Canadian Journal of Fisheries and Aquatic Sciences
Journal canadien des sciences halieutiques et aquatiques

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Journal:	<i>Canadian Journal of Fisheries and Aquatic Sciences</i>
Manuscript ID	cjfas-2016-0029.R2
Manuscript Type:	Article
Date Submitted by the Author:	14-Aug-2016
Complete List of Authors:	Yochum, Noëlle; Oregon State University, Fisheries and Wildlife Stoner, Allan; NOAA Alaska Fisheries Science Center Rose, Craig; FishNext Research Sampson, David; Oregon State University, Coastal Oregon Marine Experiment Station Pazar, Alan; Commercial fisherman, F/V <i>Delma Ann</i> Eder, Robert; Commercial fisherman, F/V <i>Timmy Boy</i>
Keyword:	BYCATCH < General, CRABS < Organisms, FISHERY MANAGEMENT < General, reflex impairment, discard mortality

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

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Abstract

We found that crab discarded from Oregon (U.S.A.) commercial and recreational fisheries for Dungeness crab (*Cancer magister*) have lower post-release mortality than previously estimated. This aligns with the goals of the ‘3-S’ management strategy currently employed for these fisheries, to protect discarded sub-legal male (Size), female (Sex), and soft-shell (Season) crab. We found that, for the commercial ocean Dungeness fishery, overall discard mortality rates (five 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 (RAMP) 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.

Keywords

Bycatch, crabs, fishery management, reflex impairment, discard mortality

Introduction

Dungeness crab (*Cancer magister*) is currently the most valuable crab fishery in the United States, yielding nearly 25 thousand metric tons and \$211 million in 2014 (National Marine Fisheries Service 2015), and has an over \$40 million dollar (CAD 2008) ex-vessel value in Canada (Yonis 2010). In Oregon (U.S.A.), the ocean fishery for these crab is the most valuable single-species commercial fishery, with 300-350 vessels landing 5-15 thousand metric tons each season (Ainsworth et al. 2012), generating up to \$50.2 million (ex-vessel; ODFW 2015a). 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 significance, in the United States there is neither a stock assessment nor a Fishery Management Plan (FMP) for the commercial or recreational Dungeness crab fisheries along the Pacific coast nor 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 2015b). 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 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 et al. 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 two to three months that it takes post-moult crab to harden and fill in muscle tissue (Dunham et al. 2011, Rasmuson 2013), the meat yield is approximately 13-14% compared to 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 sub-legal 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 December 1st, but is delayed if the crab do not meet the minimum meat weight recovery threshold of 25% (Figure 1; Didier 2002, ODFW 2009). Beginning the second Monday in June, as soft-shell crab increase in abundance,

fishermen are restricted to landing 1,200 pounds (544 kg) of crab per week. This regulation remains in effect until the season closes on August 15th (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 two months of the season. Post-winter, as catch rate decreases, fishermen often switch to alternative, concurrent fisheries (Youde et al. 1967, PSMFC 1978, Oregon Sea Grant 2008).

Fishing seasons vary across the commercial and recreational fisheries in the ocean and bays (Figure 1). The commercial bay fishery occurs from the Labor Day holiday (the first Monday in September) to December 31st, 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 December 1st to October 15th (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 run-off, 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 sub-legal 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) over the fishing season. In addition, we make recommendations toward the goal of reducing both bycatch and discard mortality rates.

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 RAMP

To quantify discard mortality rates for the Dungeness crab fisheries we utilized the Reflex Action Mortality Predictor (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 2012a, 2012b, Hammond et al. 2013, Rose et al. 2013, Yochum et al. 2015, Urban 2015).

To apply the RAMP approach to discarded crab from these 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 (AFSC) 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 sea water tanks (2 m diameter, filled to 1 m depth). In the field and 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: (i) eye retraction; (ii) mouth defense; (iii) chela closure; (iv) leg wrap; (v) leg curl; and (vi) 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 (here forward 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 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 Supplementary Data.

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 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 in order 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 millimeter), 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 post-moult (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: broken, injured, or missing legs/chela, spines, dactyli, maxillipeds, or abdominal flap; autotomized legs/ 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 one or two days post injury 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 seconds 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 to days, and legal crab were $\frac{3}{4}$ 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 2015c).

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). 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.

293

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

310

311 Given our finding of a captivity effect and evidence from other studies that Dungeness crab can
312 be difficult to keep alive in captivity (Barnett et al. 1973), we determined ways to reduce stress
313 and injury attributed to captivity and transport. We found that the captivity effect was
314 ameliorated by holding crab in individual containers. Similar to Jacoby (1983), we found
315 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 x 53 cm x 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 re-soaked 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 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. ‘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.

Equation 1 $\text{Log}_e \left(\frac{p}{1-p} \right) = \alpha + \beta_o \text{Score} + \beta_i x_i$, where:

p = probability that a crab died during the holding period

α = intercept

β_0 = model coefficient for reflex impairment score (‘Score’)

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 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 (non-specific) or absence of injuries. When analyzing the fisheries separately, (i) use of the slam bar; (ii) soak duration (days), (iii) depth (fathoms), and (iv) Beaufort wind force scale were included for the commercial analysis; and (i) soak duration (min), (ii) depth (meters), and (iii) gear type (ring or pot) 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.

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

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

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

$P(m|s = k)$ 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 $P(m|s = k) * P(s = k)$ 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- non-target crab and immediate mortalities- that die) were calculated similarly, but included crab that died prior to assessment (immediate mortality). Estimates of mortality-per-retained ratios (MPRR) and bycatch-per-retained-ratios (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., if 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 7,685 total crab. More information on sampling trips, catch composition, and size distributions can be found in the Supplemental Data (Tables S1 and S2, and Figure S1). Catch size and composition of the commercial and recreational fisheries varied by time from fishery opening and trip, respectively (Figures 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 sub-legal, hard-shell males and 26% were hard-shell females. There were few soft-shell females caught during trips for either the commercial or recreational fishery (1% and 8% respectively), nor soft-shell males (11% and 12%).

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 on the second day. Soak duration ranged from 1.5 to 30 days (6 days on average), and sea state from 1 to 6 (3 on average; Beaufort wind force scale). Pots were fished in depths ranging from 5.5 to 150 meters. 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).

The data revealed temporal trends in catch composition. This included that the number of immediate mortalities and soft-shell males per pot increased towards the end of the fishing season (Figure 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 sub-legal males were soft until July, when the percent 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% two days after the opening in the previous season (9 retained per pot), 55% two weeks after the opening (five retained per pot), then from four weeks to 28 weeks after the season opened, the range of retention was between 11-76% (1-5 retained per pot). In July, 29 weeks after fishing began, only 6-7% of the catch was retained (1-2 per pot). Additionally, 32% of discarded hard-shell males were legal size in July, indicating high-grading for crab with 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/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/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/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 (Figure 3). There were, however, slightly more crab discarded per gear for rings than pots (6.61 and 5.25 respectively) and slightly more crab retained per gear for rings than 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) 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, soft- and hard- shell. We therefore grouped the data using a sex-shell condition variable: female, hard-shell male, and soft-shell male. Model selection using Akaike Information Criteria and drop in deviance tests indicated that the most parsimonious model included only the 'sex-shell condition' variable in addition to Score (Figure 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). 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). 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 (Figure 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 (five 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, the mortality- and bycatch-per-retained ratios (MPRR, BPRR) increased over the fishing season (Figure 6). During a ride-along trip on opening day of the 2013/14 season, MPRR was 0.001 (688 crab were retained per mortality) given high catch of legal crab and low discard rates. 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 two 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). Meaning 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- vs. 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.

Quantifying Discard Mortality Rates

Delayed discard mortality rates of sub-legal, 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 crab compared to hard-shell. 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. 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 22-25% for soft-shell crab and 2-4% for hard-shell sub-legal crab.

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 to 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 weight 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 JR 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 sub-legal, female, and soft-shell crab. However, it is important to consider mortality- and bycatch-per-retained ratios (MPRR, 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 (Figure 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 sub-legal males, the ‘size’ component of the ‘3-S’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 weight per individual in future seasons. This study, however, did not evaluate the minimum size nor 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 indicates 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. For one, the percent of captured legal-size males that were soft increased from 0-2% from December to May, to 23-87% in June and July (Figure 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 sub-legal male only to legal-sized crab), there is net loss in long-term yield. The ratio for the commercial fishery (including females, and sub-legal 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 non-target 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 2011/12 and 2013/14 fishing seasons (converting pounds to individual landed crab by approximating each crab to weigh two pounds; Waldron 1958), we estimated that approximately half of the total discards and bycatch mortality took place in the first three 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 August 15th 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 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, and 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.

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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 if 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 3 rd maxillipeds	Crab defends its mouthparts with its chela making it difficult to access the maxillipeds	Crab allows it's 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

Figures

Figure 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.

Figure 2 Catch composition for each commercial ocean sampling trip (n=22), including the number of sub-legal (<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). Indicated are the calendar months that the trips took place and the sampling year: first (2011/12), second (2012/13), and third (2013/14) sampled fishing seasons correspond to number of bars. For trips in June and July, the numbers above the bars indicate the percent of legal-size male crab (those retained and discarded) that were soft. For the remaining trips, the percentage ranged from 0-2 by trip.

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

Figure 4 Logistic model predictions of the probability of mortality by reflex impairment score (‘Score’) for Dungeness crab (*Cancer magister*) 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 (five days of observation; ‘Actual Mortality’) with dot size reflecting the number of crab held by sex-shell condition and Score.

Figure 5 Estimated delayed discard mortality rates for Dungeness crab (*Cancer magister*) with 95% Confidence Intervals for the commercial ocean fishery evaluated by month of sampling and sex-shell condition.

Figure 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 (*Cancer magister*; MPRR and BPRR), and the percent 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). Indicated are the numeric months that the trips took place and the sampling year: first (2011/12), second (2012/13), and third (2013/14) sampled fishing seasons correspond to number of bars.

Figure 7 The potential stressors experienced by Dungeness crab (*Cancer magister*) in directed recreational and commercial crab fisheries, and recommendations for future research and ways to reduce these stressors.

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Supplementary Data

Additional Fisheries Assessed

Between February 2012 and April 2014, we completed 68 sampling trips for the recreational (from a boat or shoreline in the bay, and in the ocean) and commercial (in the ocean and bay) Dungeness crab fisheries. Across all fishery types, 8,657 crab were assessed for this study (Tables S1 and S2). Our paper describes the bycatch- and discard- mortality rates for the commercial ocean and recreational bay by boat fisheries. Here we present data from the sampling trips for the additional fisheries (recreational ocean and shoreline, and commercial bay fishing).

Sampling methodology for the additional fisheries was similar to that described in the paper for the commercial ocean and recreational bay by boat fisheries, with some exceptions. To assess discard in the recreational shoreline fishery, on a given sampling 'trip', we went to the Port of Newport Public Fishing Pier (on Yaquina Bay) and sampled all pots or rings of two to six willing individuals or groups of people on the pier that were crabbing for the pre-determined sampling period or until they stopped fishing. Sampling methods for the commercial bay fishery differed from those for the commercial ocean fishery in that: (i) a slam bar was not used; (ii) rings were used instead of pots (per management regulations); (iii) soak duration was measured in minutes; and (iv) the first assessed ring was selected at random and the subsequent rings were sampled as soon as all crab from the previous ring were assessed and returned to the water. Less gear (15 rings maximum) is fished during a commercial bay trip and the above protocol maximized the opportunity for sampling. However, rings to be sampled were pre-determined before coming out of the water to avoid bias. In addition, sampling trips were completed in Alsea Bay, which is approximately 25 km south of Yaquina Bay.

Commercial Bay Fishery

Four commercial bay ride-along trips were completed in the months of September and October, aboard one vessel and with one captain, in water ranging from 1.2-11.6 meters (3.6 meters on average; Table S1), and soak duration from 10 to 46 minutes (17 minutes on average). It was difficult to obtain ride-along opportunities given the small vessel size, and limited number of active permit holders. Across all trips, 53 rings were sampled, containing 348 bycaught and 16 retained crab. The average number of crab discarded per ring ranged from 3.6 to 10.5 by trip. The majority of crab assessed were Score-zero (range for rings: 92%-100%), and hard-shell females were predominant over other sex/shell hardness combinations (35%-92%; Table S2). There were no immediate mortalities in the rings that were assessed and only 6 crab (2%) were injured. Crab caught during commercial bay ride-along trips were handled less than those from sampling trips for all other fisheries. Only crab that were close to legal size were removed from the rings and measured; all obviously sub-legal males and females were left in the gear as it was reset.

Recreational Shoreside Fishery

In the variety of fishing gears sampled during 15 'trips' over each calendar month (two trips each in January, February, and March), 508 Dungeness crab were discarded, and 12 were retained. The vast majority of the catch was discarded, and the majority of discards were hard-shell males (55%) and Score-zero crab (91%), with soft-shell males having the lowest relative percent of Score-zero individuals (Table S2). Only 14% of crab assessed during shoreside sampling were soft-shell. We observed that care taken in removing crab from the fishing gear, and therefore amount of injury to the crab, often depended on the experience level of the fisherman (i.e., more

experience: less injury). In addition, the distances for returning crab to water were higher for shoreside fishing than by boat. Where we sampled, the distance from the rail of the pier to the water at mean lower low water was 6.3 meters, and there were commonly California sea lions (*Zalophus californianus*) present where crab were returned to the water. The contribution to mortality from the return to water and increased susceptibility to predation were not considered in the discard mortality assessments.

Recreational Ocean Fishery

During the one recreational ocean sampling trip (in August), there were 40 crab that would have been retained, and 116 discarded; indicating that for every retained crab, there were 3 discarded.

RAMP Relationships

Preliminary model selection to determine the relationship between probability of mortality and reflex impairment score and environmental, biological, and fishing variables, on all data combined (for all four assessed fisheries: commercial ocean, and recreational ocean and bay by boat and shoreside) indicated a significant difference (tested at an alpha value of 0.05) between fishery types. Specifically, the recreational bay fishing by boat had lower mortality probability than the other fishery types for a given reflex impairment score. We therefore combined recreational crabbing in the ocean and shoreside with commercial ocean crabbing, and determined that there were no significant differences among these fisheries. We repeated this analysis using only recreational data. Again, the bay fishery by boat was significantly different from the other recreational fisheries in that mortality was reduced. We therefore separated the data by fishery type. Captive holding datasets for shoreside and recreational ocean were not large

enough to create separate RAMP relationships (Table S3). We therefore only created them for the commercial ocean and recreational bay by boat fisheries (Table S4). No crab caught during commercial bay trips were held because the small vessel size prevented retaining crab during the fishing trip.

While RAMP relationships for the additional fisheries were not created, the lack of significant difference for fishery type when the shoreside and recreational ocean fisheries were combined with the commercial ocean fishery indicates that, until future research is conducted to create RAMP relationships for these fisheries, the commercial ocean fishery relationship could be applied with caution. For example, we applied this relationship to the single recreational ocean fishing trip. The resultant total delayed mortality for the trip was 5.4% for females, 2.3% for hard-shell males, and 13.7% for soft-shell males. For all categories combined, 5.8% of all discarded crab from this trip were expected to die after release; indicating that 17 crab would die for every 100 retained. These values should not be applied to the fishery, however, as this was only one trip and may not be representative for the fishery as a whole. With more data collected on catch composition for this fishery with respect to sex-shell condition and reflex impairment score, the RAMP application could be more useful in estimating discard mortality rates for this fishery.

Table S1   The number of sampling trips completed on a given number of fishing vessels, over specified months (listed numerically) and depths between 2012 and 2014, and the mean carapace widths (mm) of assessed crab (range in parentheses) for the indicated fisheries.

	Commercial		Recreational		
	<u>Ocean</u>	<u>Bay</u>	<u>Bay by Boat</u>	<u>Bay Shoreside</u>	<u>Ocean</u>
No. Trips	22	4	26	15	1
No. Vessels	4	1	3		1
Depth Range (m)	6-150	2-11	2-11		22
Calendar Month	1, 2, 3, 4, 5, 6, 7, 12	9, 10	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	8
Carapace Width (mm)					
Male	160 (93-193)	116 (80-160)	125 (61-167)	115 (35-147)	153 (131-173)
Female	152 (52-174)	131 (79-162)	114 (67-167)	127 (41-160)	139 (116-159)

Table S2 By fishery, the number of completed trips and pots sampled during those trips, and the number of dead Dungeness crab (*Cancer magister*) in the sampled pots (“immediate mortalities”), and those discarded alive per each reflex impairment score (0-6) by sex and shell hardness (<>: indicates crab that were thrown over before a full assessment could be completed).

Type	No. Trips/ Pots	Sex & Shell Condition	<>	0	1	2	3	4	5	6	Immediate Mortality	Total	% of Total
Commercial Bay	4 / 53	Female	2									2	1%
		FemaleHard	1	259	6	1						267	77%
		FemaleSoft		17		1						18	5%
		MaleHard		46			1					47	14%
		MaleSoft		13	1							14	4%
		Total	3	335	7	2	1	0	0	0	0		
		% of Total	1%	96%	2%	1%	0%	0%	0%	0%	0%	348	
Commercial Ocean	22 / 966		9	1							37	47	1%
		Female	18	23	4	1	2	1			18	67	1%
		FemaleHard	1	2606	355	104	42	11	5	6	69	3199	57%
		FemaleSoft		67	6	1					1	75	1%
		Male	11	4							3	18	0%
		MaleHard	1	1379	143	15	1	1			29	1569	28%
		MaleSoft	1	571	27	8	1	1		2	8	619	11%
		Total	41	4651	535	129	46	14	5	8	165	5594	
		% of Total	1%	83%	10%	2%	1%	0%	0%	0%	3%		
Recreational Bay_Boat	26 / 384	Female		1								1	0%
		FemaleHard		520	25	3				1		549	26%
		FemaleSoft		164	9	3		1				177	8%
		MaleHard		1017	63	24	2	2				1108	53%
		MaleSoft		232	20	3	1					256	12%
		Total	0	1934	117	33	3	3	0	1	0		
		% of Total	0%	92%	6%	2%	0%	0%	0%	0%	0%	2091	
Recreational Bay_Shoreside	15 / 436		1									1	0%
		Female	3									3	1%
		FemaleHard		139	6	3	1					149	29%
		FemaleSoft		26	1							27	5%
		Male	1	1								2	0%
		MaleHard		253	23	4	1					281	55%
		MaleSoft		39	3	2	1					45	9%
		Total	4	459	33	9	3	0	0	0	0		
		% of Total	1%	90%	6%	2%	1%	0%	0%	0%	0%	508	
Recreational Ocean	1 / 11	Female	1									1	1%
		FemaleHard		53	3							56	48%
		FemaleSoft		5	1							6	5%
		MaleHard		31	2			1				34	29%
		MaleSoft		17		1		1				19	16%
		Total	1	106	6	1	0	2	0	0	0		
		% of Total	1%	91%	5%	1%	0%	2%	0%	0%	0%	116	
All Combined	68 / 1850	Total	49	7485	698	174	53	19	5	9	165	8657	
		% of Total	1%	86%	8%	2%	1%	0%	0%	0%	2%		

Table S3 The number of Dungeness crab (*Cancer magister*) from the sampled pots with each reflex impairment score (0-6) by sex and shell condition (i.e., hardness) that were assessed and held in the laboratory to determine discard mortality, by fishery (immediate mortalities were not held).

Fishery	Sex_Shell Condition	Reflex Impairment Score							Total	% of Total
		0	1	2	3	4	5	6		
Commercial Ocean	Female	13	2	1	2	1			19	3%
	Female_Hard	255	62	18	12	4	1		352	54%
	Female_Soft	20	1						21	3%
	Male_Hard	173	36	3	1				213	33%
	Male_Soft	41	6		1			2	50	8%
	Total	502	107	22	16	5	1	2	655	
	% of Total	77%	16%	3%	2%	1%	0%	0%		
Recreational Bay by Boat	Female_Hard	39	5	1					45	14%
	Female_Soft	20	2						22	7%
	Male_Hard	193	15	7	1				216	67%
	Male_Soft	31	7						38	12%
	Total	283	29	8	1	0	0	0	321	
	% of Total	88%	9%	2%	0%	0%	0%	0%		
Recreational Shoreside	Female_Hard	24	1						25	54%
	Female_Soft	7	1						8	17%
	Male_Hard	7	2						9	20%
	Male_Soft	4							4	9%
	Total	42	4	0	0	0	0	0	46	
	% of Total	91%	9%	0%	0%	0%	0%	0%		
Recreational Ocean	Female_Hard	16	2						18	42%
	Female_Soft	4							4	9%
	Male_Hard	11	1			1			13	30%
	Male_Soft	6		1		1			8	19%
	Total	37	3	1	0	2	0	0	43	
	% of Total	86%	7%	2%	0%	5%	0%	0%		
All Combined	Total	864	143	31	17	7	1	2	1065	
	% of Total	81%	13%	3%	2%	1%	0%	0%		

Table S4 Results for the most parsimonious logistic model (in bold) and alternatives (including standard errors, SE, and Akaike Information Criterion, AIC) indicating that mortality is best predicted using the number of impaired reflexes (Score; integer-values 0 to 6) and sex-shell hardness (female soft- and hard-shell combined: reference category) for the commercial ocean Dungenes crab (*Cancer magister*) fishery, and using whether or not a crab has impaired reflexes (reference category) or not (Score-zero, unimpaired) for the recreational bay by boat fishery. Alternative models that were considered included the presence of new injuries (commercial and recreational), and treating Score as a continuous variable (recreational).

	<u>Parameter</u>	<u>Coefficient</u>	<u>SE</u>	<u>P-value</u>	<u>AIC</u>
Commercial Ocean	Intercept	-2.98	0.24	< 2 e-16	277.8
	Score	1.12	0.15	1.3 e-13	
	Male- Hard Shell	-1.71	0.62	0.006	
	Male- Soft Shell	0.49	0.54	0.36	
	Intercept	-3.06	0.25	< 2 e-16	278.08
	Score	1.13	0.15	1.9 e-13	
	Injury	0.73	0.53	0.17	
	Male- Hard Shell	-1.70	0.62	0.006	
	Male- Soft Shell	0.49	0.54	0.36	
	Intercept	-2.48	0.60	3.6 e-5	38.5
	Score-Zero	-3.17	1.17	0.007	
Recreational Bay by Boat	Intercept	-3.16	0.87	0.0003	38.08
	Injury	1.77	1.11	0.112	
	Score-Zero	-2.69	1.24	0.03	
	Intercept	-5.07	0.70	5.2 e-13	40.79
	Score	1.52	0.53	0.004	

Figure S1 Number, by carapace width (10 mm bins), of captured and assessed male and female Dungeness crab (*Cancer magister*) intended for discard (alive and dead) by fishery, with breaks made at 146 and 159 mm (the minimum size required for retaining male crab for the recreational and commercial fisheries respectively).