006; Davis, 2007, 2009; Stoner *et al.*, 2008; Stoner, 2009). Davis (2009) describes a three step process for validating reflex impairment as a research tool: (i) identify consistent reflex responses, (ii) conduct stress experiments, and (iii) model correlation between reflex impairment and mortality and to predict mortality in field experiments. Stoner *et al.* (2008) used reflex impairment for *Chionoecetes* spp. to create a RAMP curve, in order to estimate the mortality of crab after interaction with the bottom trawl gear. Both Stoner (2009) and Davis (2009) propose using an RAMP as a research tool to predict delayed mortality from bycatch and discard mortality. Davis (2009) explains that with validation for a given species, reflex impairment can be used to predict fish stress and mortality over a wide range of fish systems, including recreational and commercial capture fishery operations, and the gear used to catch the fish, such as rod and reel, trap, pot, seine, trawl, longline, and trolling. Once a reflex impairment model is validated, it can then be used for real-time assessment to predict mortality.

A number of methods have been used to reduce direct and indirect types of fishing mortality or bycatch, such as area closures, seasonal closures, gear regulations, bycatch reduction devices (BRDs), and modifications to fishing gear. Thanks to cooperative research between the commercial fishing industry and research scientists from both the government and the private sector, several successful examples of BRDs and modifications to fishing gear are available. These include Turtle Excluder Devices (Watson and Seidel, 1980; Brewer *et al.*, 2006), the Nordmore grate (Isaksen *et al.*, 1992; Richards and Hendrickson, 2006), separator panels such as the Eliminator (Beutel *et al.*, 2008), and an off-bottom or elevated sweep for the flatfish trawl fishery in the Bering Sea (Rose *et al.*, 2010). This research on off-bottom sweeps was a collaborative project between the flatfish bottom trawl industry in Alaska, net manufacturers, and the National Marine Fisheries Service. The idea for a gear modification (off-bottom sweep) came about as a possible alternative to closed areas in the Bering Sea.

The present study used the RAMP model to investigate whether modifications to the bottom trawl gear, specifically sweeps (cables connecting doors to trawlnet) and footrope (ground-contact gear attached to the trawlnet), reduced the unobserved mortality of snow and Tanner crab. The RAMP models for these species from Stoner *et al.* (2008) were augmented with additional observations that more than tripled the sample sizes. Alternative configurations of the resulting RAMP models were compared, examining the effects of sex, size, and shell condition, supplementing with injury observations, and application as a categorical or continuous variable. RAMP-estimated mortality rates were then applied to determine if alternative fishing gear reduced unobserved mortality compared with conventional fishing gear. Specifically, mortality rates for raised trawl sweeps (Rose *et al.*, 2010) and larger diameter footropes were compared with rates for conventional configurations (Rose *et al.*, 2013). Both modifications create larger spaces under the gear for crab escapes. These mortality rates were also compared across sex, size, and shell conditions.

Methods

Stoner *et al.* (2008) established protocols for capturing crab based on Rose (1999), scoring reflexes (Table 1), and retention of *Chionoecetes* spp. to track delayed mortality. In addition, Stoner *et al.* (2008) established a preliminary RAMP curves for snow crab (*C. opilio*) and Tanner crab (*C. bairdi*). Crab that had encountered full-scale bottom trawls were brought aboard the vessel for evaluation and holding to assess the effects of trawl contact on the probabilities of immediate and delayed mortalities. Collection methods were expanded from Rose (1999), using auxiliary nets fished behind the trawl components (i.e. sweep and footrope) to capture affected crab after contact with the gear and deliver them to the vessel with minimal additional stress and damage.

Table 1. Reflexes identified as useful for assessing stress in *Chionoecetes* spp.

Reflex	Test	Positive response	No response
Leg flare	Lift crab by the carapace, dorsum up	Legs spread wide and to near horizontal orientation in strong crab	Legs droop below horizontal, with no attempt to raise them
Leg retraction	While held as above, draw the forward-most walking legs in the anterior direction	Legs retract in the posterior direction or present resistance to the motion in weakened crab	No resistance to the manipulation occurs
Chela close	Observe for motion or hold the chelae in the fingers	Chelae open and close with or without manipulation. In weakened crab, the chelae may close slowly or show low resistance to manual opening	No motion is detected in the chelae under manipulation
Eye retraction	Touch the eye stalk with a blunt probe or lift the eye stalk from its retracted position	Eye stalk retracts in the lateral direction below the carapace hood or shows resistance to lifting	No motion or resistance to manipulation occurs in the eye stalk
Mouth close	If closed, attempt to open (extend) the third maxillipeds with a sharp dissecting probe. If open, draw the maxillipeds downwards	Third maxillipeds retract to cover the smaller mouth parts. The maxillipeds droop open or move in an agitated manner in weakened crab	No motion in the maxillipeds occurs
Kick	With the crab in ventrum-up position, use a sharp dissecting probe to lift the abdominal flap away from the body	One or more legs or chelipeds move quickly in the ventral direction, particularly in males. Motion in the hind most legs is retained in weakened crab	No motion in the legs or chelipeds occurs

Test is the manipulation required to elicit a stereotypic positive response. "No response" was recorded when no motion was detected after repeated testing of the reflex. Modified from Stoner *et al.* (2008) and Stoner (2009).

Fishing gear

A field experiment was conducted to determine whether or not alternative sweeps and footrope would reduce the unobserved mortality of *Chionoecetes* spp. For footrope and sweeps, a conventional (currently used by the fishing industry) and an alternative gear were tested. The main trawl was a two-seam Alfredo bottom trawl (with headrope and footrope overall lengths of 36.0 and 54.6 m, respectively) similar to that used by many of the flatfish fishing vessels in the Bering Sea. The forward 14 m of the footrope on each wing of the trawl was made of 20 cm disks (mud gear) strung over 2.54 cm steel cable. Continuing forward from the trawl were 27 m bare steel cable bridles that were attached to the upper wings and the same lengths of cable, covered with 9 cm diameter rubber disks that were attached to the lower wings. There were two sections to the sweeps. Extending forward immediately from the bridle was 82 of 5 cm combination rope (conventional sweep) followed by 73 m of bare steel wire leading to 3.2 m Thyboron doors. The codend of the main trawl was left open because our study addressed crab that encountered the trawl but remained on the seafloor not crab that would be caught by the main trawl.

The conventional footrope (23 m centre and wing sections), typical of those used for flatfish fishing, was constructed of bobbins and disks strung on a 19-mm long-link steel chain (Figure 1b). The alternative footrope was a 58-cm disk footrope, which the vessel used as a rock-hopper gear (Figure 1a). Historically, both the bobbin footrope and the large disk footrope were designed to be used on hard bottom seafloor; over time, it was discovered that these footropes also reduce the mortality of crab. The large disk footrope has the advantage that the disks are narrower and spaced farther apart, creating a higher and wider clearance in the spaces between the disks than the bobbin footrope; therefore, the disk footrope decreases the bottom contact.

Conventional sweeps were 5 cm diameter combination wire, 82 m in length. Conventional sweeps have continuous contact with the seafloor along their entire length to herd fish. However, this increases exposure of benthic invertebrates to damage and mortality. The disks on the alternative off-bottom sweeps (Figure 2; Rose *et al.*, 2010) raised the sweeps off the seafloor several centimetres with the goal of reducing contact with and the mortality of invertebrates without reducing the target catch.

Field experiment

Fieldwork was conducted in August 2008, east of the Pribilof Islands in the Bering Sea (latitude: 56.93 to 57.18°N, longitude: 168.17 to 168.49°W, Figure 3), at depths ranging from 83 to 91 m with muddy sand bottom type. Temperature ranges at depth and on the surface were from 1.1 to 1.5 and 7.7 to 12.5°C, respectively. The sampling location was selected from the Eastern Bering Sea (EBS) Crab and Groundfish Survey data (Alaska Fisheries Science Center, NMFS, NOAA) in order to find where both species of crab over a wide variety of sizes were occurring together.

The sampling goal was to capture 50–100 crab per tow with a relatively even mix of both species. Tow durations were kept to 10–20 min to minimize damage to recaptured animals. In order to capture and assess crab that had interacted with alternative and conventional configurations of the footropes and sweeps, auxiliary nets (Rose, 1999; Rose *et al.*, 2013) were rigged to fish behind the centre of the footrope (but underneath the main trawlnet) and behind the combination rope part of the sweeps (Figure 4). A video camera was used to observe performance of an auxiliary net when deployed behind the sweeps, assuring symmetrical shape, and consistent bottom contact. Although observations behind the footrope were obscured by suspended sediment, video was still used to assure water flow perpendicular to the centre of the headrope, an indicator of symmetrical operation. An auxiliary net was also fished in front of the net mouth to collect crab before they interacted with the main gear. This control net was used to assess handling mortality, i.e. the mortality caused by crab being caught in the auxiliary net, brought up on deck, sorted, assessed, and held. This handling mortality was then used to adjust the mortality rates observed from the nets behind the gear. Only one auxiliary net (including control net) at a time was fished due to the complex nature of setting and retrieving the augmented fishing gear. There were 19 tows each for the control net, conventional footrope, and alternative footrope, and 21 tows each for the conventional and alternative sweeps.

Once an auxiliary net was on deck, *Chionoecetes* spp. were removed from the codend and sorted by sex and species into baskets. The remaining catch (typically made up of various flatfish, sea stars, urchins, shells, anemones, and other crab species) was weighed and discarded. An initial screening of reflexes was performed for all crab (Table 1); crab were separated into two groups, those with and those without reflex impairments. Approximately 88% of the crab (11 586 of 13 211) had no reflex impairments. Following initial assessment, crab were placed in totes with constant running seawater until the full assessment could be done, usually less than 15 min. Species, sex, size (carapace width, CW), shell condition [scores based on increasing shell hardness, discolouration and encrustation: 0, premolting/molting; 1, soft shell; 2, new shell; 3, old shell; 4, very old shell; 5, graveyard; Jadamec *et al.*, 1999], reflex impairment, and injuries (for crab with impairments) were then recorded. Although no severe injuries were noted for crab with all reflexes. There were some minor injuries, particularly dropped legs (autotomies) that were not recorded, unless the crab were held for RAMP validation. This injury assessment protocol was based on the earlier result that injury scores contributed little additional precision to the mortality prediction, compared with the additional time required to assess all crab for injuries and the fact that many injuries are internal and not noticeable upon gross examination (Stoner *et al.*, 2008). Some unimpaired crab were retained as a control to strengthen the 2007 study findings.

Crab were assessed based on reflex behaviours identified as useful for predicting mortality in *Chionoecetes* spp. (Stoner *et al.*, 2008; Table 1). Reflexes assessed were leg flare, leg retraction, chela closure, mouth closure, eye reaction, and kick. Each crab was scored for each reflex with either 1 (reflex present) or 0 (reflex absent). The number of reflex absences was used as a reflex impairment score (scales 0–6). Held crab (1446 snow crab, 978 Tanner crab) were later scored on an injury scale of 0–5 (0, no injuries; 1, newly autotomized legs; 2, broken legs, chelae, or mouthparts; 3, minor carapace or abdomen damage; 4, major carapace or abdomen damage; 5, major damage to multiple parts) based on Stoner *et al.* (2008). After the crab were assessed, a large majority of the healthy/lively crab (score 0, $n = 11\,144$) were returned to the sea; crab with a score of 6 ($n = 927$) were considered moribund and most were discarded. Crab with no reflexes (score 6) and no major visible injuries ($n = 79$) were held to confirm immediate mortality. A substantial sample of unimpaired crab ($n = 442$) and all crab with reflex impairment scores of 1–5 ($n = 413$) were tagged with vinyl spaghetti tags and placed in 0.75 m^3 live boxes secured on the deck of the ship and supplied with constant flowing seawater ($\geq$20 l min^{-1}, 9.1–9.6°C, 27.2 PSU salinity, and 100% oxygen saturation) and held for 5–12 d. These systems were identical with those used in an earlier study of crab mortality (Stoner *et al.*, 2008). Crab were reassessed on a daily basis in order to determine delayed mortality. Starting 5 d before the end of cruise, no additional crab were held to assure sufficient holding time to assess delayed mortality. At the end of the cruise, all remaining crab underwent a final reassessment for mortality and reflex impairment score and were returned to the sea.

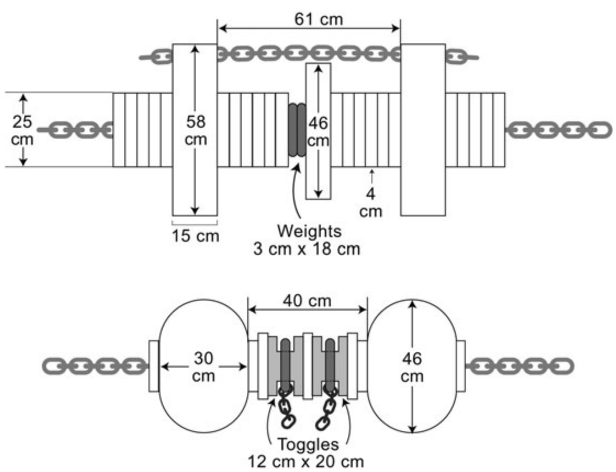

Figure 1. (a and b) Alternative footrope (top) is constructed of disks (58 cm high × 15 cm wide) and is rigged as a rock-hopper gear. In the 61-cm space between the 58-cm disks are 25 cm disks, two 5 kg (18 cm) footrope weights, a 46-cm disk, and more 25 cm disks. A conventional footrope (bottom) is constructed of bobbins (46 cm high × 30 cm wide) and disks strung on 19 mm long-link steel chain. In the space between the bobbins are two steel chain toggles weighing 6.4 kg each, 20 cm rubber disks, and one 5 kg (18 cm) footrope weight.

Comparing models relating the probability of mortality to reflex impairment scores

RAMP models for both *Chionoecetes* spp. were analysed to assess reflex impairment and injury as predictors of delayed mortality. The data used were a combined dataset of held crab from the 2007 pilot study (Stoner *et al.*, 2008) and data collected in 2008 (1446 snow crab, 978 Tanner crab). Similar to Stoner *et al.* (2008), logistic regression was used to determine if injury, sex, shell condition (new, old, very old), and size (CW) were statistically significant predictors in the RAMP model. Generalized linear modelling (GLM) with

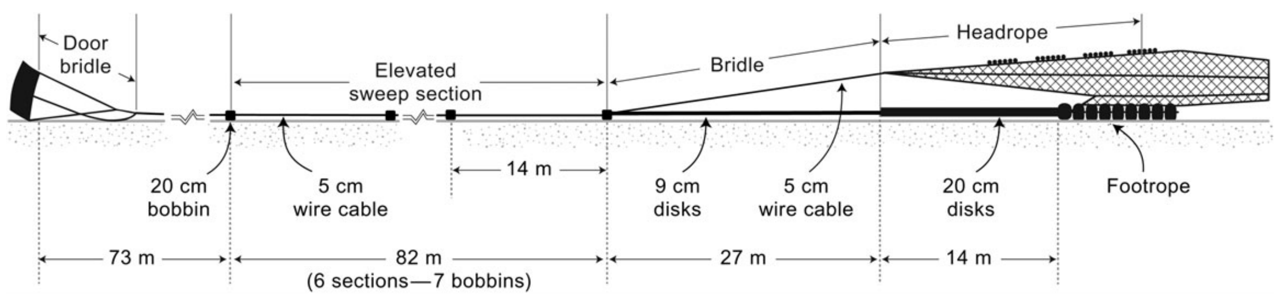

Figure 2. The alternative off-bottom sweeps were 5 cm combination wire with 20 cm disks spaced every 14 m. Conventional on-bottom sweeps do not have the 20 cm disks and have continuous contact with the seafloor along their entire length to herd fish.

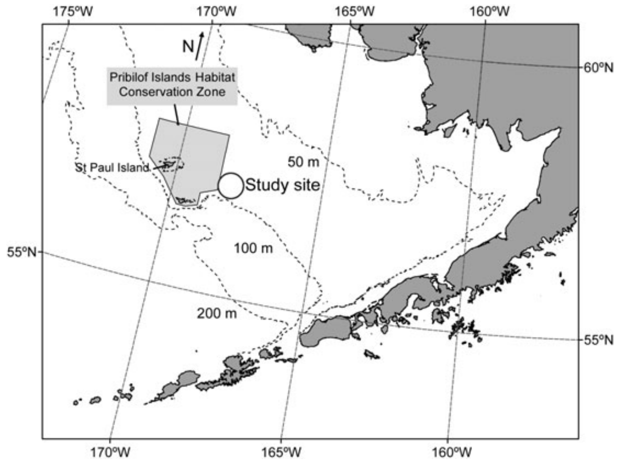

Figure 3. Sampling locations near the Pribilof Islands for snow (*C. opilio*) and Tanner (*C. bairdi*) crab in 2007 (pilot study) and 2008. Pribilof Islands habitat conservation zone (no trawl zone) and depth contours are included for reference.

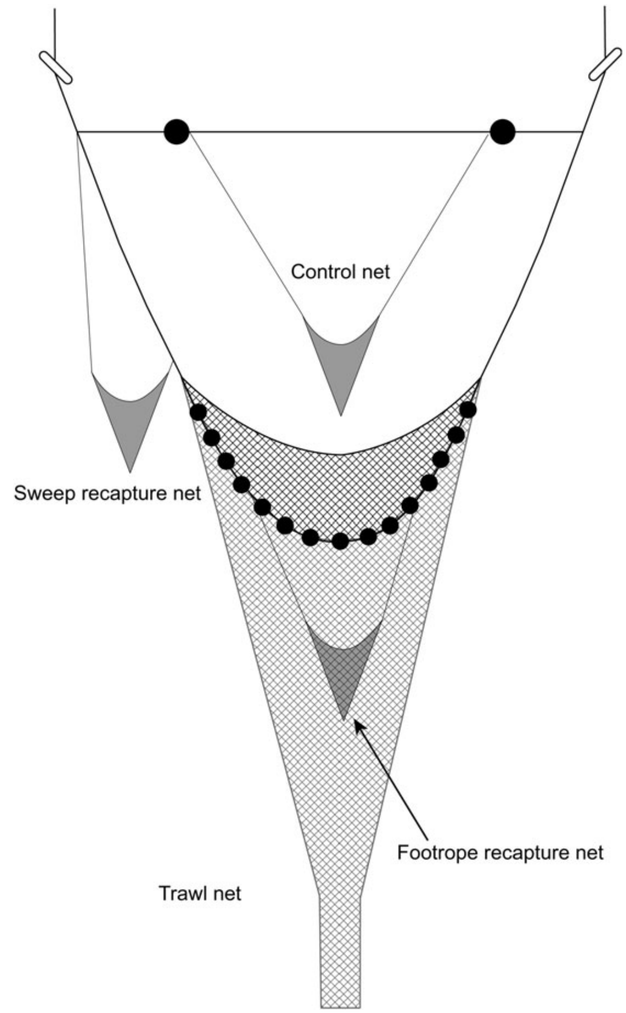

Figure 4. Diagram showing the three positions where the auxiliary and control nets were attached to the main bottom trawl (not to scale) (drawn by Karna McKinney).

binomial error in R (R Development Core Team, 2007) was used to perform the analysis. Since the crab used for this analysis were retained and mortality was known, each crab in the dataset was assigned a 1 if the animal died and a 0 if the animal lived; this binary response was used in the GLMs. GLMs are specified by the terms in the linear predictor, the link function [here the logit link, or $\log(p/(1-p))$] and the associated error distribution (Faraway, 2006). The Akaike information criterion (AIC, a form of likelihood, penalized by the number of predictors) values from the various models run were then compared to determine which was the most efficient fit for each species of crab. A lower AIC is associated with a higher likelihood and therefore a more plausible model for the data (Faraway, 2006).

In order to investigate which method (logistic regression or per cent mortality based simply on the seven discrete reflex impairment categories) was better to describe the relationship between reflex impairment and probability of mortality, the above-mentioned regression was run using only reflex impairment as a categorical or a continuous predictor variable. The AIC values were then compared to determine which model was a better fit. In addition, the maximum likelihood estimates of mortality (ρ) were calculated as

$$\rho = \frac{e^{\alpha+\beta x}}{1 + e^{\alpha+\beta x}}, \tag{1}$$

where α is the intercept, β the model coefficients, and x the model matrix of explanatory variables (Stoner *et al.*, 2008).

Mortality estimates for crab encountering the trawl gear

To calculate the mortality estimate for a species in each haul, using the 2008 crab assessments, the proportion of crab at each reflex impairment score was multiplied by the probability of mortality for that reflex impairment score from the RAMP model for that species. The resulting probabilities of mortality for each reflex impairment score were then summed to obtain an overall mortality estimate for that haul. These estimated mortality rates were weighted by the number of crab in each haul, summed, then divided by the total number of crab for all the hauls with that gear component (control, alternative, and conventional sweeps and footropes). This calculation provided a weighted "raw" mortality estimate (as yet unadjusted for handling) for each gear component. The estimate of handling mortality from the control was then used to adjust the estimated raw mortality by gear component.

The handling mortality adjustment (Rose, 1999) was derived assuming that the mortality from handling occurred sequentially after mortality from encountering the trawl gear. Equation (2) estimates the mortality rate in the nets behind the gear (M_{G+H}) in terms of the separate mortalities from the gear (M_G) and the handling (M_H), which was estimated from the control net mortalities and only applied to crab that survived the gear. That was then algebraically solved for the gear mortality rate [Equation (3)].

Sequential effects:

$$M_{G+H} = M_G + (1 - M_G)M_H \tag{2}$$

where M_{G+H} is the combined mortality rate, M_G the gear mortality rate, $(1 - M_G)$ the probability of surviving the gear, and M_H the handling mortality rate

Rewritten to isolate gear effect:

$$M_G = \frac{M_{G+H} - M_H}{1 - M_H}. \quad (3)$$

This is a conservative estimate, as any mortality due to the combination of gear and handling that would not have been caused by either separately was attributed to gear.

Analysis of factors affecting mortality due to gear encounters

Using the data from 2008 for all assessed crab for each gear category (control, alternative, and conventional sweep and footrope), further analyses were conducted to relate RAMP-predicted mortality to predictors such as gear type, sex, shell condition, and size (CW). Analyses were run as logistic binary regression models. Binary regression models require that each datapoint (in this case, each crab) be recorded as being either alive (0) or dead (1). Thus, if a crab's RAMP-predicted mortality were less than 0.5, its binary response was recorded as a 0. If the RAMP-predicted mortality were greater than 0.5, its binary response was recorded as a 1. (Initial analyses had used logistically transformed ($\log(p/(1-p))$) RAMP-predicted mortality in a normality-based regression framework, with poor model fit.) To assess the statistical significance of each predictor (whether a main effect or an interaction effect) in the model, we used a Chi-squared test to compare the change in residual deviance to a Chi-squared random variate with the degrees of freedom associated with that particular predictor.

Results

The 2008 field study assessed a total of 13 211 crab (6631 snow crab, 6580 Tanner crab), of which 1775 crab were held or dead (1047 snow crab, 728 Tanner crab). All of the assessed crab were used for the fishing gear portion of the study (Rose *et al.*, 2013, this paper). The held crab from 2007 (399 snow crab, 250 Tanner crab) and 2008 were combined for the RAMP model analysis (1446 snow crab, 978 Tanner crab).

Relating probability of mortality to reflex impairment score

Probabilities of mortality for snow crab ranged from 1.4 to 100% over the 6-point reflex impairment score range. Probabilities of mortality for Tanner crab ranged from 7.2 to 100% over the reflex impairment score range (Figure 5). Generally, mortalities by reflex impairment score from the combined 2007 and 2008 data matched well with those from the 2007 data alone. For snow crab, the RAMP model estimates were almost identical at reflex impairment scores 0, 2, 5, and 6. Mortalities for snow crab at reflex impairment scores 1 and 4 were higher in 2008, and somewhat lower at reflex impairment score 3. For Tanner crab, the mortality estimates matched up well at reflex impairment scores 0, 4, and 6, but were lower at the remaining reflex impairment scores.

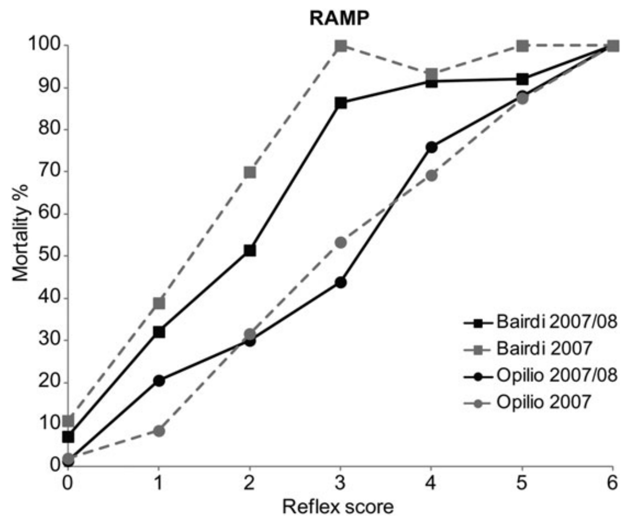

Figure 5. RAMP probability of mortality curves for *C. bairdi and C. opilio,* with a comparison between 2007 data (Stoner *et al.*, 2008) and combination of 2007 and 2008 data.

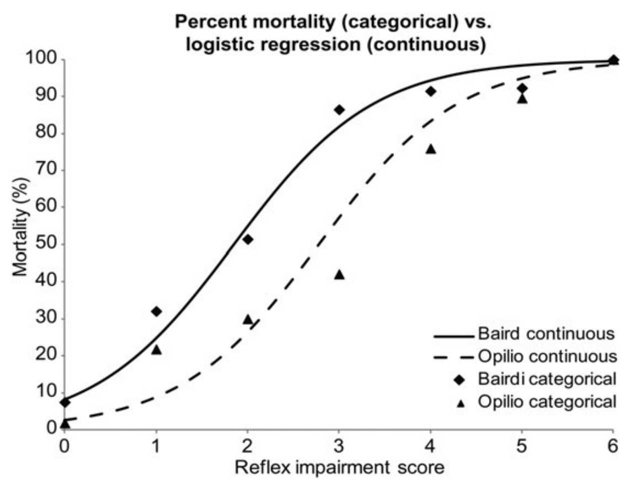

Figure 6. Comparison of logistic regression to percent mortality to describe the relationship between reflex impairment score and probability of mortality.

Comparing different models of mortality predictors

Logistic regression revealed that mortality in both species was well predicted by reflex impairment (Figure 6). Both species showed reflex impairment to be highly significant; reflex impairment explained 74% of the variability for snow crab (slope = 1.10, s.e. = 0.07, $p<0.001$) and 70% for Tanner crab (slope = 1.06, s.e. = 0.09, $p<0.001$). Injury score was also highly significant ($p < 0.001$); however, injury only explained an additional 2.9% of the variability for snow crab and 3.5% for Tanner crab after accounting for the effect of reflex impairment scores (Table 2). Sex, size, and shell condition were not significant variables for either species of crab in the regression models and explained less than 1% of the variability. No significant interactions were detected between factors.

Each species had different models with the lowest AIC values (Table 2). The model containing both reflex impairment scores and injury scores as categorical (as opposed to continuous) predictors had the lowest AIC (445.63) for snow crab (model 5). This model also explained 79% of the total deviance. For Tanner crab, the model containing all variables—sex, shell condition (categorical), size, reflex impairment score, and injury score (model 7), had the lowest AIC (347.29), explaining 75% of the total deviance. Model 8, containing sex, shell condition (categorical), size, reflex impairment score (categorical), and injury score (categorical), had small differences from the minimum AIC. All other models

Table 2. Comparison of AIC values, change in AIC (ΔAIC), and per cent variability explained for RAMP logistic regression for snow crab (*Chionoecetes opilio*) and Tanner crab (*C. bairdi*).

Model #	Predictors in the model	d.f.	Bairdi AIC	Bairdi ΔAIC	Bairdi % variability explained	Opilio AIC	Opilio ΔAIC	Opilio % variability explained
1	Reflex score (RS)	1	407.29	60	69.66%	512.93	67.3	74.40%
2	**C**Reflex score (RS, as categorical)	6	405.98	58.69	70.51%	481.08	35.45	76.56%
3	RS + injury score (IS)	2	356.66	9.37	73.54%	458.05	12.42	77.36%
4	RS + IS + (RS × IS) (testing interaction)	3	357.46	10.17	73.65%	459.63	14	77.33%
5	**C**Reflex + **C**Injury (both predictors categorical)	11	357	9.71	75%	**445.63**	0	78.89%
6	Sex + Shell + Size + RS + IS (Stoner *et al.*, 2008 model)	5	360.67	13.38	73.69%	462.84	17.21	77.42%
7	Sex + **C**Shell + Size + RS + IS (shell as categorical)	7	**347.29**	0	75.03%	464.62	18.99	77.59%
8	Sex + **C**Shell + Size + **C**RS + **C**IS (shell, RS, and IS as categorical)	16	350.58	3.29	**76.13%**	451	5.37	**79.17%**

The ΔAIC is compared with the lowest AIC, model 7 for Tanner crab and model 5 for snow crab.
A "**C**" preceding a predictor indicates that it is in the model as a categorical predictor. Sex is always categorical. d.f., the number of estimated coefficients for that model (higher d.f. results in higher AIC). Bold indicates the lowest AIC values and highest explained variability.

for both species had ΔAIC values greater than 10.0, indicating that the other models were too far away from the minimum AIC to be efficient (Burnham and Anderson, 2002). Model 6, which was the same model used in Stoner *et al*. (2008), had ΔAIC values greater than 10.0 and explained 74% (Tanner crab) and 77% (snow crab) of the variability.

Models 1 (reflex impairment as a continuous predictor) and 2 (reflex impairment as a categorical predictor) from the RAMP logistic regression for Tanner crab have similar AIC values (Table 2), indicating that either model could be efficient. However, snow crab AIC values were further apart. Additionally, visual inspection indicated that the logistic regression model fits Tanner crab much better than snow crab (Figure 6).

Effects of alternative gear on mortality estimates (adjusted for handling)

Snow crab showed lower mortality than Tanner crab after encounters with various trawl gear components (Figure 7). The alternate footrope reduced mortality from 11.4 to 7.2% for Tanner crab and from 9.7 to 5% for snow crab (Figure 8a and b). Alternate sweeps reduced mortality from 4.1 to 1% and from 4.9 to −2.2%) for Tanner and snow crab, respectively (Figure 8a and b). For snow crab, the handling mortality was actually higher than the alternate sweep, leading to a −2.2% mortality estimate for the alternate sweep after being adjusted for handling. Since negative mortality is not possible the mortality estimate was assumed to be zero, resulting in a 100% reduction in mortality with the alternate sweep. A GLM showed that the reductions in mortality gained by the alternative sweeps and alternative footrope were statistically significant, $p < 0.00001$ (see details of Chi-squared tests below).

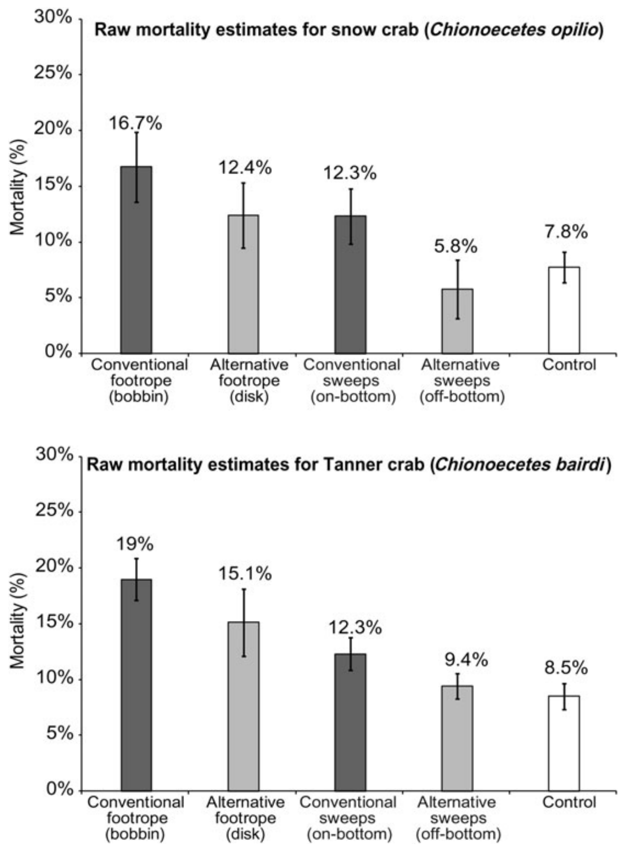

Figure 7. Raw mortality estimates for *Chionoecetes* spp. for each gear component, including the control. Error bars depict a 95% confidence interval.

Analysis of factors affecting mortality due to gear encounters

For Tanner crab encountering trawl footropes, significant effects included gear ($\chi^2 = 104.69$, d.f. = 2, $p = 0.00$), shell condition ($\chi^2 = 56.79$, d.f. = 2, $p = 0.00$), and the gear × shell condition interaction ($\chi^2 = 13.15$, d.f. = 4, $p = 0.01$). Although the control gear RAMP-predicted mortalities were lower than those for conventional and alternate footropes, differences were not consistent across shell conditions, and hence the presence of interaction (Table 3).

For Tanner crab encountering trawl sweeps, significant effects included gear ($\chi^2 = 28.61$, d.f. = 2, $p = 0.00$), shell condition ($\chi^2 = 10.31$, d.f. = 2, $p = 0.01$), size ($\chi^2 = 6.46$, d.f. = 1, $p = 0.01$), and gear × shell condition interaction ($\chi^2 = 14.39$, d.f. = 4, $p = 0.01$). RAMP-predicted mortality was 4% ($n = 1459$) for females vs. 2% ($n = 1084$) for males, marginally non-significant ($\chi^2 = 3.42$, d.f. = 1, $p = 0.06$). The relationships between the control, conventional sweep, and alternate sweep varied according

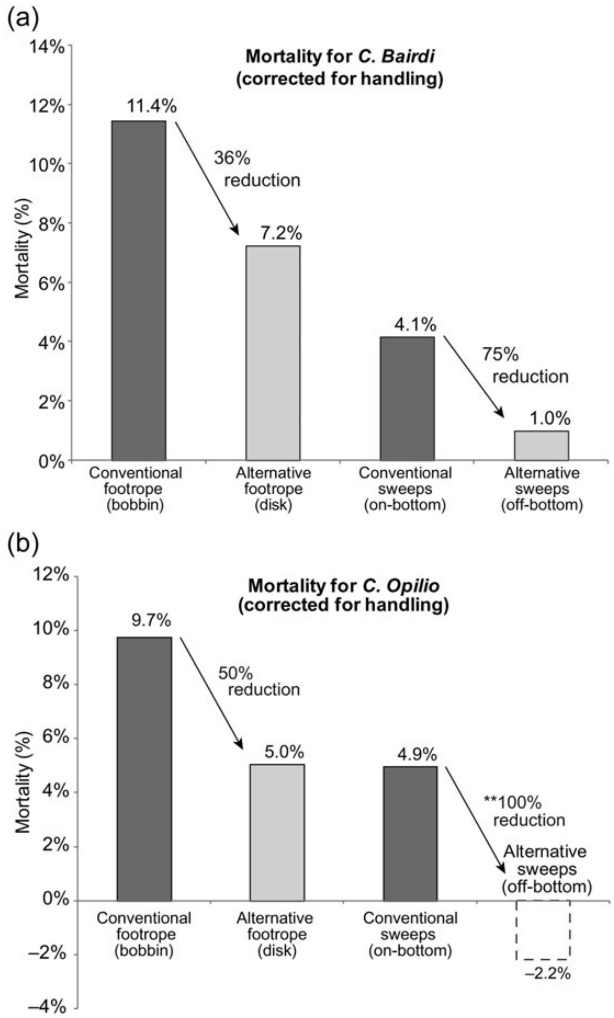

Figure 8. (a) Reduction in mortality ($p < 0.00001$) for alternative sweeps and footrope in *C. bairdi,* corrected for handling. (b) Reduction of mortality ($p < 0.00001$) for alternative sweeps and footrope in *C. opilio,* corrected for handling. **Assessment goes to zero for modified sweep.

to shell condition (Table 3), and hence the statistical interaction between gear and shell condition. Mortality increased with increasing carapace size (slope = 0.03, s.e. = 0.01).

All main effects were statistically significant for snow crab encountering trawl footropes, in addition to the gear × shell interaction (gear: $\chi^2 = 55.54$, d.f. = 2, $p = 0.00$; sex: $\chi^2 = 5.55$, d.f. = 1, $p = 0.02$, shell condition: $\chi^2 = 57.72$, d.f. = 2, $p = 0.00$; size: $\chi^2 = 27.89$, d.f. = 1, $p = 0.00$; gear × shell condition: $\chi^2 = 22.86$, d.f. = 4, $p = 0.00$). For all shell conditions, control mortality was lower than that for conventional and alternate footropes. However, the differences between gear mortalities changed among the three shell conditions (Table 3). The average mortality was statistically lower for females (9%; $n = 1155$) than for males (11%; $n = 2565$). Although the observed difference was only two percentage points, it was statistically significant due to the high statistical power associated with large sample sizes, making it possible to declare small observed differences as "statistically different" regardless of the biological importance of the difference. Mortality generally increased with increasing carapace size (slope = 0.02, s.e. = 0.003).

Table 3. Tanner crab (*C. bairdi*) and snow crab (*C. opilio*) average RAMP-predicted mortality for combinations of footrope gear and shell condition.

	New shell	Old shell	Very old shell
Tanner crab			
Control	0.5% (199)	1% (481)	9% (43)
Alternate footrope	11% (258)	6% (1121)	14% (436)
Conventional footrope	12% (328)	11% (991)	33% (112)
Alternate sweep	0% (134)	2% (710)	6% (177)
Conventional sweep	4% (140)	7% (519)	6% (140)
Snow crab			
Control	7% (153)	3% (503)	8% (62)
Alternate footrope	21% (268)	7% (1067)	14% (325)
Conventional footrope	13% (307)	12% (928)	34% (107)
Alternate sweep	2% (128)	2% (780)	12% (125)
Conventional sweep	19% (85)	8% (459)	21% (82)

The number of crab at each combination is in parentheses.

All main effects were also statistically significant for snow crab encountering trawl sweeps ($p = 0.00$; gear: $\chi^2 = 43.56$, d.f. = 2; sex: $\chi^2 = 19.62$, d.f. = 1; shell condition: $\chi^2 = 45.87$, d.f. = 2; size: $\chi^2 = 16.06$, d.f. = 1), in addition to gear × shell interaction ($\chi^2 = 10.65$, d.f. = 4, $p = 0.03$). The conventional sweep yielded the highest mortalities regardless of shell condition. By investigating the mean RAMP-predicted mortality for combinations of gear and shell condition (Table 3), it is evident that the highest predicted RAMP mortality occurs with new and with very old shells. However, the relationship between control and alternate sweep varied according to shell condition (Table 3). Females showed statistically lower average mortality (3%; $n = 827$) than males (7%, $n = 1550$). Mortality generally increased with increasing carapace size (slope = 0.03, s.e. = 0.005).

Overall, Tanner crab females showed higher average mortality than males for both footrope and sweep. For snow crab, the opposite was true; males showed higher average mortality than females for both footrope and sweep.

Discussion

Tanner and snow crab are of great economic and ecological importance in the Bering Sea, and fishery managers and the fishing industry in Alaska have been concerned about the unobserved mortality of these crab due to bottom trawling. We augmented the RAMP relationship developed by Stoner *et al.* (2008) for efficiently estimating such mortality with substantially more observations and validated the resulting model, including examining the usefulness of alternative models and supplementary information. Then, we applied this relationship in an experiment demonstrating alternative gear configurations that reduced crab mortality.

Obtaining a representative estimate of mortality associated with capture and discard using traditional assessment methods is quite costly and, therefore, available only for a limited number of species and fisheries (e.g. Suuronen, 2005). Reflex impairment indices for fish in the context of fishing-related injury have proven to be useful tools in evaluating stress that can lead to delayed mortality (Davis and Ottmar, 2006; Davis, 2007, 2009). For crab, the RAMP's composite reflex impairment score provides a graduated predictor of mortality, independent of crab size, sex, shell condition, physical injury, and exposure conditions (Stoner *et al.*, 2008; Stoner, 2009). Using additional data from our 2008 study, we rigorously tested the RAMP model's predictive capability using logistic regression. Logistic regression showed that reflex impairment was closely correlated with mortality and that sex, size, shell condition, and injury did not explain enough additional variability to be included in the RAMP model. Thus, our findings concurred with Stoner *et al.* (2008). Further results appeared with detailed examination of the data. For example, reflex impairment, either as a categorical or a continuous variable, could be used to explain the relationship between reflex impairment and mortality for Tanner crab (*C. bairdi*). However, the model using reflex impairment as a categorical variable provided a better fit for snow crab (*C. opilio*), and ultimately, this study used reflex impairment as a categorical variable for the additional analyses involving gear types.

Certain models (5 and 7, Table 2) had the lowest AIC values because some of the predictor variables were run as categorical instead of continuous variables, therefore allowing for easier fit of any non-linear relationship. The major disadvantage of such an approach is that no functional relationship can be expressed. The per cent variability explained by reflex impairment alone (continuous predictor; model 1) was within 5% of the variability explained by models 5 and 7. Although model 5 (reflex and injury categories) and model 7 (full model) explain more of the variability and have lower AICs, from a field application perspective the question arises: is the difference in models enough to warrant the time spent to collect the additional data in a field setting? In the case of Tanner and snow crab, Stoner *et al.* (2008) and this study make a good case for testing reflex impairment alone to predict unobserved mortality. A major advantage to RAMP is the simplicity of just testing reflexes which can be done in hand, thereby removing the need to retain animals for prolonged periods or to run costly and time consuming physiological lab tests. In the case of *Chionoecetes* spp. interacting with the trawl gear, Stoner *et al.* (2008) and this study have shown the reflex impairment score to be a statistically robust predictor of delayed mortality. The effect of a single additional reflex impairment multiplies the odds of mortality ($p/(1-p)$) by the exponentiated slope from the logistic regression (Faraway, 2006). The multipliers for snow and Tanner crab were 3.0 and 2.9, respectively. Thus, the absence of an additional reflex would roughly triple a crab's odds of mortality.

Logistic regression analysis of reflexes to predict mortality (RAMP model) indicated that sex, shell condition, and size did not significantly affect the relationship between reflex impairment scores and mortality. When considering the effect of the gear type, logistic regression of the RAMP-predicted mortality found that gear type, sex, shell condition, size, and the gear × shell condition interaction were significant predictor variables for snow crab mortality. Tanner crab showed gear type, shell condition, and their interaction to be significant with the footrope effect. In addition, gear type, shell condition, their interaction, and size were significant with the effect of sweeps. Although shell condition was shown to be statistically significant, the overall mortality was lower with an alternative gear than with a conventional gear, strengthening the case that alternative sweeps and footropes could be used to help reduce unobserved mortality.

The improved RAMP curves for Tanner and snow crab were used to compare unobserved mortality in alternative and conventional bottom trawl gears (footrope and sweep). The alternative footrope (24″ disk footrope) reduced mortality by 36% for Tanner crab and 50% for snow crab; and the alternative sweep (off-bottom sweep) reduced mortality by 75 and 100% for Tanner and snow crab, respectively. On a global scale, the International Council on Exploration of the Sea (ICES, 2005) and a regional level (NPFMC, 1999, 2006; AMCC, 2004; NMFS, 2004; NPRB, 2007) have cited a need to quantify and reduce unobserved/unaccounted fishing mortality. This study was able to show that not only was the overall unobserved mortality low, but that using a modified fishing gear can reduce unobserved mortality. This reduction in mortality is significant enough to justify the use of modified sweeps for the bottom trawl fishery in Alaska. Although the alternative gear significantly reduces the unobserved mortality of Tanner and snow crab interacting with a trawl gear, it is not a complete solution, but it is another step forward in the effort to reduce bycatch, specifically unobserved mortality.

Demonstrating that the alternative gear can reduce unobserved crab mortality has had application to fisheries management in the North Pacific. Elevated sweeps were implemented as a gear regulation by the NPFMC in 2011 as an alternative to closing areas to fishing. Data from this project showing that elevated sweeps reduce the mortality of Tanner and snow crab along with data indicating a potential reduction in damage to benthic habitat (Rose *et al.*, 2010 and unpublished data), aided the Council in making the elevated sweep a gear regulation.

Previous studies have shown that reflex impairment is a sign of stress that can be correlated with mortality outcomes in fish and crab (Davis and Ottmar, 2006; Davis, 2007, 2009; Stoner *et al.*, 2008; Humborstad *et al.*, 2009; Stoner, 2009). One of the limitations of this approach is that we cannot account for the possible mortality that occurs as a result of predation on the crab or fish due to its potentially weakened state from its encounters with the gear. Thus, the RAMP model yields a good relative measure of mortality, if not an absolute measure of mortality. Our study took the RAMP model one step further and used it to assess whether alternative sweeps and footropes could reduce unobserved fishing mortality; the data showed this to be the case.

Our study developed and exploited several research innovations to estimate mortalities that occur in an environment relatively inaccessible to experimental manipulation, the seafloor, following the passage of a commercial trawl. The use of auxiliary nets to capture subjected crab necessitated the use of comparable control capture methods to assess the effects of that capture and subsequent handling. We were fortunate that these crab appeared robust to substantial changes in temperature between seafloor ($<2°C$) and holding tanks ($>9°C$). Had they shown strong sensitivity, as observed with some fish (Davis and Olla, 2006; Suuronen *et al.*, 2005), the high control variability would have greatly complicated the estimation of underlying gear-related mortalities. Use of the RAMP technique also provided sample sizes that greatly increased our ability to detect differences in mortality. Stoner *et al.* (2008) and this study were able to develop a rapid real-time field assessment of crab stress that predicted delayed mortality using a measure of reflex impairment. Stoner (2009) states that the greatest utility for the RAMP model approach will occur in experiments with fishing gear or handling methods aimed at reducing bycatch or discard mortality, which this study has shown. This study is one example of many possible practical applications of the RAMP model. In the context of bycatch reduction technology and modified fishing gear, the RAMP model could prove to be a very useful tool to determine if the alternative gear or modifications to the current fishing gear could reduce the many types of bycatch mortality.

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