NRC Research Press

ARTICLE

Utilizing reflex impairment to assess the role of discard mortality in "Size, Sex, and Season" management for Oregon Dungeness crab (*Cancer magister*) fisheries

Noëlle Yochum, Allan W. Stoner, David B. Sampson, Craig Rose, Alan Pazar, and Robert Eder

Abstract: We found that crab discarded from Oregon (USA) commercial and recreational fisheries for Dungeness crab (*Cancer magister*) have lower postrelease mortality than previously estimated. This aligns with the goals of the "3-S" management strategy currently employed for these fisheries, to protect discarded sublegal male (Size), female (Sex), and soft-shell (Season) crab. We found that for the commercial ocean Dungeness fishery, overall discard mortality rates (5 days after release) were 0.080 (95% confidence interval: 0.061–0.100) for females; 0.012 (95% confidence interval: 0.002–0.022) for hard-shell males; and 0.092 (95% confidence interval: 0.026–0.157) for soft-shell males. The overall discard mortality rate for the recreational bay fishery (from a boat) was estimated to be 0.009 (95% confidence interval: 0–0.018). A reflex action mortality predictor relationship, which relates reflex impairment to mortality probability, was created and utilized to estimate mortality rates. Our study highlights the importance of looking not only at discard and mortality rates to evaluate 3-S fishery management, but also the mortality- and bycatch-per-retained ratios and temporal trends relative to changes in effort, animal condition, and catch composition.

Résumé : Nous avons constaté que les crabes rejetés à l'eau dans les pêches commerciales et sportives au crabe dormeur (*Cancer magister*) de l'Oregon (États-Unis) présentent une mortalité après le rejet plus faible qu'estimée précédemment, ce qui cadre avec les objectifs de la stratégie de gestion axée sur les « 3-S » présentement employée pour ces pêches pour protéger les mâles de taille inférieure à la limite (« size »), les femelles (sexe) et les individus à carapace molle (saison) rejetés. Nous avons constaté que, pour la pêche océanique commerciale au crabe dormeur, les taux globaux de mortalité par rejet (cinq jours après le rejet) étaient de 0,080 (intervalle de confiance à 95 % : 0,061–0,100) pour les femelles, 0,012 (intervalle de confiance à 95 % : 0,002–0,022) pour les mâles à carapace dure et 0,092 (intervalle de confiance à 95 % : 0,026–0,157) pour les mâles à carapace molle. Le taux global de mortalité par rejet pour la pêche sportive dans les baies (à partir d'un bateau) est estimé à 0,009 (intervalle de confiance à 95 % : 0–0,018). Une relation de prévision de la mortalité associée à l'action des réflexes, qui relie la dégradation des réflexes à la probabilité de mortalité, a été créée et utilisée pour estimer les taux de mortalité. Notre étude fait ressortir l'importance de tenir compte non seulement des taux de rejet et de mortalité dans l'évaluation de la gestion des pêches axée sur les 3-S, mais également des rapports mortalité:individus retenus et prises accessoires:individus retenus, ainsi que des tendances dans le temps des variations de l'effort, de l'embonpoint des animaux et de la composition des prises. [Traduit par la Rédaction]

Introduction

Dungeness crab (*Cancer magister*) is currently the most valuable crab fishery in the United States, yielding nearly 25 000 metric tons and US$211 million in 2014 (National Marine Fisheries Service 2015), and has an over CAD$40 million (2008) ex-vessel value in Canada (Yonis 2010). In Oregon (USA), the ocean fishery for these crab is the most valuable single-species commercial fishery, with 300–350 vessels landing 5000–15 000 metric tons each season (Ainsworth et al. 2012), generating up to US$50.2 million (ex-vessel; ODFW 2015*a*). In addition to the commercial fishery, Dungeness also contribute to local economies as a draw for tourism and recreational fishing (Ainsworth et al. 2012). Despite the economic importance, in the United States there is neither a stock assessment nor a fishery management plan for the commercial or recreational Dungeness crab fisheries along the Pacific coast or in adjacent estuaries. Since 1947, Dungeness fisheries have been managed by state agencies (Demory 1985) that employ, along with effort controls and gear restrictions, a predominately "3-S" management strategy: Size, Sex, and Season.

The size and sex of harvestable crab are regulated within a specified season for commercial and recreational fishing in the ocean and adjacent bays. In Oregon, commercial and recreational harvest is currently restricted to males with a minimum carapace width of 6¼ inches (159 mm) and 5¾ inches (146 mm), respectively (ODFW 2015*b*). Because males are mature by 137 mm (MacKay 1942), these size restrictions ensure crab are able to reproduce for one or two seasons before recruiting into the fisheries (Rasmuson 2013). In addition, male-only harvest protects breeding females

Received 21 January 2016. Accepted 24 August 2016.

N. Yochum.* Oregon State University Department of Fisheries and Wildlife, 2030 SE Marine Science Drive, Newport, OR 97365, USA.
A.W. Stoner. NOAA Alaska Fisheries Science Center, 2030 SE Marine Science Drive, Newport, OR 97365, USA.
D.B. Sampson. Oregon State University Coastal Oregon Marine Experiment Station and Department of Fisheries and Wildlife, 2030 SE Marine Science Drive, Newport, OR 97365, USA.
C. Rose. FishNext Research, 4707 238th Place SW, Mountlake Terrace, WA 98043, USA.
A. Pazar. Commercial fisherman, F/V *Delma Ann*, Newport, OR 97365, USA.
R. Eder. Commercial fisherman, F/V *Timmy Boy*, P.O. Box 721 Newport, OR 97365, USA.
Corresponding author: Noëlle Yochum (email: noelle.yochum@noaa.gov).
*Present address: NOAA Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle, WA 98115, USA.

and increases meat yield (Northrup 1975) given that females produce 42% less meat than male crab (PSMFC 1978).

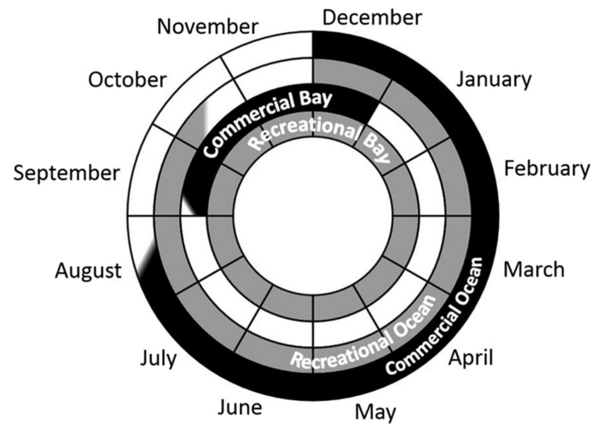
The Season component of the 3-S management regulates the timing of the fishery to avoid capture of recently moulted, soft-shell crab (PSMFC 1978). In Oregon, male crab typically moult from spring to fall (Demory 1985; Rasmuson 2013), with an increasing abundance of moulting crab from April to July, and a substantial number of soft-shell crab in October and November (Spears 1983). Timing of the moult, however, varies geographically, annually, and by sex (Robinson et al. 1977; Demory 1985). Unlike Washington, in both California and Oregon it is lawful to land soft-shell crab (PSMFC 1978), but they are seldom retained because of the poor meat quality and recovery rate (Stewart 1974). For the 2–3 months that it takes postmoult crab to harden and fill in muscle tissue (Dunham et al. 2011; Rasmuson 2013), the meat yield is approximately 13%–14% compared with 25%–30% for hard-shell crab (Robinson et al. 1977). Harder crab are preferable in meat quality and value for consumers and processors (Barry 1983; Demory 1985; Kruse et al. 1994) and so yield a higher price (Waldron 1958; PSMFC 1978). While fishermen have little incentive to harvest soft-shell crab, there is a period of time when hard- and soft-shell crab co-occur, resulting in incidental capture and discard of both sublegal and legal-size soft-shell crab.

Temporal restrictions on harvest were put in place during the approximate moulting period to mitigate handling mortality of soft-shell crab and, therefore, increase the abundance and quality of legal, hard-shell males in the subsequent season (Waldron 1958). The annual season opener for the Oregon commercial ocean crab fishery is 1 December, but is delayed if the crab do not meet the minimum meat mass recovery threshold of 25% (Fig. 1; Didier 2002; ODFW 2009). Beginning the second Monday in June, as soft-shell crab increase in abundance, fishermen are restricted to landing 1200 pounds (544 kg) of crab per week. This regulation remains in effect until the season closes on 15 August (ODFW 2009). Despite the regulated season, the majority of the effort and landings currently occur shortly after the season opens (Didier 2002) and during the first 2 months of the season. Postwinter, as catch rate decreases, fishermen often switch to alternative, concurrent fisheries (Youde and Wix 1967; PSMFC 1978; Oregon Sea Grant 2008).

Fishing seasons vary across the commercial and recreational fisheries in the ocean and bays (Fig. 1). The commercial bay fishery occurs from the Labor Day holiday (the first Monday in September) to 31 December, except on holidays and weekends (ODFW 2009). The recreational bay fishery is open year-round, both from a boat and shoreside. Recreational fishing in the ocean occurs from 1 December to 15 October (Ainsworth et al. 2012). Unlike the commercial ocean fishery, the majority of recreational fishing occurs in the summer and fall (June–October), with effort depending mostly on weather conditions (when fishing is safer and more enjoyable), catch rates, and timing of vacations. In addition, crabbing in the bay is influenced by rain and river runoff, which decreases water salinity and reduces catch (Ainsworth et al. 2012).

The objective of this study was to evaluate discard rates (i.e., proportion of the total catch that is discarded) and quantify discard mortality rates (i.e., proportion of the discarded animals that die as a result of the capture, handling, and release process) in the commercial ocean and recreational bay by boat Dungeness fisheries along Oregon's coast and in the Yaquina Bay. The 3-S management relies upon these rates being low given that this strategy is largely based on discarding females and sublegal and soft-shell males. To further assess 3-S management for Dungeness, we evaluated variation in the mortality- and bycatch-per-retained ratios (MPRR, BPRR, respectively) over the fishing season. In addition, we make recommendations toward the goal of reducing both bycatch and discard mortality rates.

Fig. 1. The fishing season for Oregon's recreational (grey) and commercial (black) fisheries for Dungeness crab (*Cancer magister*) in both the Pacific Ocean and adjacent bays.



The impetus for this project was from commercial Oregon Dungeness crab fishermen and their interest in knowing discard mortality rates for the fishery. This aligns with historic efforts by Dungeness crab fishermen to instigate changes in fishing regulations to protect the crab population (Waldron 1958; Wild and Tasto 1983). This research benefited from collaboration among industry, science, and management partners.

Materials and methods

Dungeness crab reflex action mortality predictor (RAMP)

To quantify discard mortality rates for the Dungeness crab fisheries, we utilized the RAMP approach. This methodology relates vitality to mortality probability attributed to a stressor(s) through quantifying reflex impairment (Davis and Ottmar 2006; Davis 2007). Ideally, observations on impaired reflexes (or lack of impairment) can be used to estimate the probability of delayed mortality. While this approach has not previously been utilized for Dungeness crab, it has effectively been used to determine bycatch mortality rates and to evaluate mortality attributed to individual fishing stressors (e.g., air exposure or injury from fishing gear) for several fish (Davis and Ottmar 2006; Raby et al. 2012; Barkley and Cadrin 2012; Nguyen et al. 2014) and crustacean species (Stoner et al. 2008; Stoner 2012*a*, 2012*b*; Rose et al. 2013; Urban 2015).

To apply the RAMP approach to discarded crab from theses fisheries, we first established a set of reflexes specific to Dungeness, then assessed reflex impairment in crab that endured the stressors specific to the fisheries, determined delayed mortality for crab with varying levels of reflex impairment through captive holding, and, finally, created a reflex action mortality predictor to model the relationship between reflex impairment and probability of delayed mortality.

Establishing a set of reflexes

To create a RAMP relationship for Dungeness crab, we first established a set of reflex actions ("reflexes"; e.g., eye retraction when an eye is tapped) that could reliably be used for evaluating vitality. To accomplish this, we captured male and female crab of varying sizes using recreational crab gear in the Yaquina Bay. After being captured, the test crab were placed in an ice chest with wet burlap sacks to reduce stress from air exposure and captivity (Simonson and Hochberg 1986) and were carried less than 1 km to the Alaska Fisheries Science Center laboratory in Newport, Oregon. After being "burped" to remove air that might be trapped under the carapace (Snow and Wagner 1965), the crab were placed in temperature-regulated (approximately 6 °C) flow-through seawater tanks (2 m diameter, filled to 1 m depth). In the field and

Table 1. The established reflexes used to assess Dungeness crab (*Cancer magister*) vitality to create a reflex action mortality predictor (RAMP), along with the method for assessment and metrics for determining whether a given reflex is "present" or "absent".

Reflex	Method	Present	Absent
1. Eye retraction	A probe is used to lightly tap the top of an eye	Crab retracts the eye downward	Crab does not react, leaving the eye in place
2. Mouth defense	A probe is used to attempt to pull forward the third maxillipeds	Crab defends its mouthparts with its chela, making it difficult to access the maxillipeds	Crab allows its maxillipeds to be manipulated
3. Chela closure	A probe is placed below the chela dactyl	Crab reacts by closing the chela tightly, then opening it again without manipulation	Crab does not open and close its chela without manipulation
4. Leg wrap	A probe is used to pull pereopods 2–4 to a 180 degree angle	Crab draws the pereopods back in (i.e., joints at less than a 180 degree angle)	Crab pereopods do not move without manipulation
5. Leg curl	Pereopod 5 is straightened and pulled downward	Crab pulls up and curls its pereopod in a controlled manner	Crab does not move the pereopod without manipulation
6. Abdomen response	A probe is used to attempt to pull the top of the abdominal flap away from the crab's body	Crab exhibits a strong, agitated reaction	Crab does not react

over several days in captivity, the crab were assessed several times to identify reflexes that responded consistently to a stimulus. We began by testing RAMP reflexes established for two *Chionoecetes* species (Stoner et al. 2008) and consulted with fishermen who often use vitality assessments to determine whether or not to retain or sell a crab. The crab were allowed to recover in the holding tanks for a week and were then reassessed. Subsequent assessments were completed after exposing the crab to air and mimicking handling stressors (e.g., dropping on the ground).

Through this process, we established a series of six reflexes to test Dungeness crab vitality, which gave consistent, involuntary responses to stimulation, and a protocol for assessment. The reflexes include the following: (1) eye retraction; (2) mouth defense; (3) chela closure; (4) leg wrap; (5) leg curl; and (6) abdomen response (in this order; Table 1). The reflexes are tested by holding the crab vertically (dorsal side facing away), with the left hand, and assessing the right side of the crab (assessment can be completed on either side; a video demonstrating the reflexes is available upon request). A reflex is considered absent only if there is no response to stimulation. Similar to Stoner et al. (2008), we found that it is too subjective to include additional impairment categories (e.g., strong, moderate, weak). An overall reflex impairment score (Score) is calculated by first assessing each reflex and assigning a "0" to present reflexes (including weak responses) and "1" to those absent, then summing over all reflexes. Davis and Ottmar (2006) calculated Score as a proportion (one minus the ratio of the total number of impaired reflexes to the total reflexes). This approach is advantageous if there are reflexes or individuals that cannot be tested due to missing or damaged body parts. This is seldom the case for these fisheries; therefore, Score was calculated as the sum of missing reflexes. In addition, reflex impairment is evaluated for live crab only. In some previous RAMP studies, immediate mortalities (i.e., crab that were dead in the fishing gear before assessment) were given a Score indicating maximum impairment (Hammond et al. 2013; Rose et al. 2013; Yochum et al. 2015). This is an advantageous approach if it is difficult to differentiate between dead and moribund individuals (Stevens 1990). This is not the case with Dungeness crab; therefore, the contributions to total bycatch mortality by both immediate and delayed mortality were evaluated separately.

Assessing crab

We focused on the commercial ocean and recreational bay by boat (hereinafter referred to as "commercial" and "recreational") fisheries because they account for the vast majority of landed Dungeness crab catch (94%–98% and 2%–6%, respectively; Ainsworth et al. 2012, data from 2007–2011). For the recreational fishery we focused on crab in the Yaquina Bay, as opposed to the ocean, because approximately 60% of annual recreational landings are from Oregon bays, and the Yaquina Bay is both a heavily fished site (Ainsworth et al. 2012) and is the nearest bay to the research facility. Moreover, we focused on fishing in the bay by boat instead of from shore because of the low catch-per-angler-day rates for the latter fishery. Regardless, some data were gathered to evaluate bycatch and discard mortality in these additional fisheries, which are described in the online Supplementary Data[1].

Given that a model for predicting mortality from an assessment of reflex actions can be specific to a set of stressors (Yochum et al. 2015), we were careful to both collect bycatch data that were representative of actual fishing practices and to describe the methods and likely stressors associated with crabbing (e.g., soak duration, the duration of time between when a pot was set and retrieved; Musyl et al. 2009). By doing this we endeavored to establish RAMP relationships that can be utilized in future research. To this end, commercial fishery data were collected during "ride-along" trips aboard fishing vessels, which also allowed us to gain feedback from fishermen on project methodology and insight into the fishery. We were unable, though, to dictate depth strata, location, and other sampling logistics. To evaluate differences among captains and crew members, we aimed to complete trips on multiple fishing vessels and out of several ports. Obtaining ride-along opportunities for recreational fishing was difficult due to small vessel size and research permit restrictions prohibiting crab retention. Therefore, approximately half of the recreational sampling was completed on a research vessel by scientists with recreational crab fishing experience. To incorporate intra-annual variability in stressors (e.g., air temperature), we aimed to conduct at least one sampling trip for each calendar month when the fisheries were open.

Commercial ocean

Between February 2012 and January 2014, we sampled all strings (a "continuous line of individual crab pots spaced a given distance apart from each other"; Hicks 1987) during ride-along trips. Within each string, the selection of the first crab pot to sample was randomized and, subsequently, every fifth pot was assessed. This systematic sampling protocol was put in place to maintain consistency of sampling between strings, while not slowing down

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfas-2016-0029.

or interfering with fishing operations, and minimizing handling and air exposure for the crab beyond typical fishing processes. Modifications to this protocol were allowed as necessitated by sampling logistics (e.g., poor weather), under the constraint that each sampled pot be selected before it landed on deck.

For each assessed pot, data were recorded on both the conditions under which the pot was fished and on the retained and discarded crab within. The following information was recorded per pot: (*i*) soak duration; (*ii*) sea state at the time the pot was brought onto the boat (Beaufort wind force scale); (*iii*) whether or not the crab were removed from the pot using a "slam bar" (a bar on which a pot is thrown to push crab towards the pot opening); (*iv*) how many crab were retained; (*v*) the location of the pot within the string; and (*vi*) the depth where the pot was fished. In addition, retained crab were counted. All crab intended for discard were measured (carapace width, to the nearest millimetre), and sex and shell condition were noted. "Soft" crab were described as those with little or no hardening (the crab recently moulted) to moderate hardening postmoult (carapace and legs flexible and soft). Crab designated as "hard" were those with carapace and legs nearly fully hard to near moulting (i.e., the shell condition that would be acceptable to most fishermen for retention). Crab intended for discard were also evaluated for the presence of any new injuries, including the following: broken, injured, or missing legs or chela, spines, dactyli, maxillipeds, or abdominal flap; autotomized legs or chela; smashed carapace (ventral and dorsal); holes or cracks in carapace; and damage to an eye. Warrenchuck and Shirley (2002) found that old injuries did not affect mortality in snow crab (*Chionoecetes opilio*); thus, only new injuries were recorded. After 1 or 2 days postinjury, a "sheath" or scab is visible at the site of injury (Durkin et al. 1984). We therefore considered "new injuries" those without scabbing. For each crab, we noted total air exposure duration and tested each of the established RAMP reflexes to generate a reflex impairment score. Assessments took approximately 30 s per crab.

Recreational bay by boat

During sampling trips completed between April 2012 and April 2014, all pots and rings were assessed. Recorded information was similar to the commercial fishing trips; however, there were no slam bars, soak duration was measured in minutes compared with days, and legal crab were 5¾ inches (146 mm) or larger. All legal-sized males were marked as "retained" if they were considered hard-shell by the definition of this study. Also the trips were executed, when possible, according to advice for maximizing catch from the Oregon Department of Fish and Wildlife (ODFW; ODFW 2015*c*).

Measuring mortality

To relate reflex impairment to delayed mortality probabilities for the commercial and recreational fisheries, a total of 655 and 321 crab (respectively) were held in laboratory tanks (described previously) to determine survival. In selecting crab, we aimed to hold as many crab as possible that had impaired reflexes and to fill the remaining tank space with unimpaired crab. Regardless, given the catch composition, the majority of held crab for the commercial and recreational fisheries (77% and 88%, respectively) were Score-zero (no impaired reflexes; Table S3[1]). We also attempted to hold crab of varying combinations of sex, size, injury, and shell condition over the temporal extent of the fisheries to look at the potential influence on mortality of and interactions among various biological and environmental variables. For the commercial fishery, 54% of held crab were hard-shell females, and 67% were hard-shell males for the recreational fishery. These percentages similarly reflect catch composition.

For identification purposes, all held crab were tagged with a double "t-bar" anchor tag (TBA-LEVO, Hallprint Fish Tags). This tag type was selected because it has successfully been used and has been proven to last through ecdysis for Dungeness crab (Smith and Jamieson 1989; Swiney et al. 2003; Barber and Cobb 2007) and because it can be used for a large range of sizes and cannot be lost during leg autotomization. Necropsies were performed on over 90% of crab that died in holding, which verified that mortality was likely not tag-induced.

While crab were held in the laboratory for up to 1 month, cumulative mortality was evaluated to determine if holding conditions or tagging were influencing survival over time. To this end, at the beginning of the study we held minimally stressed crab for a month to monitor survival. For these crab and those held for this study, we observed that cumulative mortality stabilized by the second day of holding, but began increasing again after day five, even for Score-zero (unimpaired) crab. Therefore, crab were only considered discard mortalities if they died within the first 5 days of holding to avoid confounding discard mortality with a captivity effect. This threshold holding duration was also based on findings by Yochum et al. (2015) that 5 days was an optimal holding duration for Tanner crab (*Chionoecetes bairdi*) when determining mortality. In previous studies estimating Dungeness crab discard mortality, crab were held for 4 (Tegelberg 1972) and 5 (Barry 1984) days. Tegelberg and Magoon (1970) found that a captivity effect for Dungeness was evident after 4 days of holding. While survival of Dungeness in the laboratory can be improved with cold water temperatures, a pattern of increased mortality over time remains (Kondzela and Shirley 1993). For discarded Dungeness crab, there may be more long-term mortality, but it cannot be accurately determined in a laboratory given the unnatural setting and potential for a captivity effect to confound results.

Given our finding of a captivity effect and evidence from other studies that Dungeness crab can be difficult to keep alive in captivity (Barnett et al. 1973), we determined ways to reduce stress and injury attributed to captivity and transport. We found that the captivity effect was ameliorated by holding crab in individual containers. Similar to Jacoby (1983), we found agonistic behaviour primarily between females. Therefore, the majority of crab were held in individual compartments. We also cleaned the holding tanks weekly, maintained cold water temperatures to reduce stress (approximately 6 °C; Burton 2001; Bellchambers et al. 2005), and periodically checked the oxygen and ammonia levels (Barrento et al. 2008). We also fed the crab weekly and performed daily checks to monitor for (and remove) dead crab. To reduce impact from at-sea holding and during transfer, crab from commercial fishing trips were placed, after assessment, into an insulated fishing tote (interior dimensions: 91 cm × 53 cm × 53 cm) equipped with flow-through seawater during fishing operations (Basti et al. 2010). They were transported in ice chests with wet burlap sacks approximately 3.5 km to the holding facility. Crab from recreational trips, following assessment, were placed directly into ice chests with wet burlap sacks that were periodically resoaked with seawater before taking the crab to the same holding facility (<1 km away).

Predicting mortality from impaired reflexes

Binary logistic regression was used to determine if there was a relationship between the number of impaired reflexes (Score) and mortality, measured as the proportion of the 655 crab that died in holding for the commercial ocean fishery and 321 for the recreational fishery. Model coefficients were estimated using maximum likelihood (Ramsey and Schafer 2002) based on the fate (mortality or survival) of individual crab that were held, as shown in Table S3[1]. Score was treated as a continuous and categorical variable (in separate analyses) and with individual reflexes as predictors. We also included fishing, environmental, and biological explanatory variables in the model to determine their role in predicting mortality.

$$(1) \qquad \log_e\left(\frac{p}{1-p}\right) = \alpha + \beta_o \text{Score} + \beta_i x_i$$

where p = probability that a crab died during the holding period, α = intercept, β_o = model coefficient for reflex impairment score (Score), and β_i = model coefficients for the explanatory variables (x_i) tested in the model.

To determine the most parsimonious logistic model for the data, we performed forward stepwise model selection in R (R Development Core Team 2011) using a function (addterm) that allowed us to determine significance of individual predictors based on Akaike's information criteria and through drop-in-deviance tests. Model selection drew from a rich model that included a large number of possible explanatory variables: (*i*) reflex impairment score; (*ii*) sex; (*iii*) shell condition; (*iv*) carapace width (continuous); (*v*) fishery type; (*vi*) month; (*vii*) air exposure duration; (*viii*) number of crab retained; (*ix*) presence of new injuries; and interactions among these variables. Model selection was completed with several categories of injury, as well as the presence (nonspecific) or absence of injuries. When analyzing the fisheries separately, (*i*) use of the slam bar (*ii*) soak duration (days), (*iii*) depth (fathoms; 1 fathom = 1.828 m), and (*iv*) Beaufort wind force scale were included for the commercial analysis; and (*i*) soak duration (min), (*ii*) depth (m), and (*iii*) gear type (ring or pot) were used for the recreational analysis.

Quantifying discard mortality rates

While only held crab were utilized to create the logistic model for predicting the probability of mortality, to quantify the overall fishery discard mortality rates we utilized data on all assessed crab from the sampling trips in the following equation:

$$(3) \qquad P(m) = \sum_{k=0}^{6} P(m|s=k) \times P(s=k)$$

We summed over all Scores (s), k = 0–6, the product of the probability of mortality, given Score, $P(m \mid s=k)$, by the probability of catching a crab with that Score (from ride-along data; Table S2[1]) using the following:

$$(4) \qquad P(s=k) = \frac{n_k}{n_{\text{total}}}$$

$P(m \mid s=k)$ was predicted by the regression model, and its prediction variance was estimated using the predict() function in R. For each Score k, we calculated the prediction variance of the product $P(m \mid s=k) \times P(s=k)$ using the delta method (Rice 1988). The prediction variance of $P(m)$ was then estimated as the sum of variances of these products across all Scores, assuming independence among Scores. Finally, the 95% confidence interval for $P(m)$ was estimated as $P(m) \pm 1.96\sqrt{[\text{variance of } P(m)]}$.

Bycatch mortality rates (i.e., proportion of bycaught animals — nontarget crab and immediate mortalities — that die) were calculated similarly, but included crab that died prior to assessment (immediate mortality). Estimates of MPRR and BPRR were calculated by dividing the number of mortalities (both immediate and predicted delayed) and bycaught crab (discarded alive or dead) by the number of crab retained.

Results

Dungeness crab RAMP

Establishing a set of reflexes

We looked for patterns in reflex impairment to determine if fewer reflexes could be used for assessment (i.e., whether some reflexes were seldom lost or linked or others were primarily lost). We found that for the majority of assessed males, if only one reflex was lost (Score-one) it was Chela Closure (64%), followed by Leg Wrap (26%). Similarly, for females, Chela Closure was most frequently the first reflex to be lost (49%); however, this was followed by Abdomen Response (20%) then Leg Wrap (18%). Of all lost reflexes, for males, 56% were Chela Closure, followed by Leg Wrap (28%), and Mouth Defense (10%). For females, Chela Closure (39%) was followed by Abdomen Response (23%), Leg Wrap (18%), and Mouth Defense (14%). For both sexes, the Leg Curl and Eye Retraction reflexes were seldom lost. Despite patterns in reflex loss, we could not determine reflexes that could be linked or eliminated given the low numbers of impaired crab (only 242 assessed live crab, both fisheries combined, had more than one impaired reflex).

Assessing crab

We completed 26 sampling trips for the recreational and 22 for the commercial Dungeness crab fisheries, assessing 7685 total crab. More information on sampling trips, catch composition, and size distributions can be found in the Supplementary Data[1] (Tables S1 and S2; Fig. S1). Catch size and composition of the commercial and recreational fisheries varied by time from fishery opening and trip, respectively (Figs. 2 and 3). Over all sampling trips (not factoring in sampling frequency by month), 57% of discarded crab from the commercial fishery were hard-shell females and 28% were hard-shell males. Conversely, for the recreational trips, 53% were sublegal, hard-shell males and 26% were hard-shell females. During trips for either the commercial or recreational fisheries, few soft-shell females (1% and 8%, respectively) and soft-shell males (11% and 12%, respectively) were caught.

Commercial ocean

Two ride-along trips were completed for each calendar month of the fishing season except for December (one trip) and August (no trips). Sampling was completed aboard four different vessels from two fishing ports (Newport and Florence, Oregon). One trip was completed on the opening day of the fishing season, and in another season ride-along trips began on the second day of the season. Soak duration ranged from 1.5 to 30 days (6 days on average), and sea state (Beaufort wind force scale) ranged from 1 to 6 (3 on average). Pots were fished in depths ranging from 5.5 to 150 m. Of all assessed crab, 83% were Score-zero, 10% were Score-one, 3% had Scores greater than one, and 3% were immediate mortalities (Table S2[1]).

The data revealed temporal trends in catch composition. This included the trend that the number of immediate mortalities and soft-shell males per pot increased towards the end of the fishing season (Fig. 2). While few soft-shell females were caught throughout the season, the percentage of legal-size males (both discarded and retained) that were considered soft-shell ranged from 0%–2% for the majority of the season, then increased in June to 23% and up to 87% in July. Similarly, 0%–10% of caught sublegal males were soft until July, when the percentage increased to 50%. In addition, females were uncommon during the trip taken on opening day and were approximately a quarter or less of the discarded catch during the first week of the season and in July. For trips completed during the middle of the fishing season, however, females comprised the majority of discards. Moreover, the portion of the catch retained decreased over the fishing season. When sampling was completed on the first trip of the season, 92% of the catch was retained (25 retained per pot), 74% retained 2 days after the opening in the previous season (nine retained per pot), 55% retained 2 weeks after the opening (five retained per pot), then from 4 to 28 weeks after the season opened, the range of retention was between 11% and 76% (one to five retained per pot). In July, 29 weeks after fishing began, only 6%–7% of the catch was retained (one to two per pot). Additionally, 32% of discarded hard-shell males were legal size in July, indicating high-grading for crab with

Fig. 2. Catch composition for each commercial ocean sampling trip (*n* = 22), including the number of sublegal (<159 mm) and legal male (hard- and soft-shell), female (all sizes and shell conditions combined), and dead ("immediate mortalities", including all sex and shell condition categories) crab intended for discard per pot, and number of retained crab per pot. Males without a specified shell condition were not included (*n* = 15). Trips are listed by number of weeks past the opening of the fishing season (*: the first two trips are listed by days from the fishery opening). Calendar months that the trips took place and the sampling year are indicated: first (2011–2012), second (2012–2013), and third (2013–2014) sampled fishing seasons correspond to number of bars. For trips in June and July, the numbers above the bars indicate the percentage of legal-size male crab (those retained and discarded) that were soft. For the remaining trips, the percentage ranged from 0 to 2 by trip.

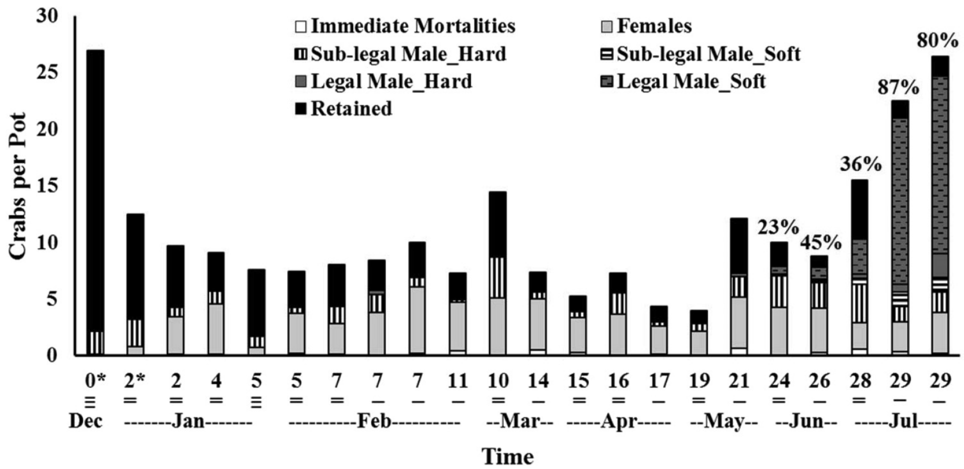
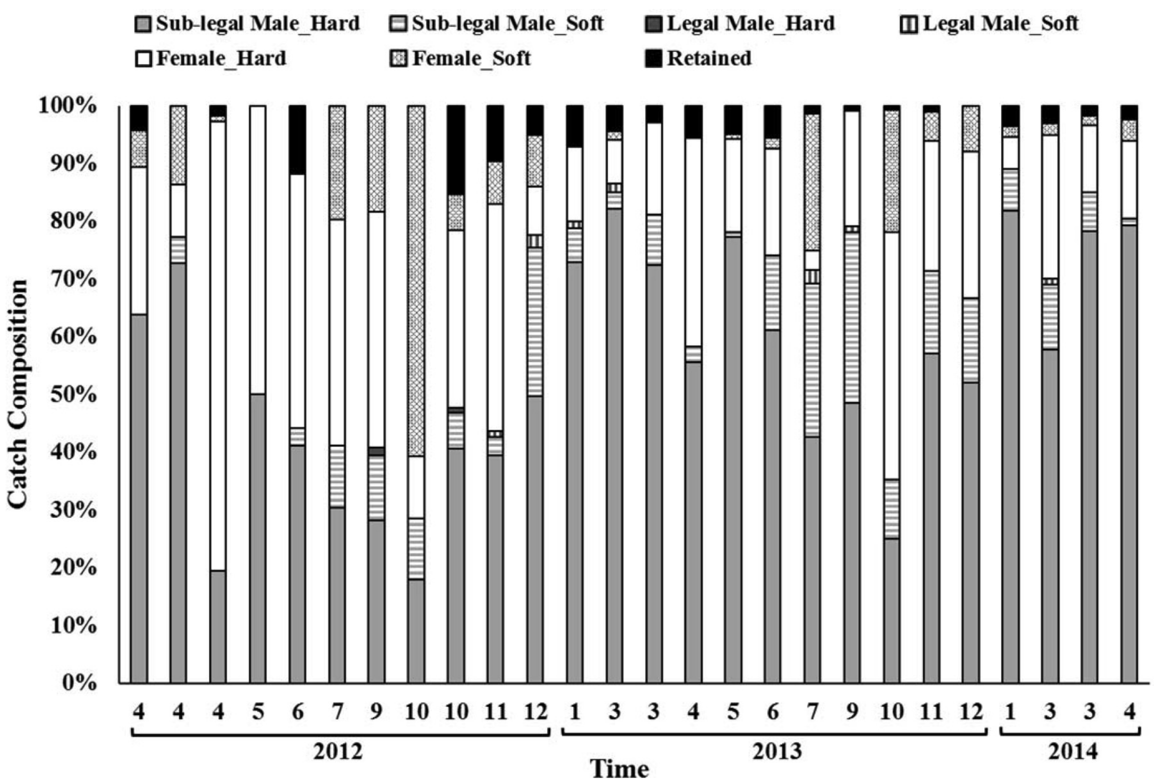


Fig. 3. Catch composition for each recreational bay by boat sampling trip (*n* = 26), shown by the numeric calendar month and year that sampling took place, of crab intended for discard (hard- and soft-shell sublegal (<146 mm) and legal male and female crab) and those retained.

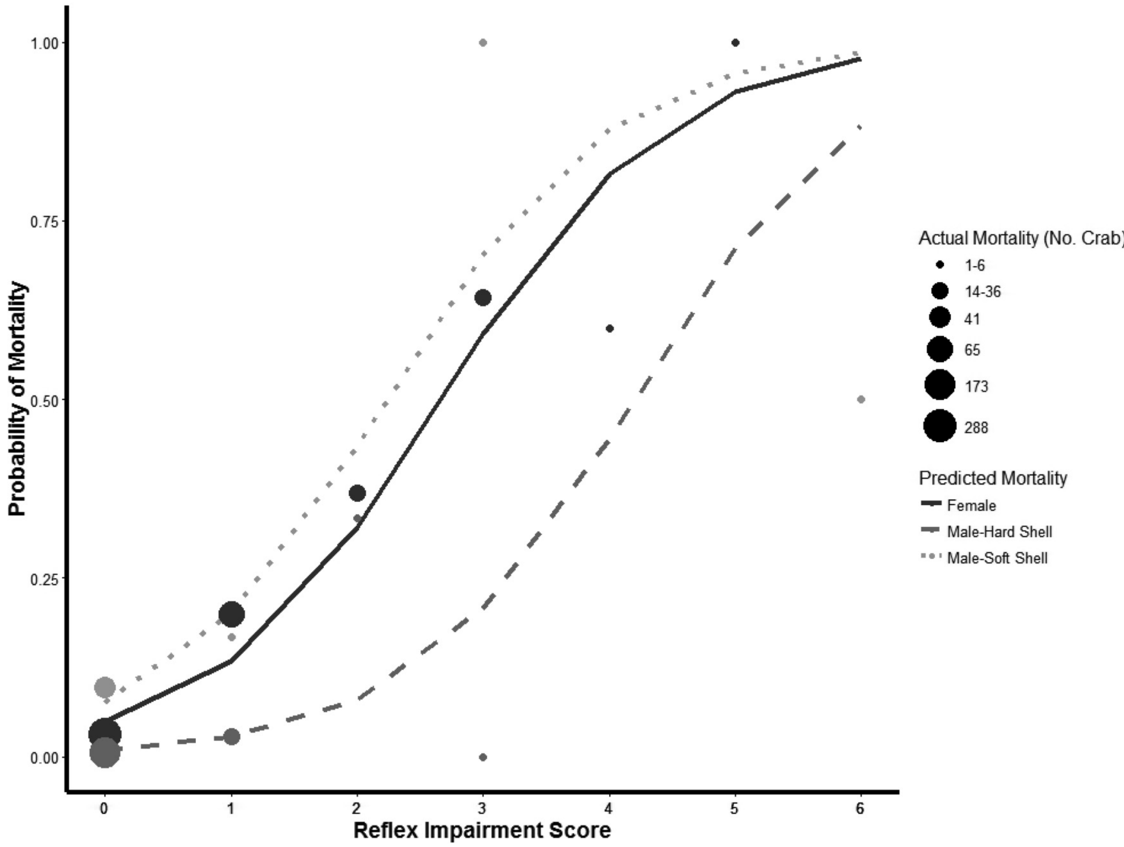


minimal superficial damage and both chela was potentially occurring coincident with when the pound limit was in effect.

Recreational bay by boat

Two recreational trips were completed during each calendar month with the exception of April (five trips), August (no trips), and October (three trips). During these trips, on average, there were 14.8 pot or ring pulls per trip (range: 8–33). Of assessed crab, on average by trip, there were 6.0 Score-zero (range 0.1–17.2) and 0.5 (range: 0–1.8) crab with Scores greater than zero per pot or ring. There were, on average by trip, 0.2 (range: 0–1.1) crab retained and 5.9 (range: 0.3–15.9) crab discarded per pot or ring. Of all assessed crab, 92% were Score-zero, 6% were Score-one, 2% were Score-two, 5% had new injuries, and there were no immediate mortalities. There were no clear patterns in the number of crab retained or discarded over time; variation was greater among trips (Fig. 3). There were, however, slightly more crab discarded per gear for rings than for pots (6.61 and 5.25, respectively) and

Fig. 4. Logistic model predictions of the probability of mortality by reflex impairment score (Score) for Dungeness crab discarded from the commercial ocean crab fishery by sex–shell condition (predicted mortality) and the actual proportions of the 392 female (Scores 0–5), 213 hard-shell male (Scores 0–3), and 50 soft-shell male (Scores 0, 1, 3, and 6) crab that died during laboratory holding (5 days of observation; actual mortality), with dot size reflecting the number of crab held by sex–shell condition and Score.



slightly more crab retained per gear for rings than for pots (1.98 and 1.56, respectively) when all data were combined.

Predicting mortality from impaired reflexes

Preliminary model selection on all data combined indicated a significant difference (significance in this paper tested at an alpha value of 0.05) between fishery types, namely that recreational had lower mortality probability than commercial. We therefore analyzed the data discretely by fishery type (Table S4[1]) to allow for fishery-specific variables in the analysis (e.g., use of the slam bar).

For the commercial crabbing data, preliminary analyses indicated that Score, sex, and shell hardness were variables that influenced mortality. The data indicated that there were differences between females and males and, within males, between soft- and hard- shell crab. We therefore grouped the data using a sex–shell condition variable: female, hard-shell male, and soft-shell male. Model selection using Akaike's information criteria and drop-in deviance tests indicated that the most parsimonious model included only the sex–shell condition variable in addition to Score (Fig. 4). Overall, hard-shell males had the lowest mortality probability for a given Score, and those with soft shells had the highest. Alternative models including (*i*) interactions and (*ii*) the presence of new injuries did not significantly improve model fit (p values 0.08 and 0.20, respectively; Table S4[1]). Moreover, Score best predicted mortality probability when it represented the summation of all six reflexes as a continuous variable rather than as a categorical Score (p value 0.05) or modeling the reflexes discretely (p value 0.24). Model selection for the recreational fishery indicated that the most parsimonious model included only one variable: whether or not the crab was Score-zero (Table S4[1]). While the presence of new injuries appeared to increase the probability of mortality, it did not significantly improve model fit (p value 0.12). Resultant mortality probabilities, from the data and model, were 0.3% for Score-zero crab and 7.7% for those with higher Scores.

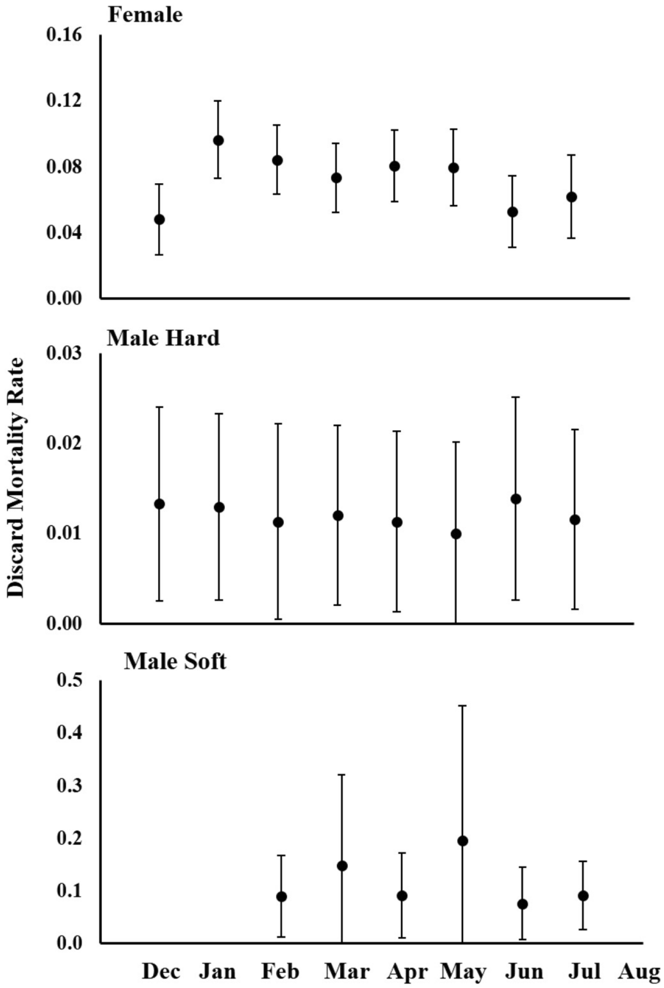
Quantifying discard mortality in the fisheries

Commercial ocean

Delayed discard mortality rates were calculated grouping the data by string, trip, and month and also combining all data. Differences were observed in these estimated rates for soft-shell males. This was attributed to uneven sample sizes in the different data groupings. We therefore constructed 95% confidence intervals for estimates by string, trip, and month to see if there were trends in mortality rates that were overlooked in the logistic regression analysis. This analysis indicated that there were no significant differences by these data groupings, with the exception of grouping female data by month (Fig. 5). During one trip in December, only four female crab were caught, which heavily influenced mortality rates. No other significant patterns were determined; therefore, we calculated final rates with all data combined.

Predicted discard mortality rates (5 days after release, integrated over Scores) were 0.080 (95% confidence interval: 0.061–0.100) for females; 0.012 (95% confidence interval: 0.002–0.022) for hard-shell males; and 0.092 (95% confidence interval: 0.026–0.157) for soft-shell males. While we did not detect significant monthly variations in discard mortality rates, MPRR and BPRR increased over the fishing season (Fig. 6). During a ride-along trip on opening day of the 2013–2014 season, MPRR was 0.001 (688 crab were retained per mortality) given high catch of legal crab and low discard rates.

Fig. 5. Estimated delayed discard mortality rates for Dungeness crab with 95% confidence intervals for the commercial ocean fishery evaluated by month of sampling and sex–shell condition.



On the second day (in the previous season), MPRR was 0.014 (73 crab retained per mortality). MPRR increased through the season until July when the value, at its highest, was 1.46 (range 0.23–1.46). Likewise, the BPRR was 0.092 and 0.35 for trips conducted on the opening day and 2 days following the opener of the fishing season and increased through the fishing season until July when 14.4 crab were bycaught (range 2.016–14.4) for each retained crab.

Recreational bay by boat

Delayed discard mortality rates were similarly evaluated with 95% confidence intervals when analyzing the data by trips and months. Because there were no significant differences detected, we combined data over all trips. The discard mortality rate was estimated to be 0.009 (95% confidence interval: 0–0.018). There were no clear spatial or temporal trends in mortalities. With respect to MPRR and BPRR, not including trips when no crab were retained (n = 6), there were 39.93 crab, on average, bycaught per retained crab (range 5.53–127.0). This means that, on average, only 4% of the catch (by number) was retained (range 0%–15%). Moreover, there were, on average, 0.26 predicted mortalities per retained crab (range 0.00–1.60; i.e., for every 3.8 crab that were retained, a discarded crab was predicted to die).

Discussion

Dungeness crab RAMP

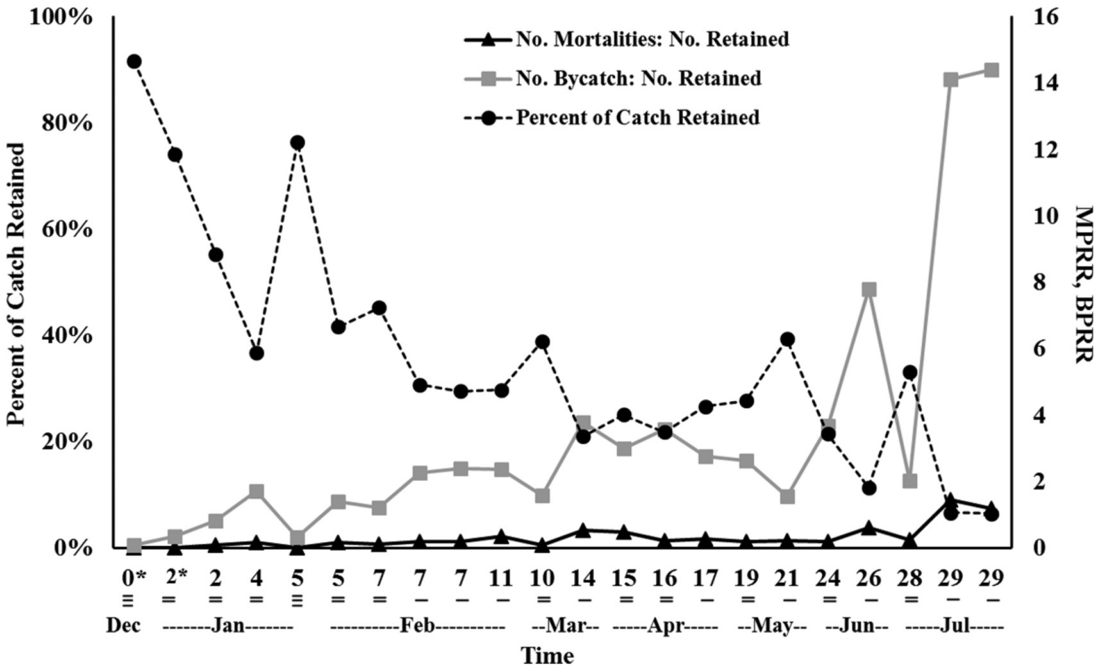
The RAMP approach was effective in determining the primary influences on short-term (5-day) delayed discard mortality and quantifying discard mortality rates for Dungeness crab. An advantage of RAMP is that it eliminated possible bias linked with selecting animals for captive observation. If bycaught crab are held in captivity to determine discard mortality without using RAMP, and only the healthiest or most impaired animals are unknowingly selected for evaluation, estimates will not be accurate (Musyl et al. 2009). In addition, by applying the regression models relating mortality with Score to ride-along data for the frequency of the different Scores collected over the extent of the fishing season, and on a number of trips and a variety of vessels, our mortality rates were estimated over a broad sample of crab. This allowed for estimated rates that are more representative of the fishery than if a non-RAMP approach was applied, given limitations in the number of crab that can be logistically held in captivity. Moreover, the reflex impairment score incorporated the effects of injury. This was similar to findings by Stevens (1990) that vitality scoring is a better predictor of survival than presence of injuries. Without needing to score for injury, there is a reduction in subjectivity bias in assessment given that it is easy to overlook an injury. Also, it is time-consuming to do a thorough assessment of injuries for each individual crab and all injuries are not necessarily external.

While we felt the RAMP approach was effective, we acknowledge that there were limitations in data analysis and collection. When mortality is determined by holding animals in captivity, long-term survival and mortality attributed to increased susceptibility to predation or inability to eat cannot be assessed. Therefore, the discard mortality rates from this study should be viewed as minimum values that do not include possible long-term mortality resulting from capture and discard. With respect to limitations in analysis, low numbers of impaired crab (i.e., crab with Scores greater than zero) prevented a thorough assessment of some of the potential explanatory variables and interactions among them (e.g., mortality rates for soft- versus hard-shell females). The infrequency of impaired crab also required us to extrapolate and interpolate mortality rates for Scores with limited to no data using the logistic curve. In addition, consistent with findings by Yochum et al. (2015) that a RAMP relationship can be specific to a set of stressors, we determined that separate RAMP relationships are required for the commercial and recreational fisheries. This result could have been influenced, however, by the fact that 67% of crab held for the recreational fishery were hard-shell males, and only 19% had soft shells. Given that hard-shell males have the highest survival rate, this could have affected our ability to differentiate mortality probabilities between the fisheries, making the recreational mortality rate sensitive to the composition of held animals. For RAMP information related to recreational shoreside and ocean fishing, see the Supplementary Data[1].

Quantifying discard mortality rates

Delayed discard mortality rates of sublegal, soft-shell male, and female Dungeness crab from this study are similar to, yet lower than, previous estimates for the commercial fishery. Barry (1984) found that the discard mortality rate for soft-shell Dungeness was 12.9% (and as low as 11.3%) and 0% for hard-shell crab after 3 days of holding. Tagging studies by Cleaver (1949), Waldron (1958), and Kruse et al. (1994) similarly indicated increased discard mortality for soft-shell compared with hard-shell crab. Likewise, a study by Tegelberg and Magoon (1970) found that hard-shell crab had a handling mortality rate of 4% and 16% for soft-shell crab. Tegelberg (1972) also found that when tagged with Peterson disc tags (but not with epimeral suture line dart tags that were more similar to those used in our study), these rates increased (23%–41%, the latter with increased holding and handling) and that mortality increased to 57% when soft-shell crab were dropped. Alverson et al. (1994) reported that mortality estimates for the coast-wide pot fishery ranged from 22% to 25% for soft-shell crab and from 2% to 4% for hard-shell sublegal crab.

Fig. 6. By commercial ocean sampling trip (*n* = 22), the number of mortalities (discard mortality and immediate mortality, those dead in the pot) and the number of bycaught crab (discard and immediate mortality) per retained Dungeness crab (MPRR and BPRR), and the percentage of the total catch retained listed by number of weeks past the opening of the fishing season (*: the first two trips are listed by days from the fishery opening). The numeric months that the trips took place and the sampling year are indicated: first (2011–2012), second (2012–2013), and third (2013–2014) sampled fishing seasons correspond to number of bars.



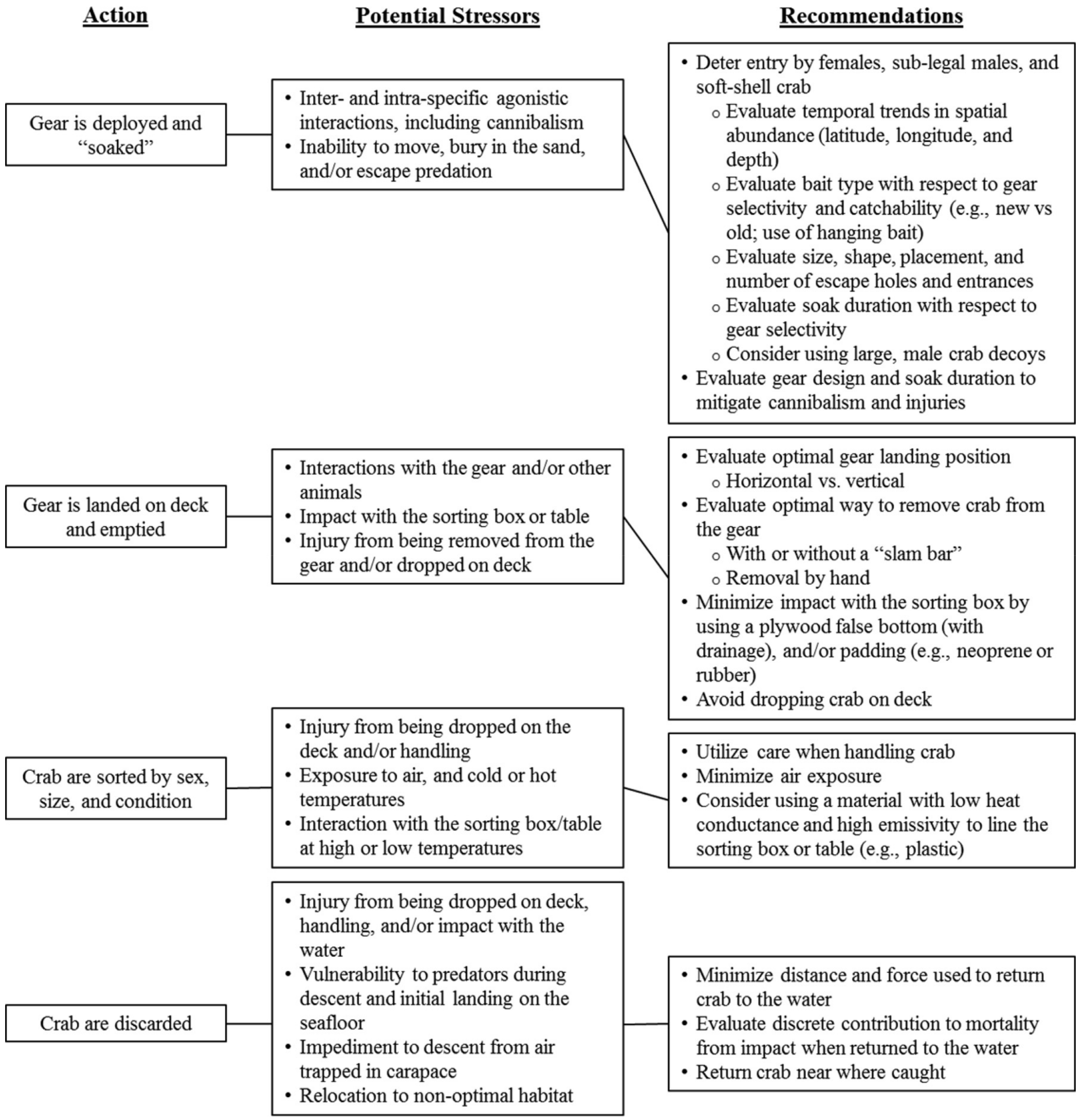
Previously estimated mortality rates are higher than those estimated from this study, likely due to differences in study methodology. For example, Tegelberg (1972) held crab together in groups of 25. Given that he estimated cannibalism rates to be 6.8% on soft-shell crab, depredation could have contributed to relatively high mortality rates from that study compared with ours, in which crab were held captive individually. Mortality attributed to tagging could have also influenced estimated rates from previous studies. We were able to improve upon prior methodologies and to generate discard mortality rates that are more representative of Oregon fisheries. We incorporated representative composition of the levels of reflex impairment that result from the fishing process and detected differences in mortality rates not only by shell condition but by sex and fishery. We acknowledge, however, that our estimates and confidence limits may not be representative of fishermen that are less careful with handling than those with whom we sampled crab.

We note that in comparing soft-shell mortality rates among studies there may be problems due to inconsistent definitions of "soft". For Dungeness, soft-shell crab have been defined as such based on meat mass recovery rates (Robinson et al. 1977; ODFW 2009); physical appearance (encrustation, color, etc.), and flexibility of carapace and legs (Waldron 1958; Tegelberg 1972; Barry 1983; Hicks 1987; Fisheries and Oceans Canada 2014); and time relative to moulting (Reilly 1983; Dunham et al. 2011). Other studies have utilized a combination of these descriptors to define shell condition (Spears 1983; Penson and Tetty 1988 from Somerton and Macintosh 1983; Hicks and Johnson 1999; Lippert et al. 2002), and others used durometer measurement (Hicks and Johnson 1999; Fisheries and Oceans Canada 2014). The durometer is a spring driven device that measures, in durometer units 0–100, the pressure required to indent the exoskeleton (Hicks and Johnson 1999). While the durometer has the advantage of generating an objective, measured value for shell hardness, there are limitations to this method. These include that the measurement (*i*) is subjective to the body part measured, as there is variation in how quickly different parts of the crab harden; (*ii*) cannot be repeated because the device softens and cracks the shell; (*iii*) varies with how quickly the operation is completed; and (*iv*) does not factor in decreases in shell hardness with old age (Foyle et al. 1989). In addition to the concern of accurate readings, the terms "hard", "intermediate", and "soft" for some studies were largely undefined (e.g., Northrup 1975) and vary in practice. During our ride-along trips we noted that what was considered "too soft" for retention varied by fisherman, typically by the amount of experience handling crab and the target market for the product, and was influenced by whether or not the crab was caught when the pound limit was in effect (starting the second Monday in June). We therefore highlight the importance of clarifying what is meant by "soft" and the importance for consistency in designation of shell condition, including how "soft" is defined, what part of the crab is assessed, and how much pressure is exerted when testing. Also, dividing "soft" into two categories (very recent moult or "jelly crab", and soft with some hardening) might provide more information on discard mortality. Moreover, we recommend measuring an area of the crab that hardens last, namely the ventral surface of the carapace, halfway between the 10th anterolateral spine and the coxa of the second walking leg (Hicks and Johnson 1999).

3-S management

Previous research has deemed the current management practices for the Oregon Dungeness crab fishery to be conservative "relative to what the population can sustain" (Heppell 2011). Moreover, the commercial fishery was awarded a certification for sustainability by the Marine Stewardship Council (Daume and DeAlteris 2014). In accordance with these findings, we determined that discard mortality rates are relatively low for the commercial and recreational Dungeness crab fisheries. This finding supports the goals of the 3-S management strategy to protect sublegal, female, and soft-shell crab. However, it is important to consider MPRR and

Fig. 7. The potential stressors experienced by Dungeness crab in directed recreational and commercial crab fisheries and recommendations for future research and ways to reduce these stressors.



BPRR and occurrence of soft-shell crab when evaluating management for this fishery, especially with respect to temporal trends.

In addition, while Dungeness discard mortality rates are relatively low, the potential suite of stressors experienced by discarded crab could be reduced, and future research to determine optimal fishing locations and ways to conduct fishing operations would benefit bycatch and discard mortality mitigation (Fig. 7). To determine best practices for reducing discard mortality rates, we recommend utilizing the RAMP approach and, where applicable, the RAMP relationships created from this study.

Size

Given the low discard- and immediate-mortality rates for sublegal males, the "size" component of the 3-S benefits the population and fishery by allowing male crab to reproduce for one or more additional reproductive cycles and to grow, yielding more meat mass per individual in future seasons. This study, however, did not evaluate the minimum size or the potential benefits of adjusting this regulation.

Sex

While females were the majority of discard and discard mortality for the commercial fishery, and discard- and immediate-mortality rates were higher than that for hard-shell males, the relatively low discard mortality rates indicate that it is advantageous to release females. This allows for protection of reproductive females and avoidance of harvesting crab with inferior meat yield. Moreover, current management regulations with the estimated discard mortality rates allow the population to maintain high levels of eggs-per-recruit (Heppell 2011).

Season

The most evident pattern in discard and discard mortality was in the temporal variation for the commercial fishery. The percentage of captured legal-size males that were soft increased from 0%–2% from December to May to 23%–87% in June and July (Fig. 2). These latter values exceed the 10% threshold used by the Fish Commission of Oregon in 1948 to determine when to close the fishery (Waldron 1958). We note, however, that the percentages from our study were calculated from a limited number of sampling trips that were not stratified by depth or location.

In addition, MPRR and BPRR increased as the season progressed. As available legal-size crab abundance decreased, each retained crab came at an increasing cost in terms of discards and discard mortality. Zhang et al. (2004) found that, for Dungeness, with a handling mortality rate of 5% or 10%, above a BPRR of 40 or 20 (respectively; discarded sublegal male only to legal-sized crab), there is net loss in long-term yield. The ratio for the commercial fishery (including females and sublegal and legal size males) is below these thresholds and, while BPRR is near these levels for the recreational fishery, the mortality rate is lower. We note that our estimates of MPRR and BPRR are based on a limited number of sampling trips and could be influenced by fisherman skill level and definition of a "soft" crab and high-grading when the pound limit is in effect. Regardless, the trend of increasing MPRR and BPRR is apparent and reflects a decrease in catch of legal crab and an increase in nontarget catch as the season progresses. In contrast, when monthly values of MPRR and BPRR (average of trips by month) were speculatively applied to ODFW commercial landings data for the 2011–2012 and 2013–2014 fishing seasons (converting pounds to individual landed crab by approximating each crab to weigh 2 pounds (1 pound = 0.453 kg); Waldron 1958), we estimated that approximately half of the total discards and bycatch mortality took place in the first 3 months of the season. While MPRR and BPRR were lowest for the commercial fishery at the beginning of the season, the fleet-wide effort was highest at this time, resulting in higher total mortality and discard than in the subsequent months.

To determine whether the commercial fishery closure is appropriately set on 15 August, an in-depth assessment is required of the trade-offs between discard and discard- and natural-mortality rates, while factoring in socioeconomic considerations and fleet dynamics. It should also be considered, given that mortality is a function of effort, how the impact on soft-shell crab would be affected if effort in the spring and summer were to increase in the future due to increased price per pound of crab or to low prices or catch in concurrent alternative fisheries. Moreover, in evaluating efficacy with the current management strategy, high effort with low bycatch and discard mortality rates in the beginning of the season should be weighed against the increase in soft-shell crab, and hence higher mortality rates, and in MPRR and BPRR later in the season.

Acknowledgements

We are grateful for the ride-along opportunities and feedback on the study provided by B. Lisi, D. Lemon, M. Newell, T. Nowlin, I. Olsen, R. Carel, and crews of the F/Vs *Apache*, *Delma Ann*, *Maggie*, *Silver Quest*, and *Timmy Boy*. We also thank C. Ryer and the NOAA Alaska Fisheries Science Center Newport Laboratory for providing project support and holding facilities, and M. Ottmar, S. Haines, C. Magel, and E. Hanneman for assistance with monitoring captive crabs. We thank P. Iseri and B. Milano for their extensive assistance in the laboratory and field. We also acknowledge A. Levings, K. Corbett, M. Vance, and J. Ainsworth at the Oregon Department of Fish and Wildlife for contributing feedback on the project, J. Van Sickle for analytical advice, and M. Davis along with the associate editor and anonymous reviewers for thoughtful comments on drafts of the manuscript. Funding for this project and logistic support was provided by the Oregon Dungeness Crab Commission.

References

Ainsworth, J.C., Vance, M., Hunter, M.V., and Schindler, E. 2012. The Oregon recreational Dungeness crab fishery, 2007–2011. Oregon Department of Fish and Wildlife.

Alverson, D.L., Freeberg, M.H., Pope, J.G., and Murawski, S.A. 1994. A global assessment of fisheries bycatch and discards. FAO Fisheries Technical Paper. No. 339. FAO, Rome.

Barber, J.S., and Cobb, J.S. 2007. Injury in trapped Dungeness crabs (*Cancer magister*). ICES J. Mar. Sci. **64**(3): 464–472. doi:10.1093/icesjms/fsm021.

Barkley, A.S., and Cadrin, S.X. 2012. Discard mortality estimation of yellowtail flounder using reflex action mortality predictors. Trans. Am. Fish. Soc. **141**(3): 638–644. doi:10.1080/00028487.2012.683477.

Barnett, H.J., Nelson, R.W., Hunter, P.J., Einmo, A.E., and Plant, D.N. 1973. The overland shipment of live Dungeness crabs by self-contained van. Mar. Fish. Rev. **35**(11): 18–24.

Barrento, S., Marques, A., Pedro, S., Vaz-Pires, P., and Nunes, M.L. 2008. The trade of live crustaceans in Portugal: space for technological improvements. ICES J. Mar. Sci. **65**(4): 551–559. doi:10.1093/icesjms/fsn037.

Barry, S. 1983. Coastal Dungeness crab project (October 1, 1977 – September 30, 1982). Washington Department of Fisheries Project Progress Report to the National Marine Fisheries Service.

Barry, S. 1984. Coastal Dungeness crab project (October 1, 1982 – September 30, 1983). Washington Department of Fisheries Project Progress Report to the National Marine Fisheries Service.

Basti, D., Bricknell, I., Hoyt, K., Chang, E., Halteman, W., and Bouchard, D. 2010. Factors affecting post-capture survivability of lobster *Homarus americanus*. Dis. Aquat. Org. **90**(2): 153–166. doi:10.3354/dao02205. PMID:20662372.

Bellchambers, L.M., Smith, K.D., and Evans, S.N. 2005. Effect of exposure to ice slurries on nonovigerous and ovigerous blue swimmer crabs, *Portunus pelagicus*. J. Crustac. Biol. **25**(2): 274–278. doi:10.1651/C-2531.

Burton, C. 2001. Transport of live crustaceans. Shellfish News CEFAS, No. 11. pp. 18–19.

Cleaver, F.C. 1949. Preliminary results of the coastal crab (*Cancer magister*) investigation. State of Washington, Department of Fisheries.

Daume, S., and DeAlteris, J. 2014. Marine Stewardship Council (MSC) Third Annual Surveillance Audit Report, Oregon Dungeness Crab Fishery [online]. SCS Global Services Surveillance Audit Report. Available from https://www.msc.org/track-a-fishery/fisheries-in-the-program/certified/pacific/oregon-dungeness-crab/assessment-downloads-1/20140428_SR_CRA93.pdf.

Davis, M.W. 2007. Simulated fishing experiments for predicting delayed mortality rates using reflex impairment in restrained fish. ICES J. Mar. Sci. **64**(8): 1535–1542. doi:10.1093/icesjms/fsm087.

Davis, M.W., and Ottmar, M.L. 2006. Wounding and reflex impairment may be predictors for mortality in discarded or escaped fish. Fish. Res. **82**(1–3): 1–6. doi:10.1016/j.fishres.2006.09.004.

Demory, D. 1985. An overview of the Oregon Dungeness crab fishery with management concepts for the future. *In* Proceedings of the Symposium on Dungeness Crab Biology and Management. University of Alaska Fairbanks, Alaska Sea Grant Report 85-3. pp. 27–32.

Didier, A.J. 2002. The Pacific coast Dungeness crab fishery. Report submitted to the Committee on Commerce, Science, and Transportation of the United States Senate and Committee on Resources of the United States House of Representatives, Pacific States Marine Fisheries Commission.

Dunham, J.S., Phillips, A., Morrison, J., and Jorgensen, G. 2011. A manual for Dungeness crab surveys in British Columbia. Canadian Technical Report of Fisheries and Aquatic Sciences 2964.

Durkin, J.T., Buchanan, K.D., and Blahm, T.H. 1984. Dungeness crab leg loss in the Columbia River estuary. Mar. Fish. Rev. **46**(1): 22–24.

Fisheries and Oceans Canada. 2014. Pacific region integrated Fisheries management plan. Crab by trap. January 1, 2010 to December 31, 2010.

Foyle, T.P., Hurley, G.V., and Taylor, D.M. 1989. Field testing shell hardness gauges for the snow crab fishery. Canadian Industry Report of Fisheries and Aquatic Sciences No. 193.

Hammond, C.F., Conquest, L.L., and Rose, C.S. 2013. 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*). ICES J. Mar. Sci. **70**(7): 1308–1318. doi:10.1093/icesjms/fst085.

Heppell, S.S. 2011. Development of monitoring and assessment tools for the Dungeness crab fishery. Report to the Oregon Dungeness Crab Commission.

Hicks. 1987. 1986 King/Dungeness crab survey, Kodiak, Alaska [online]. ADF&G Technical Data Report, Alaska Department of Fish and Game. Available from http://www.adfg.alaska.gov/fedaidpdfs/TDR.204.pdf.

Hicks, D., and Johnson, B.A. 1999. A device to measure shell hardness of Dungeness crabs and trial application in the Kodiak Island, Alaska, commercial fishery. N. Am. J. Fish. Manage. **19**(2): 581–590. doi:10.1577/1548-8675(1999)019<0581:ADTMSH>2.0.CO;2.

Jacoby, C.A. 1983. Ontogeny of behavior in the crab instars of the Dungeness crab, *Cancer magister* Dana 1852. Z. Tierpsychol. **63**(1): 1–16. doi:10.1111/j.1439-0310.1983.tb00736.x.

Kondzela, C.M., and Shirley, T.C. 1993. Survival, feeding, and growth of juvenile Dungeness crabs from southeastern Alaska reared at different temperatures. J. Crustac. Biol. **13**(1): 25–35. doi:10.2307/1549120.

Kruse, G.H., Hicks, D., and Murphy, M.C. 1994. Handling increases mortality of softshell Dungeness crabs returned to the sea. Alaska Fish. Res. Bull. **1**(1): 1–9.

Lippert, G., Hoffmann, S., and Clarke, P. 2002. Dungeness crab shell condition field manual. Washington Department of Fish and Wildlife.

MacKay, D.C.G. 1942. The Pacific edible crab, *Cancer magister*. Fisheries Research Board of Canada.

Musyl, M.K., Moyes, C.D., Brill, R.W., and Fragoso, N.M. 2009. Factors influencing mortality estimates in post-release survival studies. Mar. Ecol. Progr. Ser. **396**: 157–159. doi:10.3354/meps08432.

National Marine Fisheries Service. 2015. Fisheries of the United States, 2014 [online]. US Department of Commerce, NOAA Current Fishery Statistics No. 2014. Available from https://www.st.nmfs.noaa.gov/commercial-fisheries/fus/fus14/index.

Nguyen, V.M., Martins, E.G., Robichaud, D., Raby, G.D., Donaldson, M.R., Lotto, A.G., Willmore, W.G., Patterson, D.A., Farrell, A.P., Hinch, S.G., and Cooke, S.J. 2014. Disentangling the roles of air exposure, gill net injury, and facilitated recovery on the postcapture and release mortality and behavior of adult migratory sockeye salmon (*Oncorhynchus nerka*) in freshwater. Physiol. Biochem. Zool. **87**(1): 125–135. doi:10.1086/669530. PMID:24457927.

Northrup, T. 1975. Coastal Dungeness crab study. Completion Report for Period July 1973 – June 1975 Prepared for the National Marine Fisheries Service.

ODFW. 2009. Commercial shellfish and marine invertebrate fisheries, general regulations. Oregon Administrative Rules Commercial Fisheries Division, **005**: 49.

ODFW. 2015*a*. Oregon commercial Dungeness crab landings [online]. Available from http://www.dfw.state.or.us/mrp/shellfish/commercial/crab/.

ODFW. 2015*b*. 2015 Oregon Sport Fishing Regulations. Oregon Department of Fish and Wildlife.

ODFW. 2015*c*. Oregon, a great catch [online]! Available from http://www.dfw.state.or.us/MRP/shellfish/crab/.

Oregon Sea Grant. 2008. Traps [online]. Oregon State University. Available from http://seagrant.oregonstate.edu/files/sgpubs/onlinepubs/g08002.pdf.

Penson, J.B., Jr., and Tetty, E.O. 1988. Appendage injury in Dungeness crabs, *Cancer magister*, in southeastern Alaska. Fish. Bull. **86**: 156–160.

PSMFC. 1978. Dungeness crab project of the state–federal fisheries management program. Pacific States Marine Fisheries Commission, Portland, Oregon.

R Development Core Team. 2011. R: a language and environment for statistical computing [online]. R Foundation for Statistical Computing, Vienna, Austria. Available from http://www.R-project.org/.

Raby, G.D., Donaldson, M.R., Hinch, S.G., Patterson, D.A., Lotto, A.G., Robichaud, D., English, K.K., Willmore, W.G., Farrell, A.P., Davis, M.W., and Cooke, S.J. 2012. Validation of reflex indicators for measuring vitality and predicting the delayed mortality of wild coho salmon bycatch released from fishing gears. J. Appl. Ecol. **49**(1): 90–98. doi:10.1111/j.1365-2664.2011.02073.x.

Ramsey, F., and Schafer, D. 2002. The statistical sleuth: a course in methods of data analysis [online]. Duxbury Press, Pacific Grove, Calif. Available from http://www.abebooks.com/Statistical-Sleuth-Course-Methods-Data-Analysis/18617715651/bd?cm_mmc=gmc-_-used-_-PLA-_-v01&product=COM9780534386702USED.

Rasmuson, L.K. 2013. The biology, ecology and fishery of the Dungeness crab, *Cancer magister*. *In* Advances in marine biology. Elsevier. pp. 95–148.

Reilly, P.N. 1983. Effects of commercial trawling on Dungeness crab survival. Fish. Bull. **172**: 165–169.

Rice, J.A. 1988. Mathematical statistics and data analysis [online]. Wadsworth and Brooks/Cole, Pacific Grove, Calif. Available from http://www.amazon.com/Mathematical-Statistics-Data-Analysis-Sets/dp/8131501833/ref=mt_paperback?_encoding=UTF8&me=.

Robinson, J.G., Odemar, M.W., Richards, J.A., and Westley, R. 1977. Report on the proposal for extension of Dungeness crab state federal fisheries management plan development for the California, Oregon, and Washington Dungeness crab fishery. State/Federal Dungeness Crab Fisheries Management Program. Pacific Marine Fisheries Commission.

Rose, C.S., Hammond, C.F., Stoner, A.W., Munk, J.E., and Gauvin, J.R. 2013. Quantification and reduction of unobserved mortality rates for snow, southern Tanner, and red king crabs (*Chionoecetes opilio*, *C. bairdi*, and *Paralithodes camtschaticus*) after encounters with trawls on the seafloor. Fish. Bull. **111**(1). doi:10.7755/FB.111.1.4.

Simonson, J.L., and Hochberg, R.J. 1986. Effects of air exposure and claw breaks on survival of stone crabs *Menippe mercenaria*. Trans. Am. Fish. Soc. **115**(3): 471–477. doi:10.1577/1548-8659(1986)115<471:EOAEAC>2.0.CO;2.

Smith, B.D., and Jamieson, G.S. 1989. Exploitation and mortality of male Dungeness crabs (*Cancer magister*) near Tofino, British Columbia. Can. J. Fish. Aquat. Sci. **46**(9): 1609–1614. doi:10.1139/f89-205.

Snow, C.D., and Wagner, E.J. 1965. Tagging of Dungeness crabs with spaghetti and dart tags [online]. Fish Commission of Oregon. Available from http://docs.streamnetlibrary.org/Oregon/FishComn/FCO-ResearchBriefs-v11n1-1965.pdf#page=5.

Somerton, D.A., and Macintosh, R.A. 1983. Weight-size relationships for three populations in Alaska of the blue king crab, *Paralithodes Platypus* (Brandt, 1850) (Decapoda, Lithodidae). Crustaceana, **45**(2): 169–175. doi:10.1163/156854083X00596.

Spears, C.J. 1983. How to identify a soft-shell crab [online]. Oregon State University Extension Service. [Corvallis, Ore.] Available from http://ir.library.oregonstate.edu/xmlui/handle/1957/25075.

Stevens, B.G. 1990. Survival of king and Tanner crabs captured by commercial sole trawls. Fish. Bull. **88**: 731–744.

Stewart, N.E. 1974. Discussion on crab mortality associated with certain fishery practices. Technical Report Prepared for the State/Federal Dungeness Crab Management Program, Fish Commission of Oregon.

Stoner, A.W. 2012*a*. Evaluating vitality and predicting mortality in spot prawn, *Pandalus platyceros*, using reflex behaviors. Fish. Res. **119–120**: 108–114. doi:10.1016/j.fishres.2011.12.014.

Stoner, A.W. 2012*b*. Assessing stress and predicting mortality in economically significant crustaceans. Rev. Fish. Sci. **20**(3): 111–135. doi:10.1080/10641262.2012.689025.

Stoner, A.W., Rose, C.S., Munk, J.E., Hammond, C.F., and Davis, M.W. 2008. An assessment of discard mortality for two Alaskan crab species, Tanner crab (*Chionoecetes bairdi*) and snow crab (*C. opilio*), based on reflex impairment. Fish. Bull. **106**(4): 337–347.

Swiney, K.M., Shirley, T.C., Taggart, S.J., and O'Clair, C.E. 2003. Dungeness crab, *Cancer magister*, do not extrude eggs annually in Southeastern Alaska: An in situ study. J. Crustac. Biol. **23**(2): 280–288. doi:10.1651/0278-0372(2003)023[0280:DCCMDN]2.0.CO;2.

Tegelberg, H.C. 1972. Condition, yield, and handling mortality studies on Dungeness crabs during the 1969 and 1970 seasons [online]. *In* 23rd Annual Report of the Pacific Marine Fisheries Commission for the year 1970. Portland, Oregon. pp. 42–47. Available from http://www.psmfc.org/resources/publications-maps-2/psmfc-annual-reports?sl=4.

Tegelberg, H.C., and Magoon, D. 1970. Handling mortality on softshell Dungeness crabs [online]. *In* Proceedings of the National Shellfisheries Association. Published for the National Shellfisheries Association by MPG Communications., Plymouth, Mass. p. 13. Available from http://www.biodiversitylibrary.org/item/22129.

Urban, J.D. 2015. Discard mortality rates in the Bering Sea snow crab, *Chionoecetes opilio*, fishery. ICES J. Mar. Sci. **72**(5): 1525–1529. doi:10.1093/icesjms/fsv004.

Waldron, K.D. 1958. The fishery and biology of the Dungeness crab (*Cancer magister* Dana) in Oregon waters. Fish Commission of Oregon.

Warrenchuck, J.J., and Shirley, T.C. 2002. Effects of windchill on the snow crab (*Chionoecetes opilio*). Alaska Sea Grant, University of Alaska Fairbanks. pp. 81–96. doi:10.4027/ccwrbme.2002.09.

Wild, P.W., and Tasto, R.N. 1983. Life history, environment, and mariculture studies of the Dungeness crab, *Cancer magister*, with emphasis on the central California fishery resource. Fish Bulletin 172. State of California Marine Resources Branch.

Yochum, N., Rose, C.S., and Hammond, C.F. 2015. Evaluating the flexibility of a reflex action mortality predictor to determine bycatch mortality rates: A case study of Tanner crab (*Chionoecetes bairdi*) bycaught in Alaska bottom trawls. Fish. Res. **161**: 226–234. doi:10.1016/j.fishres.2014.07.012.

Yonis, R. 2010. The economics of British Columbia's crab fishery: socio-economic profile, viability, and market trends [online]. Statistical and economic analysis series. Publication No. 1–4. Available from http://www.deslibris.ca/ID/222938.

Youde, J.G., and Wix, J.R. 1967. Economics of the Dungeness crab industry [online]. Agricultural Experiment Station, Oregon State University, Corvallis, Ore. Available from http://ir.library.oregonstate.edu/xmlui/handle/1957/24435.

Zhang, Z., Hajas, W., Phillips, A., and Boutillier, J.A. 2004. Use of length-based models to estimate biological parameters and conduct yield analyses for male Dungeness crab (*Cancer magister*). Can. J. Fish. Aquat. Sci. **61**(11): 2126–2134. doi:10.1139/f04-155.