An assessment of discard mortality for two Alaskan crab species, Tanner crab (*Chionoecetes bairdi*) and snow crab (*C. opilio*), based on reflex impairment

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Abstract—Delayed mortality associated with discarded crabs and fishes has ordinarily been observed through tag and recovery studies or during prolonged holding in deck tanks, and there is need for a more efficient assessment method. *Chionoecetes bairdi* (Tanner crab) and *C. opilio* (snow crab) collected with bottom trawls in Bering Sea waters off Alaska were evaluated for reflexes and injuries and held onboard to track mortality. Presence or absence of six reflex actions was determined and combined to calculate a reflex impairment index for each species. Logistic regression revealed that reflex impairment provided an excellent predictor of delayed mortality in *C. opilio* (91% correct predictions). For *C. bairdi*, reflex impairment, along with injury score, resulted in 82.7% correct predictions of mortality, and reflex impairment alone resulted in 79.5% correct predictions. The relationships between reflex impairment score and mortality were independent of crab gender, size, and shell condition, and predicted mortality in crabs with no obvious external damage. These relationships provide substantial improvement over earlier predictors of mortality and will help to increase the scope and replication of fishing and handling experiments. The general approach of using reflex actions to predict mortality should be equally valuable for a wide range of crustacean species.

Manuscript submitted 25 March 2008.
Manuscript accepted 7 May 2008.
Fish. Bull. 106:337–347 (2008).

Numerous species with economic and ecological significance are discarded from fishing operations because of harvest restrictions or low value compared with the target species or size groups. Although discarded catch can exceed that retained (Alverson et al., 1994; Witherell and Pautzke, 1997), discard mortality rates are rarely known. Mortality can occur on deck (immediate and observed mortality) or after the animal is released or escapes capture (delayed and unobserved mortality) (Stevens, 1990; Davis, 2002; Suuronen, 2005). Delayed mortality can result directly from physical injury and physiological stress or indirectly by an increased susceptibility to disease and predation, and through an inability to feed. Although a significant effort has been made to reduce unwanted bycatch through improvements in gear selectivity and handling procedures, unobserved discard mortality continues to be an important source of uncertainty for fishery management (Harrington et al., 2005; Broadhurst et al., 2006; Coggins et al., 2007).

Directed fisheries for *Chionoecetes* spp. and *Paralithodes camtschaticus* (red king crab) in the North Atlantic, North Pacific, and Bering Sea are prosecuted with baited pots, the only legal commercial gear for these crabs in the United States and Canada. Harvesting is restricted to males within strict size limits; consequently all females and undersized males are discarded. Crabs are also captured and discarded or escape from trawl gear. Given the difficulties of determining mortality for discarded crabs, fixed mortality rates have been assumed for specific fishing sectors in most fishery management models on the basis of a handful of experiments (see below). For example, fishery managers in Alaska have assumed fixed values of 20%, 50%, and 20%, respectively, for the discard mortality rates of *Chionoecetes bairdi* (southern

Tanner crab), *C. opilio* (snow crab) and *P. camtschaticus* in pot fisheries, and a fixed value of 80% for the discard mortality of both red king crab and snow crab in Bering Sea trawl fisheries (Siddeek, 2003).

Estimates for discard-related mortality in fishery species normally require experimental research whereby individuals or populations captured in different fishing operations or under different conditions are monitored for subsequent survival. Mortality can be evaluated through tag recovery studies, but this method requires handling large numbers of individuals, often for low returns. Holding fish or crabs in tanks or cages is a good method for direct evaluation of mortality in different fishing operations and handling, but experiments are often limited to relatively small numbers, short follow-up periods, and a few specific treatments or fishing variables.

A useful predictor for discard mortality may be crab condition. Blood and tissue chemistry (e.g., lactate, glucose, glycogen levels) have been used to evaluate stress in crustaceans (Crear and Forteath, 2001; Harris and Andrews, 2005; Ridgway et al., 2006). Recent experiments with marine fishes, however, show that chemical measures are often poor predictors of mortality because they typically reach peak values before any mortality occurs and because chemical measures often respond differently to physiological stress and physical injury (Davis et al., 2001, Davis and Schreck, 2005). Two other types of condition indicators have been explored for predicting mortality rates in crabs: injuries to the exoskeleton and behavioral impairments. In the first category, correlations between externally visible physical injuries and mortality were reported for *Chionoecetes* spp. (Rosenkranz, 2002) and red king crabs (Zhou and Shirley, 1995). However, internal injuries and bleeding that result in mortality can occur without apparent external injuries. Given that limitation, Stevens (1990) considered both external injuries and an index of spontaneous activity, termed vitality, as possible correlates with delayed mortality in red king crabs and Tanner crabs caught incidentally in Bering Sea trawls. The crabs were assessed and held for 48 hours in shipboard tanks to observe mortality. Logistic models showed that the vitality index was useful in predicting delayed mortality, and injury information did not significantly improve model power. Subsequently, others proposed that impaired righting behavior provides a sensitive indicator of freeze-related stress in snow crabs (Warrenchuk and Shirley, 2002), and might be used to predict mortality (van Tamelen, 2005). However, complex behaviors are difficult to quantify at sea because they require space and controlled conditions, and often do not yield graduated results. As an alternative to assessments determined by complex behavioral patterns, Davis and Ottmar (2006) recently discovered that easily acquired observations on a suite of simple reflex actions can provide excellent predictions of mortality in fishes related to both physical (i.e., wounding) and physiological (e.g., thermal stress, air exposure) injury.

We hypothesized that an assessment of reflex actions in crabs would directly reflect their condition and provide a good predictor for mortality, independent of external injury. The goals of this study were to identify reflexes for potential use in assessing crab condition, and then test their ability to predict mortality of *Chionoecetes bairdi* and *C. opilio* captured in Bering Sea trawls. Crabs were tested for reflex actions and injuries, and monitored for mortality in shipboard tanks. These experiments yielded excellent predictions of mortality based on reflex actions.

Materials and methods

Identification and scoring of individual reflexes

Laboratory studies were conducted at the Kodiak Fisheries Research Laboratory (National Marine Fisheries Service, Alaska Fisheries Science Center) during April 2007, to identify reflex actions of *Chionoecetes* spp. that could be reliably used in evaluating their likely survival. Thirty-two individuals of *C. bairdi* were collected by divers from Kodiak nearshore waters between February and April 2007. Males (n=24) ranged from 79 to 128 mm carapace width (CW). Females (n=8) ranged from 88 to 98 mm CW. The crabs were transported to the Kodiak Laboratory in buckets and placed in large fiberglass tanks (1.8 m diam., 1 m deep) where they were held with flowing seawater. Temperature ranged 1.5° to 4.6°C during the holding period. The crabs were fed twice each week with a diet of frozen chopped fish and squid. At the time of testing all of the crabs were in new shell condition, having molted in the past few months, and they were active and feeding. The crabs were marked with vinyl spaghetti tags tied loosely around the basiischium of the second or third walking leg. During the preliminary experiments seawater temperature was 5.0°C in the laboratory, and air temperature ranged 16° to 18.6°C.

From prior experience with various crab species, we expected that *C. bairdi* would demonstrate stereotypic responses to being lifted and to manipulation of their appendages. The goal was to identify simple reflex actions that could be evaluated rapidly in the tester's hand (out of water), during shipboard operations, with a high degree of reliability. After one day of manipulations we identified six reflex actions that appeared to be reliable (Table 1). These were tested on every individual crab on two consecutive days and were scored as strong, weak, or as no response.

Field experiment

A field experiment was conducted in June and July 2007 to evaluate the feasibility of using reflex actions as predictors of delayed mortality in *Chionoecetes* spp. Trawling operations for this study were conducted on the Bering Sea shelf east of St. Paul Island in the Pribilof Islands of Alaska (57°12′ to 57°25′N, 169°30′ to

Table 1

Reflexes identified as useful for assessing stress in *Chionoecetes* spp. The test was the manipulation required to elicit a stereotypic response. Characteristic strong and weak responses are described. When no motion was detected in response to repeated testing a "No response" score was recorded.

Reflex	Test	Strong response	Weak response
Leg flare	Lift crab by the carapace, dorsum up.	All legs spread wide and high, near horizontal orientation.	Legs droop below horizontal.
Leg retraction	While held as above, draw the forward-most walking legs in the anterior direction.	Legs respond with a strong retraction in the posterior direction.	Leg retraction is diminished. Low resistance to legs pulled forward.
Chela closure	Observe for motion or hold the chelae in the fingers.	Chelae open and close rapidly without manipulation. Manipulation results in immediate strong closure.	Chelae close slowly and weakly upon manipulation, or with a delayed response. Low resistance to manual opening of the chelae.
Eye retraction	Touch the eye stalk with a blunt probe, or lift the eye stalk from its retracted position.	Eye stalk retracts strongly in the lateral direction below the carapace hood.	Eye stalk retracts weakly or demonstrates low resistance to lifting.
Mouth closure	If closed, attempt to open (extend) the 3rd maxillipeds with a sharp dissecting probe. If open, draw the maxillipeds downward.	3rd maxillipeds retract quickly and strongly to cover the smaller mouth parts.	The maxillipeds droop open or move in an agitated manner, but do not close tightly.
Kick	With the crab in ventrum-up position, use a sharp dissecting probe to lift the abdominal flap away from the body.	Immediate, strong agitation of the legs and chelipeds. Males respond more strongly than females. Testing with the latter often requires greater extension of the entire abdominal flap.	Response is diminished or slow. Motion is observed in only the hind-most legs.

169°45′W) in depths ranging from 35 to 75 m. Crabs were collected from 22 locations where the bottom was relatively homogenous muddy sand. Temperature on the bottom and near surface ranged from –0.3° to 1.7°C and from 3.5° to 4.9°C, respectively.

An important objective of the trawling operation was to acquire crabs in various states of stress and injury for assessment and monitoring. Also, we wanted to test crabs that had experienced the suite of stressors typical of those produced during encounters with fishing gear used in the Bering Sea bottom-trawl fishery. Therefore, the crabs were collected in various locations around a commercial trawl by means of recapture nets (see Rose, 1999). The main trawl was a two-seam Alfredo bottom trawl (with headrope and footrope lengths of 36 and 54.6 m, respectively) similar to that used from many vessels in the Bering Sea. The center section of the footrope was composed of 46-cm diameter rounded cones separated by approximately 70-cm long sections of 20-cm diameter disks. The forward 14.2 m of the footrope on each wing of the trawl was made of 20-cm disks strung over a 19-mm long link chain. These sections were not directly attached to the netting panel above them, and thus formed so-called "flying wings." Extending forward from the trawl, 27.4-m bridles, made of bare cable, were attached to the upper wings and the same lengths of cable, covered with 9-cm diameter rubber disks, were attached to the lower wings. Ahead of these were 88 m of 4.8-cm diameter combination rope and 27.4 m of bare cable, leading to the trawl doors. The main trawl was towed with an open codend.

The recapture nets were small 2-seam trawls with longer headropes than footropes (14.3 m and 12.0 m, respectively). The long headrope maximized escape of fish, and the small diameter (5-cm) footropes were used to enhance crab capture. These nets were fished directly behind the main net sweeps, wings, or footrope. In some cases, two recapture nets were fished simultaneously at different locations. As a control for damage in the recapture nets, the nets were also fished ahead of the main trawl, capturing crabs with no previous damage. Tows were short (15 minutes) so that the stress or damage to crabs was created by the main trawl gear, and less by packing within the net or handling. However, evaluation of gear impact was not the primary goal of this cruise.

Once a recapture net was hauled on deck, the volume of the catch (normally comprising *Gadus macrocephalus*

Table 2

Composition of *Chionoecetes bairdi* (Tanner crab) and *C. opilio* (snow crab) populations tested and monitored in the field experiment. Values are means and ranges (in parentheses) for the nonrandom experimental population and do not represent the overall results of the fishing operations. Shell condition is a relative index of molt stage, ranging from molting or recently molted crabs with no hardening of the shell (0) to old and heavily encrusted shells (5). Reflex impairment index A is reported, representing the number of reflex actions that were entirely lost; this index can range from 0 to 6. Injury scores can range from 0 to 5, representing crabs with no visible exoskeletal damage to those with badly broken carapaces and limbs.

Species and gender	*n*	Carapace width (mm)	Shell condition	Reflex impairment	Injury scores	Mortality (%)
C. bairdi	250					29.2
Female	89	79 (58–97)	2.6 (2–4)	0.94 (0–6)	0.85 (0–5)	34.8
Male	161	98 (67–140)	2.7 (1–4)	0.73 (0–6)	0.66 (0–5)	26.1
C. opilio	399					24.3
Female	74	63 (52–81)	2.7 (2–4)	1.40 (0–6)	0.62 (0–5)	23.0
Male	325	83 (49–133)	2.6 (0–4)	1.42 (0–6)	0.72 (0–5)	24.6

[Pacific cod], *Atheresthes stomias* [arrowtooth flounder], and other unidentified flatfishes, seastars, and crabs) was estimated and *C. bairdi*, *C. opilio*, and *P. camtschaticus* were separated by species and gender into baskets. Air temperature during the crab handling process ranged 5° to 10°C. Sorting normally took <15 minutes and the sorting baskets were placed in fish totes with flowing seawater if the sorting and subsequent handling exceeded that time limit. The crabs were then tested individually for loss or weakness according to the six selected reflexes (loss=0, weak=1, strong=2) (Table 1), and notes were made on autotomy and obvious injuries such as broken legs, cracked carapace, or torn abdomen. Later, injuries were scaled from 0 to 5, where 0=no injuries, 1=newly autotomized legs, 2=broken legs, chelae, or mouthparts, 3=minor carapace or abdomen damage, 4=major carapace or abdomen damage, and 5=major damage to multiple parts (carapace, leg, and other parts). Crab gender, shell condition, and CW were recorded during the assessment period. Briefly, shell condition in *Chionoecetes* spp. was scored from 0 to 5, where 0 represented molting or recently molted crabs with no hardening of the shell whatsoever, crabs with shell condition 1 represented a soft flexible shell, condition 2 represented full hardness, and scores 3 to 5 showed increasing stages of discoloration and encrustation with shell age. Following assessment the crabs were either discarded overboard or tagged and held for monitoring mortality. Initially, all crabs were marked and held. However, it soon became apparent that a large proportion had relatively low reflex impairment. Thus, as the cruise progressed, emphasis was shifted to gear configurations producing greater damage to crabs, and we chose individuals with observable reflex impairment or injury for holding. As a result, the impairment, injury, and mortality rates reported in Table 2 do not represent the fishing conditions, only the crabs included in this analysis.

Crabs held for monitoring were marked with uniquely numbered vinyl spaghetti tags tied securely but loosely around the basi-ischium of the third leg, or fourth leg (if the third leg had been autotomized). Tagged crabs were immediately moved to one of 12 large fish totes (98×110×85 cm deep; ~900 liters) secured on the ship's trawl deck. Each tote was supplied with a constant flow of seawater (≥20 L/minute). Water temperature during 8–11 day holding periods ranged from 2.7° to 5.9°C, and oxygen (monitored morning and evening in every tote) never fell below 100% saturation. Mortality was assessed and dead crabs were removed each afternoon for the first five days of holding, then every other day until the end of the experiment. On the last day of holding all of the remaining crabs were re-assessed for reflex scores.

Reflex impairment indices and statistical procedures

Scores for reflex actions were combined into impairment indices and used in the analysis. Composites provided robust indices of overall condition for the animal and provided the advantage of reducing the weight of any one reflex (Davis, 2007). Analyses described below were conducted with two different impairment indices. Reflex impairment index A was calculated as the total number of zero scores for individual reflex actions (i.e., lost reflexes), and reflex impairment index B was the total number of scores that were either 0 or 1 (i.e., lost or weak reflexes). Both index scores ranged from 0 to 6.

Before analysis of the relationships between reflex impairment, injury, and mortality, we wanted to be certain that the holding period was sufficiently long to provide an accurate estimate for mortality. The time course for mortality was evaluated as a simple cumulative curve of deaths for *C. bairdi* and *C. opilio* shown as a function of time in days. We used simple linear regression to explore relationships among mortality-related variables, injury scores, and reflex impairment.

Logistic regression was used to model mortality, by using potential predictors and mediators including reflex impairment, injury score, gender, size, and shell condition. Models were fitted by the method of maximum likelihood for binary data (i.e., dead or alive) with the regression module of Systat 12 (SYSTAT Software, Inc., San Jose, CA) (Peduzzi et al., 1980). A backward stepwise approach was used to determine the most parsimonious model for mortality, with an alpha value of 0.15 to remove a variable from the full model. This model for mortality was described by

$$Log_e\left(p/(1-p)\right)=\alpha+\beta' x,$$

Where p = proportion of y = 1;
y = 1 if crab was determined to be dead, and 0 if alive;
α = intercept;
β' = model coefficients; and
x = the model matrix of explanatory variables.

The maximum likelihood estimates of mortality (ρ) were calculated as

$$\rho = e^{(\alpha+\beta' x)}/1+e^{(\alpha+\beta' x)}.$$

Initially, the data for each species were split randomly into equal halves, one representing a learning set and the other a test set. The most parsimonious logistic model was developed with the learning set and validated with the test set. After cross-validation, a final model was fitted to the entire data set. Finally, the logistic model for each species was used to develop a surface plot showing the probability of mortality based upon fixed values for the key observations of crab condition.

Results

Laboratory results

The six reflex actions identified for testing with *C. bairdi* (Table 1) were highly reliable and consistent among individuals. Strong responses in leg flare, leg retraction, eye retraction, and mouth close were observed with every individual every time they were tested. Weak chela closure was observed just once, and the kick response to lifting the abdominal flap was weak in eight instances (seven females) and missing entirely in one test (also female). The weak responses generally occurred in the same individuals in duplicate trials.

Field evaluation of reflex impairment

Crabs collected in the recapture nets demonstrated a wide range of size, shell condition, reflex impairment, and injury level (Table 2), and reflex actions were lost at different frequencies. When just one reflex was absent, kick and leg retraction were the reflexes lost most frequently (Table 3). Among the crabs where one to five reflexes were lost, leg retraction, kick, and leg flare were most often lost, and eye retraction and mouth closure were absent least frequently.

Table 3

Percentages of reflex actions lost in *Chionoecetes bairdi* (Tanner crab) and *C. opilio* (snow crab). When just one reflex was absent in a crab. it was considered the 1st reflex lost. The right column represents the percentage of specific reflexes that were lost among all of the crabs where between one and five reflexes were lost.

Reflex	1st reflex lost	% of total losses
C. bairdi	(*n*=18)	(*n*=147)
Kick	44.4	26.5
Leg retraction	44.4	32.0
Leg flare	5.6	19.0
Chelae closure	5.6	14.3
Eye retraction	0	4.1
Mouth closure	0	4.1
C. opilio	(*n*=35)	(*n*=210)
Kick	51.4	23.3
Leg retraction	31.4	30.0
Leg flare	14.3	24.8
Chelae closure	0	13.8
Eye retraction	2.9	4.8
Mouth closure	0	3.3

Mortality increased with increasing reflex impairment, regardless of the specific index used (Fig. 1). However, mortality at a given impairment value was consistently higher with index A than with index B, and the differences were greatest between index values of 1 and 5. Hence, we judged index A, from the count of completely lost reflexes (scores=0), to provide a more sensitive predictor of mortality than the index based on reflexes scored as lost or weak. A lost reflex was more definitive and less ambiguous than a weak reflex; therefore, reflex impairment index A was used for all subsequent analyses.

Appropriateness of experimental holding

Adequacy of the field experiment depended upon two important experimental requirements. First, holding needed to be sufficiently long to allow detection of delayed mortality in crabs. Second, the holding methods themselves did not induce mortality.

Most of the mortality in the two species occurred within the first few days of collection (Fig. 2). For both species, all the crabs with reflex impairment equal to 6 died within the first hour after reflex assessment. Among the balance of the individuals with less impairment, 80% of the mortality occurred within 3 days for *C. bairdi* and 2 days for *C. opilio*. For both species, >95% died by day 7. Not surprisingly, time to mortality decreased with increasing reflex impairment (Fig. 3). Some crabs with low reflex impairment died in holding, but these crabs tended to have substantial physical injuries. Time to mortality averaged ~3 days for these individuals, and a high variability in time to mortal-

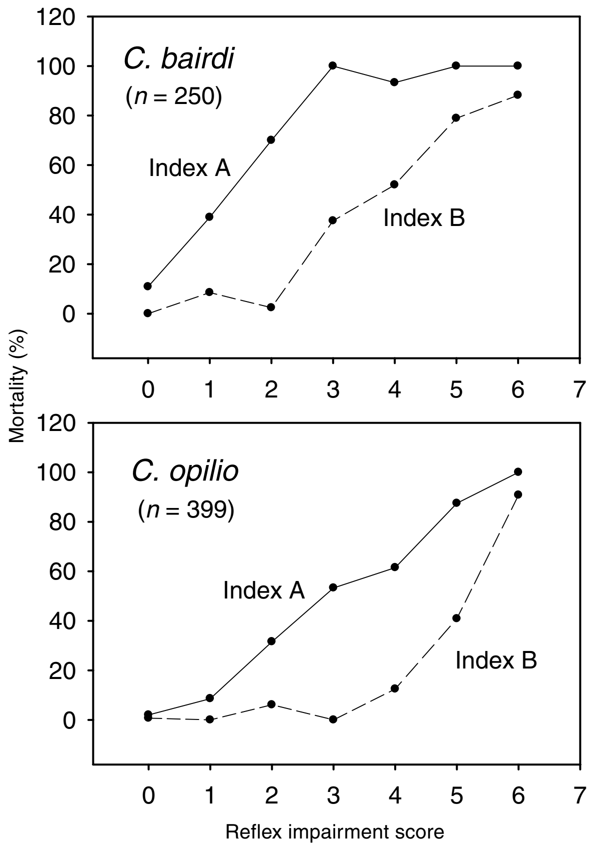

Figure 1

Percent mortality of *Chionoecetes bairdi* (Tanner crab) and *C. opilio* (snow crab) shown as a function of reflex impairment indices A and B. Index A was calculated as the sum of completely lost reflexes (score=0) and index B was calculated as the sum of reflexes either lost or weak (scores=0 or 1).

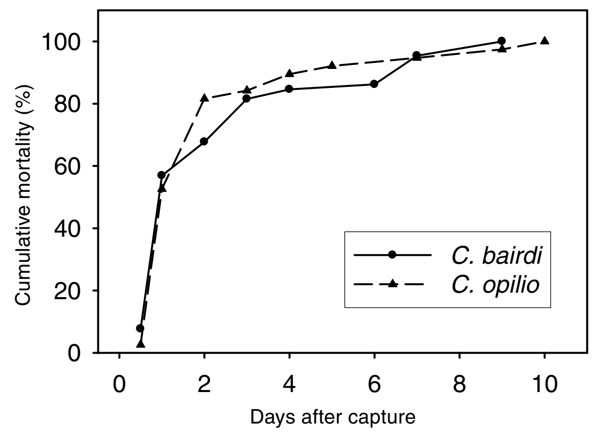

Figure 2

Percent cumulative mortality of *Chionoecetes bairdi* (Tanner crab) and *C. opilio* (snow crab) over time during holding at sea. Total numbers of *C. bairdi* and *C. opilio* dying over the course of the experiment were 73 and 96, respectively.

ity was observed for *C. opilio*. Crabs with high reflex impairment (4 to 6) usually died within 1 to 2 days and there was little variation in this period of mortality. From these results, we concluded that the holding period for the experiment (11 days) was sufficiently long to test the relationship between reflex impairment and mortality.

Re-assessment of reflex impairment in surviving crabs at the end of the experiment revealed that condition of the vast majority did not deteriorate during the holding period at sea. Only two of the surviving *C. bairdi* (n=176) had increased reflex impairment. One of these had multiple new leg autotomies and the other had multiple weak responses upon capture. Improvement in the reflex impairment index by one or two points occurred in 7.4% of the crabs, whereas the balance showed no changes. Only 8.5% of the survivors had reflex impairments >0 by the end of the study. Among the 295 *C. opilio* survivors, none had higher or lower reflex impairment, although most of the survivors (98%) had no impairment initially. These results indicate that the deck tanks provided a suitable means of holding to assess delayed mortality in the subject species.

Mortality and its relationship to reflex impairment

Logistic regression analysis revealed that mortality in *C. bairdi* was associated primarily with reflex impairment index and injury score (Table 4). Despite a wide range of crab size and shell condition (Table 2), neither these variables nor crab gender was a significant variable in the regression model. In the most parsimonious model, containing a constant, reflex impairment and injury score correctly predicted 82.7% of the mortality and survival (Table 4), whereas the full model (with all variables) predicted 82.8% correctly. Cross-validation showed that the model was robust; i.e., the random learning set produced a model that correctly predicted 86.7% of the test set for *C. bairdi*. When the injury score was removed from the regression model, 79.5% of the observed outcomes were predicted correctly, demonstrating the value of the assessed reflexes. A similar analysis for *C. opilio* revealed reflex impairment to be the only significant predictor of mortality (Table 5). The most parsimonious model, containing a constant and the reflex impairment index, correctly predicted 91.0% of the mortality and survival—a percentage almost identical to that of the full model (82.8%). As with *C. bairdi*, cross-validation for *C. opilio* with a learning set resulted in 94.0% correct predictions for the test set. Consequently, models for both species were robust for the field study.

Surface plots for probability of mortality with the logistic models for each species (Fig. 4) showed the strong relationships between reflex impairment and mortality. For *C. bairdi*, mortality increased rapidly

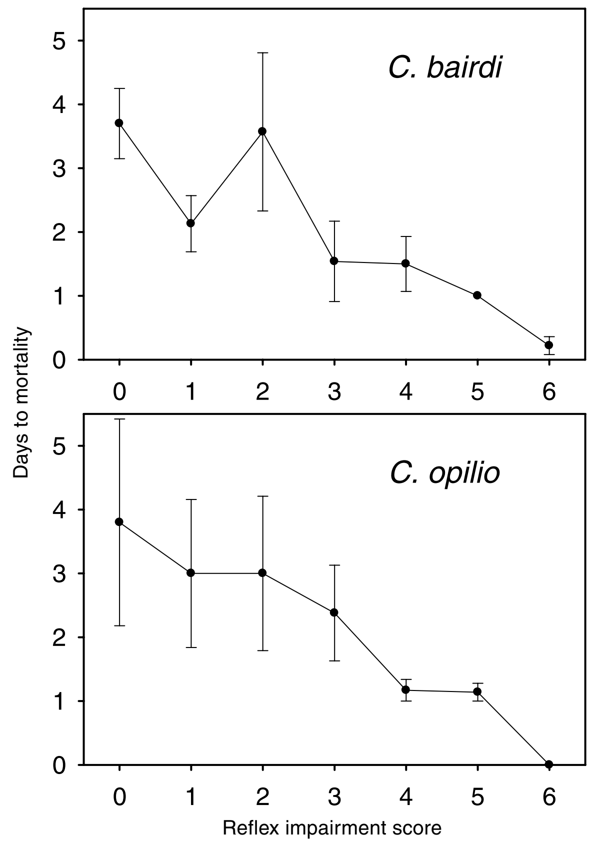

Figure 3

Time to mortality (days) observed for *Chionoecetes bairdi* (Tanner crab) and *C. opilio* (snow crab) shown as a function of reflex impairment (index A). Values are mean, ±standard error (in parentheses). Index A was calculated as the sum of completely lost reflexes (score=0) and index B was calculated as the sum of reflexes either lost or weak (scores=0 or 1).

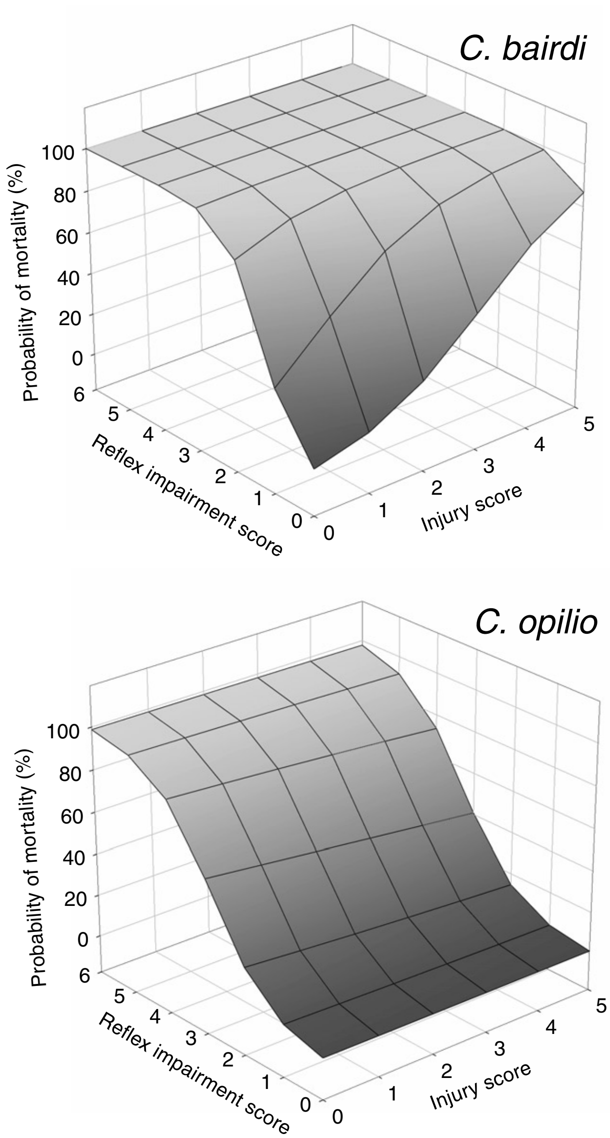

Figure 4

Surface plots, resulting from logistic regression, showing the probabilities of mortality for *Chionoecetes bairdi* (Tanner crab) and *C. opilio* (snow crab) with varied levels of reflex impairment (index A) and injury. Index A was calculated as the sum of completely lost reflexes (score=0) and index B was calculated as the sum of reflexes either lost or weak (scores=0 or 1).

with increasing impairment, reaching an asymptote at an index equal to 3. Mortality also increased with injury score, but the effect was smaller and more gradual. Probability of mortality in *C. opilio* was determined primarily by reflex impairment (with no obvious or significant effect of injury score). Reflex impairment and injury scores were correlated in both *C. bairdi* (R=0.514, $F_{1,248}$=89.024, P<0.001) and *C. opilio* (R=0.725, $F_{1,397}$=440.504, P<0.001).

The number of crabs representing each reflex impairment index (0 to 6) was not uniform, and we wanted to be certain that these unequal numbers did not bias the resulting relationship between mortality and reflex impairment. For example, among the 399 *C. opilio* tested, reflex impairments equal to 0, 1, and 6 were over-represented. Therefore, we randomly drew up to 20 individuals for each impairment level, reducing the number of crabs entering the model to 115. The reduced database resulted in a relationship between mortality and reflex impairment that was identical to that incorporating the larger data set. A similar analysis for *C. bairdi* produced a similar result, showing that the uneven distribution of data did not bias the experimental outcome and that the logistic models shown in Figure 4 were robust.

Discussion

Behavior of animals reflects a host of internal and external conditions, and, in the context of fishing-related

Table 4

Results of logistic modeling for mortality in *Chionoecetes bairdi* (Tanner crab). A backward stepwise approach was used to determine the most parsimonious model for mortality, and an alpha value of 0.15 was required to remove a variable from the full model.

Parameter	Estimate	t-ratio	*P*-value
Full model			
constant	–2.346	–1.226	0.220
gender	–0.114	–0.383	0.701
shell condition	–0.274	–0.805	0.421
size	0.005	0.244	0.807
reflex impairment	1.316	5.364	<0.001
injury score	1.029	4.743	<0.001
Most parsimonious model			
Parameter			
constant	–2.710	–8.957	<0.001
reflex impairment	1.353	5.731	<0.001
injury score	1.044	4.767	<0.001

Prediction matrix for the most parsimonious model	No. dead predicted	No. alive predicted	Actual total
Dead	51.4	21.6	73
Alive	21.6	155.4	177
Total predicted	73	177	250
Correct (%)	70.4	87.8	
False (%)	29.6	12.2	
Total correct (%)			82.7

Table 5

Results of logistic modeling for mortality in *Chionoecetes opilio* (snow crab). A backward stepwise approach was used to determine the most parsimonious model for mortality, and an alpha value of 0.15 was required to remove a variable from the full model.

Parameter	Estimate	t-ratio	*P*-value
Full model			
constant	–2.716	–1.933	0.053
gender	0.333	0.815	0.415
shell condition	–0.089	–0.292	0.770
size	–0.016	–1.128	0.259
reflex impairment	1.416	8.240	<0.001
injury score	–0.102	–0.384	0.701
Most parsimonious model			
Parameter			
constant	–3.913	–10.529	<0.001
reflex impairment	1.349	9.622	<0.001

Prediction matrix for the most parsimonious model	No. dead predicted	No. alive predicted	Actual total
Dead	78	18	96
Alive	18	285	303
Total predicted	96	303	399
Correct (%)	81.2	94.1	
False (%)	18.8	5.9	
Total correct (%)			91.0

injury, provides a neurological integration of both physiological stress and physical wounding (Davis, 2002). In fact, a variety of behaviors such as feeding (and growth) (Carls and O'Clair, 1990, 1995; Zhou and Shirley, 1995), molting (O'Brien et al., 1986; Carls and O'Clair, 1990), and righting behavior (Carls and O'Clair, 1990, 1995; Zhou and Shirley 1995; Warrenchuk and Shirley, 2002) are useful for evaluating crab condition. However, all these complex behaviors require some form of holding in seawater tanks for observation. For example, preliminary experiments at the Kodiak Fisheries Research Laboratory confirmed that lack of righting behavior in *C. bairdi* can be a useful predictor of mortality caused by both internal and externally visible injuries, but the evaluation can take >5 minutes, the behavior is highly variable, and yields only a binary response (i.e., yes or no). The vitality index described by Stevens (1990) also has just two possible outcomes—alive or moribund—for live crabs. In contrast, Davis and Ottmar (2006) and Davis (2007) have shown that testing a suite of reflex actions yields a graduated response variable with excellent potential for mortality prediction in fishes. They called the resulting relationship a reflex action mortality predictor (RAMP). Our results show that a similar approach is possible for *Chionoecetes* spp.

We identified six reflexes in *Chionoecetes* spp. that are stereotypic, repeatable, and easy to assess. These reflexes, associated with simple movements of the primary limbs, mouth parts, and eye stalks, represent the most fundamental and involuntary responses of the crabs, and they can be rapidly assessed in hand (i.e., without holding a crab in water). The most sensitive indicators of trawl-related stresses observed in this study were kick and leg retraction. These reflexes were generally lost first, followed by leg flare and chela closure, and reflexes associated with the eyes and mouth were least sensitive. The latter two reflexes probably require the lowest energy expenditures and movements of the mouth parts play an important role in ventilating the gills. Mouth movements were maintained in crabs near death and loss of motion could be used as the final determination of death (Stevens, 1990; this study). The order of reflex loss might shift somewhat under different fishing conditions or specific types of injury; however, a reflex impairment index, calculated by summing reflex actions without weighting individual reflexes (as in this study), has the advantage of representing condition over a wide range of stressor types in fishes (Davis and Ottmar, 2006; Davis, 2007). The same representation over a wide range of stressors is likely for crabs.

The most important finding of this study was that mortality in *Chionoecetes* spp. was closely correlated with reflex impairment. Although others have evaluated injuries to the exoskeleton in an attempt to predict mortality (Stevens, 1990), a thorough assessment of exoskeletal injuries is time consuming and minor and potentially fatal injuries, such as finely cracked carapaces, are easily missed. On the other hand, internal injuries and bleeding that can occur without external injury can contribute significantly to delayed mortality (Grant, 2003). Rose (1999) reported exoskeletal injury rates for red king crabs captured or struck with different types of trawl footropes, but it is now clear that these injury rates may or may not correlate well with mortality. Injury and reflex impairment were correlated in the present study, but our more general assessment of crab condition acquired through testing reflex actions provided a better predictor of mortality and an obvious improvement over tedious and subjective evaluations of shell damage. As observed with fishes (Davis, 2005, 2007), reflex impairment appears to integrate the effects of different kinds of stress and injury that can occur in gear encounters and in routine handling and discard practices.

Another key finding of this study was that the reflex impairment index provides a relatively universal indicator of condition and likely mortality for *Chionoecetes* spp. For example, shell condition can affect mortality rates in crabs handled in fishery operations and returned to sea (Kruse et al., 1994). However, our logistic analyses showed that reflex impairment indices provided the best predictors of mortality in both *C. bairdi* and *C. opilio*, regardless of shell condition and crab gender and size. Similarly, reflex impairment indices have provided excellent predictions of mortality for several different fish species over a wide range of sizes, and a good integration of cumulative stress (Davis and Ottmar, 2006; Davis, 2007).

Reflex action mortality predictors have also proven to be robust over a wide range of different stressor types, including tow time in a trawl, air exposure, and temperature shock, at least for fishes. The present study emerged from an interest in evaluating impacts of trawling operations on crab mortality rates and we believe that the response curves provided for *C. bairdi* and *C. opilio* should be robust for the kinds of injuries sustained under typical trawl operations in Alaska. The results, however, should be regarded primarily as a first proof of principle for crab species and the best possible RAMP models will depend upon additional fishing experiments conducted over a broader range of stressor types and fishing conditions. For example, other variables, such as freezing temperatures and windchill stress (Carls and O'Clair, 1995; Warrenchuk and Shirley, 2002) encountered in pot fishing warrant experimental investigation and may necessitate modifications to the mortality prediction models.

Once a RAMP curve is well developed for a species it should be widely applicable in fishing experiments designed to improve fishing practices and reduce discard mortality. Instead of the traditional approach, where fishing and handling variables are evaluated directly through multiday holding, either in deck boxes (Stevens, 1990) or in sea cages (Grant, 2003), crabs can be evaluated immediately in the field, without holding, and probabilities of mortality can be estimated with the RAMP model. For example, we have been interested in mortality of crabs that encounter trawls, but are not captured. In the future, we should be able to use recapture nets in front of and behind different trawl components (see

Rose, 1999), especially footropes, bridles, and sweeps, to quickly evaluate mortality for *Chionoecetes* spp. with the use of RAMP estimators. Neither assessments of exoskeletal injuries nor holding in cages or deck boxes will be required. Similarly, the sublethal and lethal effects of fishing conditions such as bottom type, water and air temperature, net packing, and time in air could be evaluated with a RAMP approach. Effects of soak times for pots and handling procedures could be assessed with the same tool. Also, with an increasing interest in the live market for crabs, the RAMP approach may be useful in perfecting shipping and holding procedures for the best possible live products. The largest direct benefit of RAMP approach will be to increase the scope and replication of experiments on gear and handling. More broadly, discard-related mortality is not constant, and we believe that this new approach will facilitate substantial improvements in fishery models that incorporate mortality for crabs, lobsters, and other crustaceans that are routinely discarded at sea.

Acknowledgments

This project was funded in part by the National Oceanic and Atmospheric Administration Bycatch Reduction Program and the North Pacific Research Board. D. King and J. Smart prepared the recapture nets, S. McEntire assisted with electronics, S. McDermott loaned the deck boxes for holding crabs, and S. Walters and K.-H. Lee participated in the field study. We are grateful to Captain R. Haddon and crew of the FV *Pacific Explorer* for assistance with tank set-ups and handling our unconventional fishing gear. T. Hurst provided suggestions on statistical approach and anonymous reviewers helped to improve the manuscript.

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