Abstract.—King crabs *Paralithodes camtschaticus* and Tanner crabs *Chionoecetes bairdi* captured incidentally by Bering Sea trawlers were examined for immediate mortality, vitality, and injuries resulting from trawl capture. A number were held aboard ship for 2 days in seawater to determine delayed mortality. Overall survival, including immediate and delayed effects, was 21% (±2.0%) for king crabs and 22% (±3.6%) for Tanner crabs. Immediate mortality of king crabs decreased significantly with shell age, and increased significantly with time in captivity prior to assessment, from 0% at 3 hours to 100% at 17 hours. Vitality, an index of spontaneous activity level, was a better predictor of delayed mortality than was the presence/absence of injuries. The effect of leg and body injuries on mortality of king crabs was similar, but injuries to leg segments proximal to the plane of autotomy resulted in higher mortality than injuries distal to the autotomy plane, or autotomization alone.

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Survival of King and Tanner Crabs Captured by Commercial Sole Trawls

Bradley G. Stevens
Kodiak Laboratory, Alaska Fisheries Science Center
National Marine Fisheries Service, NOAA, P.O. Box 1638, Kodiak, Alaska 99615

Capture and subsequent mortality of nontarget (bycatch) species is a major problem facing managers of multispecies fisheries. In the U.S. eastern Bering Sea (EBS), joint-venture (JV) trawl fisheries targeting on yellowfin sole *Limanda aspera*, rock sole *Lepidopsetta bilineata*, and Pacific cod *Gadus macrocephalus*, routinely catch red king crabs *Paralithodes camtschaticus* and Tanner crabs *Chionoecetes bairdi* and *C. opilio*. In 1988, 88000 red king crabs, 751000 *C. bairdi*, and 2.4 million *C. opilio* were captured in 1.30 million metric tons (t) of groundfish by JV fishing vessels, representing catch rates of 0.07, 0.58, and 1.84 crabs/t, respectively (Berger and Weikart 1989). Additional quantities of these crab species were also captured by domestic fishermen, but their numbers are unknown due to the absence of an effective domestic fishery observer program. All three species of crab are designated as 'Prohibited species' by the North Pacific Fishery Management Council (NPFMC), and must be returned to sea. Nonetheless, mortality of incidentally caught crab is considered to be 100%, and represents losses from the directed crab fisheries.

Due to concerns expressed by crab fishermen about the effects of bycatch on crab populations, a portion of the EBS was closed to trawling by the NPFMC in 1986 to protect king crabs, and has remained closed to date. In addition, maximum catch rates (crabs/t) and caps on total crab catch have been defined for particular regions of the EBS. Somerton and June (1984) attempted to quantify the relative costs to the crab fishery and benefits to the trawl fishery from conducting trawl fisheries on crab grounds, in order to designate those areas with negative relative costs as a king crab conservation zone, but their recommendations were never implemented per se.

The establishment of caps and maximum allowable catch rates was predicated on the assumption that all crabs captured incidentally to trawl fisheries subsequently die. However, this is not necessarily the case. In August of 1988, the opportunity arose to conduct an experiment to determine the survival rate of crab caught incidentally by the JV trawl fishery. This was conducted in conjunction with a study to determine the effectiveness of experimental nets designed to reduce the bycatch of crab. The goals of the study were to determine immediate and delayed survival and mortality of crabs, and the effects on survival of injuries, size and shell age of crabs, processing time, and gear (trawl) type.

Materials and methods

Definitions

The term survival (S), as used in this report, means the proportion of a given group of crabs which was alive at a specified time. Mortality (M) is the complement of this value, i.e., 1 – S. In this investigation, survival was treated as a two-step process; immediate survival (ISURV) or mortality (IMORT) is the proportion determined to be alive or dead, respectively, when the crabs were first examined and measured. Delayed survival (DSURV) or mortality (DMORT) is that portion alive or dead after crabs were held in seawater for a specified time period.

Sampling technique

An experiment was conducted during the period 12 August—12 September 1987 to compare catch rates between standard Bering Sea joint venture commercial sole trawls and two experimental nets designed to reduce the bycatch of crabs (Highliners Association 1988). Although the results of that experiment are not discussed in this report, the experimental design will be briefly described in order to facilitate understanding of the survival experiment. During the study, five Bering Sea combination trawlers made 307 tows within an area of the EBS between lat. 57° and 58°N, and between long. 162° and 163°W. Tows ranged from 1 to 6.4 hours in length and averaged 20 metric tons (t) of fish. Target species were yellowfin sole *Limanda aspera*, rock sole *Lepidopsetta bilineata*, and Pacific cod *Gadus macrocephalus*. One vessel fished continuously with a previously used 'Standard' trawl (STD). The four other vessels rotated four trawls between them including two new and unused standard trawls, referred to as 'Control 1' (C1) and 'Control 2' (C2), and two experimental trawls. One of the experimental trawls, referred to as the 'Panel' (PAN) trawl, had the front portion of the bottom panel removed and replaced with longitudinal lines, such that crabs could fall out the bottom of the net after passing over the footrope. The second experimental trawl, referred to as the 'Chute' (CHU) trawl, had a webbed funnel-shaped chute sewn into the lower half of the net at the junction between the belly and intermediate section, such that anything entering the mouth of the chute would exit the bottom of the net. During the experiment, codends from each trawl were delivered to the USSR MV *Sulak* at 2–3 hour intervals, where they were sampled by biologists before processing.

Once onboard the *Sulak*, codends were dumped, and all crabs were recovered by sorting through the entire catch. The first 21 tows were dumped on deck and crabs sorted there. The remainder of the tows were dumped directly into storage bunkers, and crabs were recovered from the processing line conveyor in the factory, as the fish were processed. All crabs were sorted by species (and usually by sex), placed into plastic baskets (~25 kg capacity), and weighed. Because of logistic constraints, higher priority was assigned to collecting data on king crabs than on Tanner crabs. Total numbers were determined either by direct counting, or by counting and weighing a subsample. When subsampling occurred, each crab was assigned a sampling factor equal to the proportion of the total number of crabs in the tow represented by the subsample. Crabs were then treated in one of four ways:

(A) Measured crabs Up to 150–200 crabs of each species from each haul were measured to the nearest 1.0 mm with steel vernier calipers. Subsampling occurred when >200 of either species were captured. King crabs were measured from the rear of the right eyesocket to the midpoint of the rear margin of the carapace (carapace length, CL). Tanner crabs were measured across the widest portion of the carapace, including spines (carapace width, CW). Shell conditions were coded as 1 = molting, or recently molted with a soft or flexible shell; 2 = hard shelled but molted within recent year, without epifauna or scratches; 3 = oldshell or skipmolt, with scratches, epifauna, scars, or damaged dactyls.

(B) Vitality coding For most hauls, all measured crabs were also given a vitality code on a 3-point scale: (1) alive and active, i.e., exhibiting spontaneous vigorous movement of appendages and attempting to escape or pinch the examiner; (2) moribund (alive but inactive), i.e., exhibiting only slow weak movements, or only in response to prodding; and (3) dead. In practice, death was not easy to determine, as some crabs which initially appeared dead would exhibit spontaneous movements after examination. After the first few tows, a criterion was developed which consisted of (a) looking for spontaneous movement of appendages, (b) lacking that, attempting to stimulate movement by moving and bending appendages, followed by (c) flicking the mouthparts with a finger three times at 5–10 second intervals. The minimum requirement for a vitality code of 2 was any spontaneous movement of the antennules or any other appendage. These criteria were tested by placing 30 crabs which were classified as dead into the live tanks; none recovered. Presence or absence of injuries was not a criterion used in this coding procedure.

(C) Injury assessment Approximately 30–40 king crabs per tow (usually the first basket examined of each sex) and occasional Tanner crab were examined for injuries. Since there was considerable shuffling and repositioning of crabs and baskets during the weighing and subsampling process, this was assumed to be a random sample, and represents a subset of the crabs examined for vitality in step B above. Examination entailed a visual scan of the carapace, sternum, abdomen, and each leg in turn. Bodily injuries were recorded as present or absent. Leg injuries were categorized as being distal to the autotomy or breakage plane, proximal to the breakage plane, or recent autotomy, distinguished by the presence of a clear membrane with no discoloration or scarring. The number of legs with each of these three types of injuries was recorded.

(D) Survival or delayed mortality A subset of the injury-assessed crabs (Step C) was placed into one of four tanks of flowing seawater, ~1.0 × 1.0 × 0.7 m, and held for 48 hours, after which they were reexamined for delayed mortality, using the same procedures outlined above for vitality. The subset usually consisted of all crabs coded for injures from one haul per day, although towards the end of the experiment several hauls per day were treated in this manner. Crabs which were determined to be dead before placement into the tanks were retained for at least 6 hours for confirmation before removal.

Crab processing time was recorded for each tow as the interval between the arrival of the codend on deck and the time the crabs were examined and measured. Although examination usually required anywhere from 0.5 to 1.5 hours for an entire sample, the midpoint of that period was used as the mean endpoint of processing time for all crabs in a haul. Towing time, i.e., the difference between the time the net was determined to be on bottom and the time haulback started, was obtained from each catcher vessel and divided by 2, in order to approximate the average time each crab spent in the net before delivery to the *Sulak*. Total capturing and processing time (CAPTIME) was calculated as the sum of (towing time)/2 and processing time.

Total weight of the catch in each haul was estimated by measuring the height and width of the codend at several intervals along its length, and calculating the volume based on the shape of an oblate cylinder, with density determined by weighing a known volume of fish.

Data analysis

In order to improve the precision of the survival estimates, overall survival was calculated for each species in a stratified manner (Cochran 1963). Vitality codes were used as strata because they provided additional information on the probability of survival, i.e., crabs coded as alive and active were deemed more likely to survive than crabs coded as moribund. For immediate survival estimates only, each crab was weighted by the sampling factor for the tow from which it originated. Estimates of delayed mortality were not weighted, because subsampling was accounted for at the level of immediate mortality. The formulae used were:

$$S_{st} = 1/N \sum N_v p_v \quad (1)$$

and

$$V(S_{st}) = 1/N^2 \sum N_v(N_v - n_v)p_v q_v/(n_v - 1) \quad (2)$$

where S_{st} = stratified estimate of population survival rate,
$V(S_{st})$ = variance of stratified estimate,
N_v = number of crabs in stratum (vitality group) v,
n_v = number sampled from stratum v (placed in live tanks),
p_v = proportion of subsample surviving in live tanks,
$q_v = 1 - p_v$,
N = weighted total number of crabs given vitality codes.

The effect of CAPTIME on immediate mortality was determined by fitting the data to a logistic curve. Crabs were grouped into hourly intervals of CAPTIME (as described above), and mortality data (weighted by sampling factors) for each interval were fitted using an iterative procedure (FSAS FISHPARM, Saila et al. 1988). The equation fitted was:

$$M = 1/\{1 + \exp(-r[X - X_{50}])\} \quad (3)$$

where M is expected mortality and $0 \leq M \leq 1$, X is the value of the predictor variable (CAPTIME) in hours, and r and X_{50} are parameters of the equation, the latter representing the time required for 50% mortality to occur. Both king and Tanner crabs were treated separately. Delayed and overall survival were not fitted because there were too few observations. The effect of total catch weight on immediate survival was also determined in the same manner, with crab data grouped by catch weight intervals of 1.0 t.

To determine the effect of size, crabs were grouped by 15-mm intervals of CL (king crab) or CW (Tanner crab). For king crabs, immediate, delayed, and overall mortality were calculated for each size group. Only immediate mortality was calculated for each size group of Tanner crabs, due to limited data. Immediate mortality was also determined for each gear type, by species.

Procedures used by National Marine Fisheries Service (NMFS) observers aboard fishing vessels to code crab vitality differ from those used in this study. In this study, vitality codes were based on activity level of crabs regardless of injuries, and injuries were coded separately, whereas the NMFS observer method is to assign a vitality code of 1 for crabs which are active and uninjured, and a vitality code of 2 for crabs which are either inactive or injured. Contingency table and loglinear analysis was performed in order to assess the difference between these two methods and determine which provided the best estimate of delayed mortality, and to determine the relative contribution of vitality and injuries to subsequent delayed mortality. Three sets of 2 x 2 contingency tables were analyzed using the X^2 statistic, which is approximately distributed as the chi-squared distribution, and which is equivalent to the G-statistic for 2 x 2 contingency tables (Sokal and Rohlf 1981). Only two-way interactions can be identified with this procedure, so factors tested were vitality vs. injuries, vitality vs. mortality, and injuries vs. mortality. The null hypothesis tested was that effects of both factors were independent of each other, i.e., that no interactions occurred.

Loglinear analysis was accomplished to determine the odds of mortality associated with vitality level and injury presence. The SPSS LOGLINEAR (SPSS Inc. 1986) procedure was used to fit a logit model, in which one dichotomous factor—delayed mortality (DMORT)—was designated as a dependent variable, and the remaining factors—vitality (VIT) and injuries (INJ)—were the independent variables. Only live crabs were used, i.e., those with vitality codes of 1 or 2; injury codes were 1 (uninjured) or 2 (injured), and DMORT was coded as 1 (survived) or 2 (died). The data fit by the model were the log-transformed survival odds (ratio of survivors to mortalities), often referred to as logits, in each category of the independent variables (vitality and injuries):

$$\text{Logits} = \ln(\text{ODDS}) = \ln(f_s/f_m) \quad (4)$$

where f_s and f_m are the observed frequencies of survivors and mortalities, respectively. The logit model used for fitting entails expressing the logits as a linear model of several parameters:

$$\ln(f_s/f_m) = 2(l_D + l_{D*V} + l_{D*I}) \quad (5)$$

where f_s, f_m = observed number of survivors or mortalities,
l_D = parameter estimate for DMORT (mean odds of mortality),
l_{D*V} = parameter for interaction of DMORT and vitality,
l_{D*I} = parameter for interaction of DMORT and injuries.

The proportion of crabs in any cell of the model which survive is related to the survival odds by the formula:

$$S = (1 + \text{ODDS}^{-1})^{-1} \quad (6)$$

This model assumes that a mean level of mortality would occur regardless of other factors, and that each confounding factor increases mortality in a logarithmic fashion, or that the overall odds of survival are the sum of the logs of the parameter estimates for each contributing factor. In this model, there are two alternative outcomes for each category, which have equal and opposite parameter values which must sum to 0. For instance, parameter 1 represents the alternatives of survival vs. mortality; parameter 2 represents the positive contribution of a 'good' vitality code of 1 vs. the negative influence of a 'poor' vitality code of 2; parameter 3 is similar to parameter 2 with regard to the influence of the presence vs. absence of injuries. Since the model represents the log of a ratio, the effect attributable to any single factor is calculated as the difference between parameter estimates for alternative outcomes, e.g., the total effect of DMORT is $l_D - (-l_D)$, or $2(l_D)$. Thus the entire equation is multiplied by a factor of 2.

Table 1

Number of crabs sampled during survival study. Each category below "Measured" is a subset of the one above it.

Disposition	King crab	Tanner crab
Measured	18804	31318
Vitality coded	6113	4645
Injuries coded	2835	518
Survival coded	617	74

Each cell of the contingency table was coded as 1 or 2 for each factor. Crabs which were active, uninjured, and survived, for instance, were coded as 1,1,1. Similarly, crabs which were inactive, injured, and died were coded 2,2,2. The parameter value for the effect of vitality on mortality (l_{D*V} in the above model) was calculated for cases with equal codes for DMORT and VIT (i.e., both equal to 1 or both equal to 2); the parameter estimate for cases with unequal codes was equal but opposite in sign. Individual parameters were converted to odds by calculating the antilog. Odds for any combination of categories is equivalent to the product of antilogs of parameters (or the sum of all parameters times 2) for all factors in the model.

The interaction of immediate mortality (IMORT) with body injuries (BODY) and leg injuries (LEGS) was investigated in an identical manner. Values of the variables BODY and LEGS were set to 1 if no injury was present, or 2 if an injury was present.

Contingency table analysis using the X^2 statistic was performed to test the null hypothesis that immediate mortality was independent of three types of leg injury, defined as autotomization, injuries distal to the autotomy or breakage plane, and injuries proximal to the breakage plane. The X^2 statistic was also used to test the independence of immediate and delayed mortality from shell condition, and the number of legs with injuries.

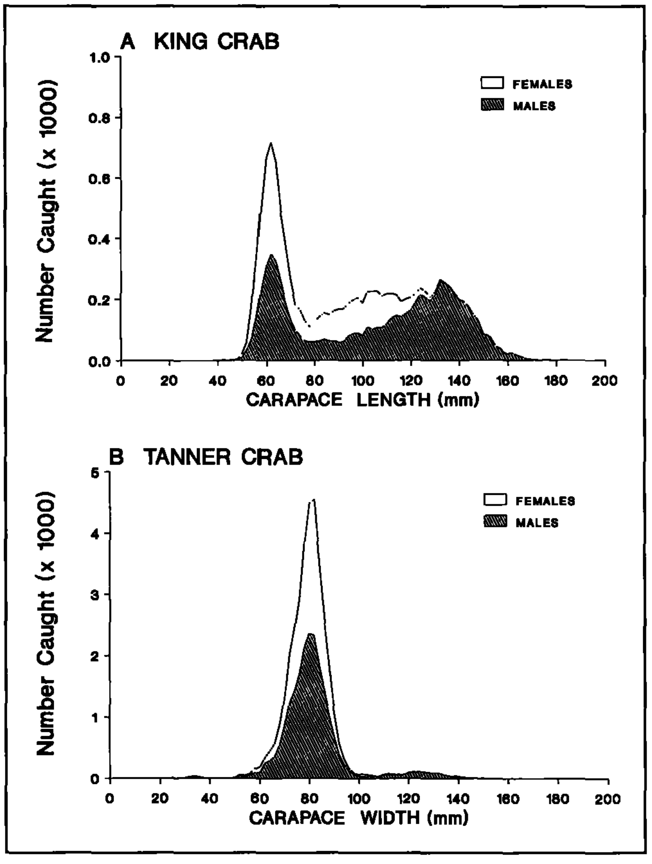

Figure 1
Size frequency of crabs caught during the experiment, shown as a moving average of three 1-mm intervals. Numbers are expanded from number measured by sampling factors. Sexes are stacked.

Results

Over 6200 t of fish were sorted through during the study, and over 50000 crabs were recovered and measured (Table 1), the majority being Tanner crabs (which shall be used herein to refer only to the species *Chionoecetes bairdi*), and the remainder mostly king crabs *Paralithodes camtschaticus*. A few *C. opilio* were encountered but are not discussed here. Vitality was coded on over 10750 crabs, representing 23985 total crabs after expansion by subsampling factors. Injuries were recorded for 3353, and 691 were held in tanks for delayed mortality studies. The size distribution of king crabs was bimodal (Fig. 1A); males exhibited modes near 62 and 135 mm CL, and females near 62 and 100 mm CL. Both sexes of Tanner crabs exhibited a single mode near 80 mm CW (Fig. 1B).

Overall survival

Overall survival was 21% (± 2.0%) for king crabs, and 22% (± 3.6%) for Tanner crabs (Table 2). Results for Tanner crabs are less accurate because fewer crabs were retained, especially from vitality group 1. Virtually no crabs were recorded as moribund after holding in live-tanks, regardless of initial condition; crabs either "recovered" or died. Potential sublethal effects, such as reduced feeding or growth rates due to injuries, could not be accounted for. At least one crab which

Table 2
Survival of crabs captured by Bering Sea trawls. Vitality codes: A = active, M = moribund, D = dead. Total number is weighted by subsampling factors. Letters in parentheses identify variables used in Equations 1 and 2.

Vitality group			Retained subsample			
				Survivors		
Code	Weighted no. (N_v)	Proportion of total	No. kept	No.	Prop. (P_v)	Overall survival (no.)
King crab						
A	307	0.041	134	124	0.925	284
M	3617	0.486	455	158	0.347	1256
D	3521	0.473	28	0	0.000	0
Total	7445		617		0.207	1540
Standard error of estimate					0.010	
Confidence interval (± 2 SE)					0.020	
Confidence range					0.187–0.227	
Tanner crab						
A	154	0.009	1	1	1.000	154
M	5261	0.319	72	47	0.653	3434
D	11083	0.672	1	0	0.000	0
Total	16498		74		0.217	3588
Standard error of estimate					0.018	
Confidence interval (± 2 SE)					0.036	
Confidence range					0.182–0.253	

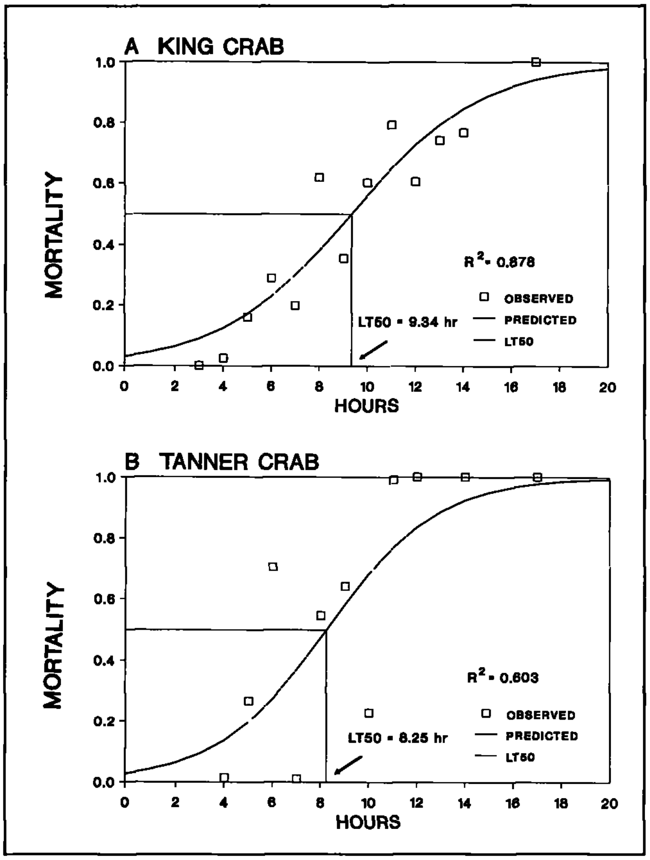

Figure 2
Logistic regression of immediate mortality vs. total time spent in captivity. Crabs were grouped into 1-hour intervals before analysis. (A) 6113 observations representing 7487 individuals. (B) 4645 observations representing 16498 individuals. Squares are observed data, solid lines represent predicted values.

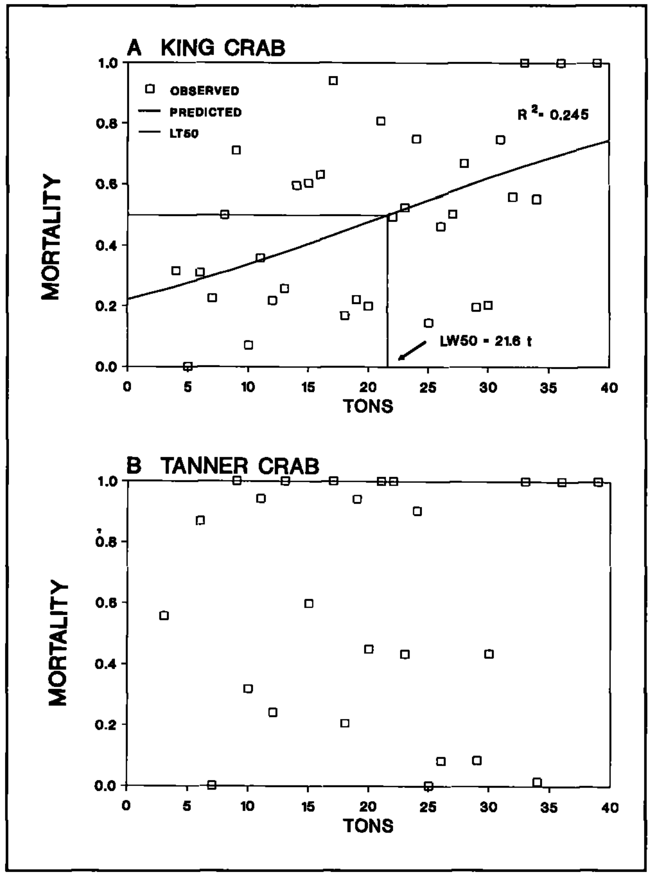

Figure 3
Logistic regression of immediate mortality vs. total weight of catch. Crabs were grouped into 1-t intervals before analysis. Squares are observed data, solid lines represent predicted values, which were incalculable for B.

had been tagged, held for observation, and released was recaptured with its tag still attached. Others may have been recaptured as well, but since most of the tags were removed prior to discarding the crabs, they could not have been identified as recaptures.

Effects of time in captivity and weight of catch

CAPTIME, the total time in captivity (prior to vitality/injury assessment) ranged from 3 to 17 hours (Fig. 2). The logistic fitting procedure indicated a significant relationship ($r^2 = 0.878$, $n = 13$, $\alpha < 0.001$) between CAPTIME and immediate mortality of king crabs (Fig. 2A); the relationship for Tanner crabs (Fig. 2B) was weaker but still significant ($r^2 = 0.603$, $n = 11$, $\alpha = 0.05$). The LT_{50}'s (time required for 50% immediate mortality) were 9.3 hours for king crabs and 8.3 hours for Tanner crabs.

Haul weights ranged from 4 to 39 t ($\bar{x} = 20.4$ t). The relationship between haul weight and immediate mortality for king crabs (Fig. 3A) was poor and non-significant ($r^2 = 0.245$). The relationship for Tanner crabs was so poor (Fig. 3B) that the iterative fitting procedure could not converge on a solution.

Shell conditions

Soft shell or molting crabs (shell condition 1) accounted for only about 1.1% of male king crabs, and <0.1% of females. All other females and most males were hardshell crabs (condition 2). About 9.4% of males were oldshell crabs (condition 3), and virtually all of these were above 100 mm CL. During the NMFS summer EBS survey in June of 1987 (Stevens et al 1987), 2.8% of males were soft or molting and many others were hardshell but recently molted. Immediate survival odds (ratio of survivors to deaths, Fig. 4) increased significantly ($X^2 = 81.63$, $p < 0.001$) with increased shell condition, i.e., hardness, but delayed survival was independent of shell condition ($X^2 = 0.60$, $p > 0.74$).

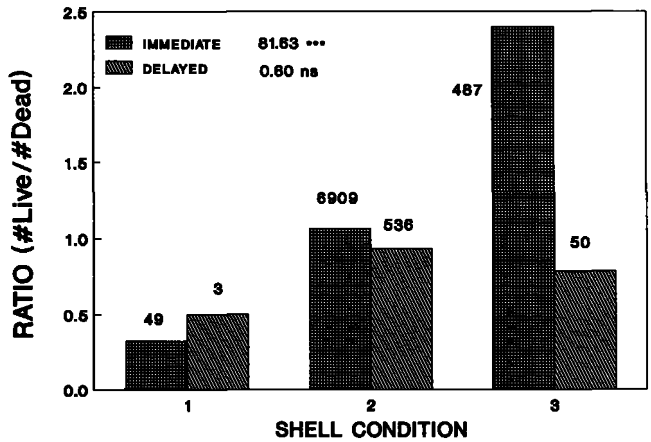

Figure 4

Effects of shell condition on immediate and delayed survival odds of king crabs. Condition coded as 1 = soft, 2 = new hardshell, 3 = old hardshell. Immediate effects are weighted by sample factors, delayed effects are not. *** indicates X^2 value significant at $p<0.001$. Sample size indicated above bars.

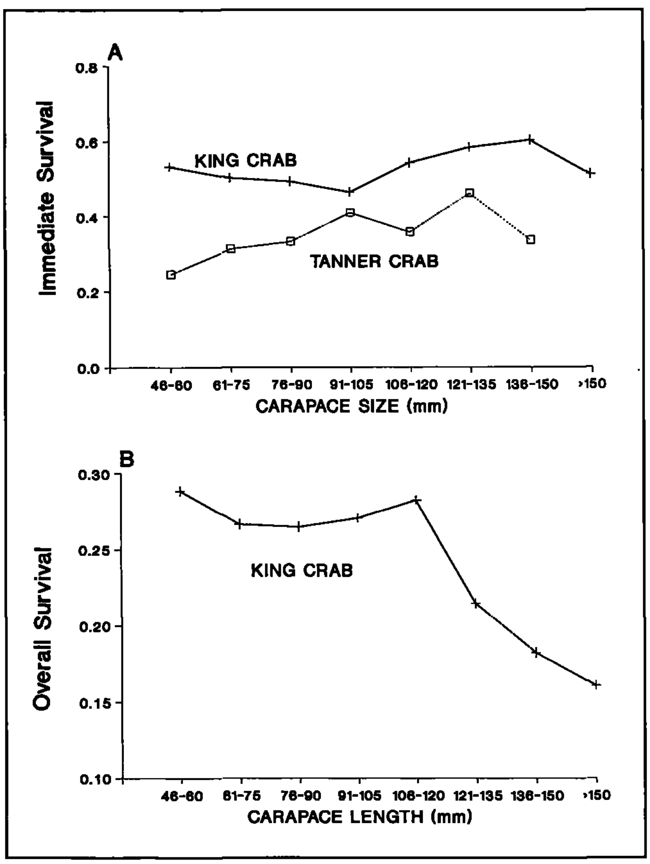

Figure 5

Effects of size on survival. (A) Immediate survival of king and Tanner crabs by 15-mm intervals of carapace length (king crabs) or carapace width (Tanner crabs). Numbers represented by each interval are 226–1520 king crabs and 71–9752 Tanner crabs. (B) Overall survival of king crabs, calculated as the product of immediate and delayed survival estimates.

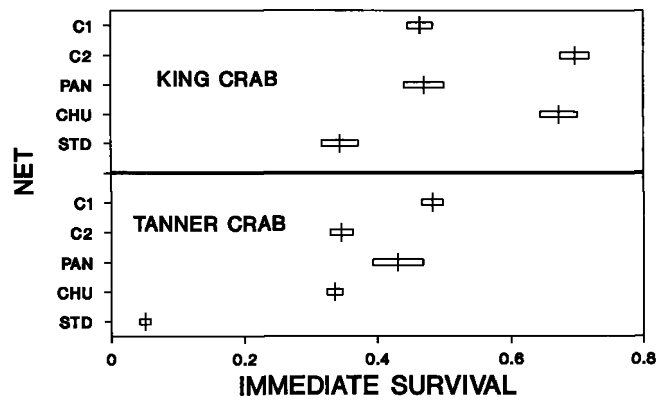

Figure 6

Effect of gear type on immediate survival of king and Tanner crabs. Vertical bar represents the mean; outer ends of box represent upper and lower confidence intervals, defined as $1.96(pq/n)^{1/2}$.

All female and most male Tanner crabs were hardshell (condition 2). Less than 0.3% of males were oldshell (condition 3), and less than 0.01% were softshell (condition 1). Low incidence of softshell and oldshell Tanner crabs prevented contingency table analysis due to too many empty cells.

Size effects

Immediate survival of king crabs did not vary much over the range of sizes captured (Fig. 5A). For Tanner crab, however, immediate survival increased slightly with size. Overall survival of king crabs (Fig. 5B) decreased markedly at sizes above 120 mm CL, mostly as a result of increased delayed mortality. Delayed mortality and overall survival could not be determined for Tanner crabs because of the limited number of observations.

Effects of gear type

Since survival was strongly related to CAPTIME, an analysis of variance was performed to determine if CAPTIME differed between the nets used. No significant differences were found ($F = 0.570$, $\alpha = 0.685$, df = 4181), so any differences in survival between nets can be attributed directly to the nets.

Immediate survival was least for the standard net (STD), for both species (Fig. 6). Nets C2 and CHU produced the best survival for king crabs, whereas C1 and PAN produced better survival for Tanner crabs. Overall, the experimental nets produced no clear differences in survival from the control nets for either species of crab. Extremely poor survival of Tanner crabs occurred in the standard net, and was probably the result of a biased vitality sample, which included

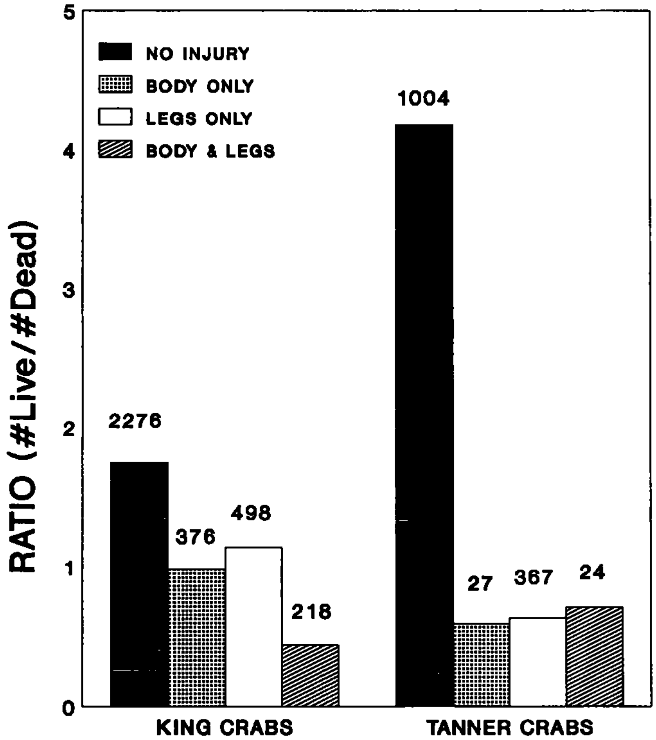

Figure 7
Effects of body and leg injuries on immediate survival odds (ratio of number surviving to number of deaths) of king and Tanner crabs. Sample size indicated above bars. Only injury-assessed crabs were used.

only six tows with this gear type, three of which had large sampling factors and mostly dead Tanner crabs. Delayed mortality was not compared between nets due to limited data.

Effects of injuries

A weighted number of 3368 king crabs and 1421 Tanner crabs were assessed for injuries. Figure 7 shows the survival odds (ratio of number alive to number dead) within each of four combinations of injury types: (1) none, (2) legs only, (3) body only, and (4) legs and body, calculated only for injury-assessed crabs. The majority of crabs suffered no detectable injuries, and had the best survival odds of 1.8 for king crabs and 4.2 for Tanner crabs. The most common type of injury for all crabs was leg injuries, which resulted in survival odds of 1.14 and 0.63 for king and Tanner crabs, respectively. Injuries to the body and combined body and leg injuries were less frequent, resulting in survival odds of 0.98 and 0.44, respectively, for king crabs, and 0.59 and 0.71 for Tanner crabs. Body injuries were more frequent but less serious among king crabs than Tanner crabs and were predominantly broken spines, which are more abundant and prominent on king crabs and thus more likely to be damaged. Body injuries of Tan-

Table 3
Contingency table analysis of interactions between delayed mortality, vitality, and injuries of king crabs. Null hypothesis was that row and column factors were independent. Data were taken only from survival experiment for king crab. Values are observed numbers of crab in each category; numbers in parentheses are calculated expected values or percent of grand total in row or column. All are 2 × 2 tables with 1 degree of freedom, and all are significant at $p<0.005$ (**).

	Vitality		Row		
Mortality	Active	Moribund	Sum	(%)	X^2 value
Vitality vs. delayed mortality					
Lived	124 (64)	158 (218)	282	(47.9)	138.6**
Died	10 (70)	297 (237)	307	(52.1)	df = 1
Column sum (%)	134 (22.8)	455 (77.2)		Total = 589	
	Injuries		**Row**		
	Uninjured	Injured	Sum	(%)	
Injuries vs. delayed mortality					
Lived	241 (221)	41 (61)	282	(47.9)	16.46**
Died	220 (240)	87 (67)	307	(52.1)	df = 1
Column sum (%)	461 (78.3)	128 (21.7)		Total = 589	
Vitality vs. injuries					
Active	118 (105)	16 (29)	134	(22.8)	9.77**
Inactive	343 (356)	112 (99)	455	(77.2)	df = 1
Column sum (%)	461 (78.3)	128 (21.7)		Total = 589	

ner crabs were typically broken or crushed carapaces which were associated with lower survival. In general, injuries were present in a greater proportion of dead crabs than live crabs. Combined body and leg injuries were most fatal for king crabs, whereas leg-only injuries accounted for the greatest number of dead Tanner crabs. The low survival odds for uninjured king crabs suggests that suffocation in the net or bunkers may have contributed strongly to their mortality.

Contingency table analysis (Table 3) showed that significant interactions occurred between vitality (VIT) and delayed mortality (DMORT; $X^2 = 138.6$), indicating that VIT was an excellent predictor of future survival or mortality for those king crabs held in survival tanks. Similarly, interaction between presence or absence of injuries (INJ) and DMORT ($X^2 = 16.46$) indicated that significantly more injured crabs died than were expected to, and that between VIT and INJ ($X^2 = 9.77$) suggests that injuries were partly responsible for observed vitality levels.

Loglinear analysis with DMORT as the dependent variable, and the interactions of DMORT with both VIT and INJ as independent variables (Table 4) indicated that the overall odds of survival were 2.087:1. These odds were increased by a factor of 4.713 for crabs coded as active (VIT = 1), and by a factor of 1.395 for crabs without injuries (INJ = 1). The total delayed survival odds for active, uninjured crabs equaled 13.73, the product of all three values. Similarly, survival odds for inactive, injured crabs were 0.317, the product of the mean odds (2.087), the odds for inactive crabs (0.212),

Table 4

Parameter estimates and survival odds for each factor in the logit model for king crabs. The dependent factor, DMORT, represents the mean survival odds (ratio of survivors to mortalities) and has no alternative outcome. Each interaction term has two alternative outcomes; alternative 1 represents cells with equal indices, i.e., values for Vitality and Injuries both equal 1 or both equal 2 (Table 5, lines 1 and 4), and alternative 2 represents cells with unequal indices (Table 5, lines 2 and 3). The survival odds for active crabs with no injuries (Vitality and Injuries = 1) is the product of antilogs for DMORT, $DMORT \times VIT_1$, and $DMORT \times INJ_1$, or 13.73. Survival odds are equal to the antilogs of 2(coefficient).

			Survival odds	
Factor	Coefficient	×2	Alt. 1	Alt. 2
DMORT	0.368	0.736	2.087	
DMORT × VIT	0.775	1.550	4.713	0.212
DMORT × INJ	0.167	0.333	1.395	0.717
Sum		2.619	13.73	0.317

Table 5

Contingency tables used for calculating survival odds (ratio of survivors to mortalities) of king crabs and parameters of logit model. Expected odds are calculated as the product of individual parameters from Table 4. (A) Cells of table shown separately, with expected odds. Numbers in parentheses are factor codes. (B) Cells combined to show overall survival and survival odds calculated using alternative grouping procedures. Procedure 1 used only the criterion of vitality. Procedure 2 simulated the NMFS observer procedure by placing only active, uninjured crabs in category 1. Procedure 3 used only presence or absence of injuries as the criterion.

Cell category		Observed				Expected
Vitality	Injuries	Lived	Died	Proportion surviving	Odds	Odds
A Separate cells						
Active (1)	No (1)	110	8	0.932	13.750	13.727
(1)	Yes (2)	14	2	0.875	7.000	7.051
Morbid (2)	No (1)	131	212	0.382	0.618	0.618
(2)	Yes (2)	27	85	0.241	0.318	0.317
B Combined cells						
1 VIT only						
All active		124	10	0.925	12.4	
All inactive		158	297	0.347	0.532	
2 Observer procedure						
Active, uninjured		110	8	0.932	13.750	
Inactive or injured		172	299	0.365	0.575	
3 INJ only						
All uninjured		241	220	0.523	1.095	
All injured		41	87	0.320	0.471	

Table 6

Comparison of effects of body and leg injuries on immediate mortality of king crabs. (A) Loglinear analysis of immediate mortality (IMORT) as a function of body and leg injuries. Survival odds are equal to the antilog of 2(Coeff.), and are multiplicable. (B) Contingency table of data used for loglinear analysis. Numbers in parentheses are factor codes. Note that expected odds differ from observed odds, but not significantly. $\chi^2 = 3.084$, with df = 1, and $p = 0.08$.

A Parameters of logit model

Factor	Coefficient	×2	Antilogs Alt. 1	Antilogs Alt. 2
IMORT	−0.017	−0.034	0.966	
IMORT by BODY	0.171	0.341	1.407	0.711
IMORT by LEGS	0.127	0.255	1.290	0.775
Sum		0.562	1.755	0.532

B Contingency table. U = Uninjured, I = Injured

Cell category Body	Cell category Legs	Observed Alive	Observed Dead	Observed Percent survival	Observed Odds	Expected Odds
U (1)	U (1)	1428	828	0.633	1.725	1.755
	I (2)	264	234	0.530	1.130	1.054
I (2)	U (1)	185	190	0.493	0.972	0.886
	I (2)	68	152	0.309	0.447	0.532

Table 7

Results of contingency table analyses of effects of types of leg injuries on immediate mortality (IMORT). Null hypothesis tested was independence of each injury type vs. IMORT. Expected ratio of percent live to dead crabs = 1.0 for all cases. Note that totals include uninjured as well as injured crab. ns = not significant at $p = 0.05$. ***significant at $p < 0.001$.

Type of injury	Number alive with injury	Percent of live crabs	Number dead with injury	Percent of dead crabs	Ratio % dead to % live	X^2
King crabs						
Autotomy	35	1.8	36	2.6	1.44	2.48 ns
Distal	284	14.4	313	22.3	1.55	34.86**
Proximal	29	1.5	113	8.1	5.47	88.06***
Total	1967		1401			
Tanner crabs						
Autotomy	47	4.8	123	27.4	5.67	149.85***
Distal	112	11.5	136	30.3	2.63	76.16***
Proximal	11	1.1	35	7.8	6.89	43.63***
Total	972		449			

and the odds for injured crabs (0.717). Alternatively, the log(ODDS) can be predicted as a linear function of each coefficient by substituting these values into Equation 5, e.g., for active, uninjured crabs,

$$\ln(f_s/f_m) = 2(l_D + l_{D*V} + l_{D*I})$$
$$= 2(0.368 + 0.775 + 0.167)$$
$$= 2.619$$
$$\text{ODDS} = \exp(2.619) = 13.74.$$

Thus a 'good' vitality code of 1 was a better predictor of future survival odds than lack of injuries.

Table 5A shows the observed frequencies, percent survival, and survival odds, as well as the survival odds predicted by the logit model, for each combination of factors. Expected odds were calculated as the product of odds for each combination of interaction represented in Table 4. For instance, the expected survival odds for active (VIT = 1), injured (INJ = 2) crabs equalled 7.05, the product of odds for overall survival (2.087), active crabs (4.713), and injured crabs (0.717). The likelihood ratio chi-squared value, calculated over all categories, was 2.30 with $p = 0.317$, indicating a good fit between the observed and expected survival odds.

In order to compare different methods of crab vitality assessment as tools for predicting future survival, cells of Table 5A were combined. Table 5B shows that using only vitality codes as an indicator of future survival resulted in survival estimates of 0.925 for VIT = 1, and 0.347 for VIT = 2, identical to those shown in Table 2. Simulation of the NMFS observer program procedure resulted in survival estimates which were slightly higher for both categories (0.932 and 0.365, respectively), but otherwise very similar. Use of only data on presence or absence of injuries did not provide adequate information about future survival.

Loglinear analysis was also conducted using immediate mortality (IMORT) as the dependent variable and the interactions of IMORT with body injuries (BODY) and leg injuries (LEGS) as the independent variables (Table 6A). The parameter for mean survival odds was 0.966, or about 1:1. Absence of body injuries increased the odds of survival by a factor of 1.407; their presence decreased survival odds by 0.711. Absence of leg injuries increased survival odds by a factor of 1.290. Coefficients for IMORT × BODY and IMORT × LEGS were not significantly different. Expected odds differed slightly but not significantly ($\chi^2 = 3.084$, df = 1, $p = 0.08$) from observed odds (Table 6B).

Evidence of recent leg autotomy was not significantly associated with immediate mortality of king crabs ($X^2 = 2.48$; Table 7A). However, leg injuries which occurred distal to the autotomy plane were significantly ($X^2 = 34.86$) associated with IMORT, as were those which occurred proximal to it ($X^2 = 88.06$). Proximal injuries had the greatest effect, increasing deaths above the expected proportion by a factor of 5.47. All three types of injuries were significantly associated with IMORT for Tanner crabs (Table 7B). Immediate survival odds, expressed as the ratio of live/dead crabs, decreased significantly with the number of legs injured for both king ($X^2 = 86.5$) and Tanner crabs ($X^2 = 225.3$; Fig. 8A). Delayed survival odds also decreased significantly with the number of injured legs for king crabs ($X^2 = 17.0$), but not Tanner crabs ($X^2 = 4.8$), perhaps due to inadequate sample size for the latter.

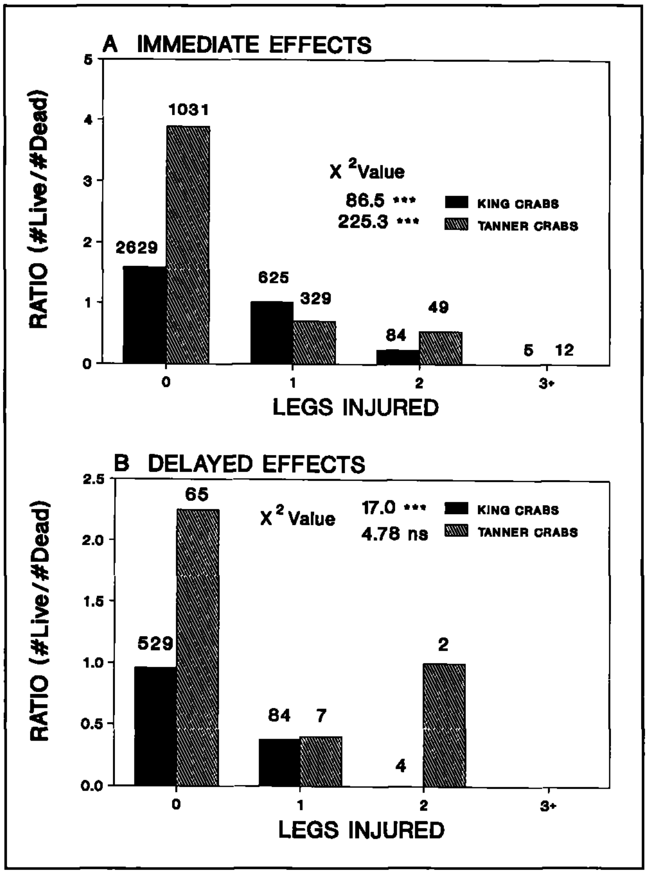

Figure 8

Effects of multiple leg injuries on survival odds of king and Tanner crabs. *** indicates X^2 value significant at $p<0.001$. Sample size indicated above bars.

Discussion

The results of this study show that, although the majority of crabs died as a result of capture incidental to commercial trawling operations, a significant proportion (>20%) can survive the process. The major factors associated with increased crab mortality were shell condition and time in captivity (CAPTIME) prior to recovery. The present study was conducted in August, when both king and Tanner crabs are typically hard-shelled. However, molting for both species usually occurs from January through June, coincident with the season in which most sole trawling occurs in the EBS, so mortality due to molting would probably be greater during the normal fishery. Processing times observed in this study ranged from 0.8 to 12.5 hours, which may have been longer than normal due to the sampling operation, so they probably caused higher than normal mortality. If average processing times for the commercial fishery are less than those observed here, expected mortality would also be less. The study conditions also differed from normal operations in that crabs were retained for several hours after recovery for examination, whereas those recovered during normal operations would have been placed on discard conveyors and returned to sea sooner, probably increasing their survival rates.

For king crabs, the relationship between time in captivity and immediate mortality was strong enough that knowledge of average processing times for a particular trawl fishery could be used to estimate overall survival of crabs. It can also allow estimation of the effects of reduced captivity time on survival. In this study, immediate survival (0.527) and delayed survival (0.472) of king crabs were approximately equal (Table 2). For illustrative purposes we can assume that this equivalency is a general phenomenon, and these two aspects of survival vary proportionally, since increased stress should result in increases in both immediate and delayed mortality. Based on this assumption, the estimated overall survival at the median lethal time of 9.3 hours would be approximately 0.5 × 0.5 or 0.25, which is very close to the value of 0.21 estimated in Table 2, but differs slightly because the latter was calculated in a stratified manner over all conditions rather than just representing the median lethal time. Overall survival could theoretically be doubled to 50% by reducing CAPTIME such that immediate (and consequently delayed) survival was equal to $0.5^{1/2}$, or 0.71, i.e., by reducing mortality to 1–0.71, or 0.29. Solving the logistic equation (Eq. 3) for X results in:

$$X = X_{50} - \{\ln[(1-M)/M]\}/r \qquad (3.1)$$

Substituting $0.29 = M$ (as determined above), $9.34 = X_{50}$, and $0.367 = r$ (the latter two values are fitted parameters from the logistic model for king crab survival) results in $X = 6.90$ hours. Thus, for this example, reducing the median total time in captivity from 9.34 to 6.9 hours (a 26% reduction) would increase the immediate and delayed survival rates from 0.50 to 0.71 (a 42% increase), and consequently increase the overall survival to a value equal to the square of immediate survival, $0.71 \times 0.71 = 0.50$, i.e., a 100% increase in overall survival, assuming immediate and delayed survival to be approximately equal, as stated above.

Reduction of CAPTIME, the time crabs spend in the trawlnet or the processing bins, could be accomplished by reducing either towing time, processing time, or both. If towing time cannot effectively be reduced (and may in fact need to be increased to efficiently use the experimental trawls because of reduced fish catch rates) then delay time (between net haulback and delivery to the processing vessel) and processing time (time spent on deck or in the bunkers prior to recovery) should be reduced as much as possible. This could be achieved through better communication and coordination between catcher and processor vessels in order to more evenly distribute deliveries to the processor over time, and reduce or prevent a backup in processing. Towing time may actually contribute less to mortality than processing time, since fish and crabs are less densely packed in the net during towing, and have access to free flowing water. However, neither of these variables (towing or processing time) provided a significant predictive relationship by themselves. Once the codend is recovered on deck, the packing density and pressure within the codend increase greatly and probably contribute substantially to mortality of fish and crabs therein.

Observers placed aboard trawlers by NMFS or the State of Alaska have a variety of tasks to perform, and assessing crab vitality has usually been one of low priority. If one objective were to determine the proportion of crabs that clearly have the best chance of survival, then a two-step process using both vitality and the presence of injuries, such as that currently used by the NMFS observer program, is a better method, as crabs which fell into the "best" category of this scheme exhibited 93.2% survival. Even better predictions could probably be made if degrees of injury (e.g., none, mild, severe) were coded and used to predict survival. However, if the object were to predict survival using the quickest and most efficient method of assessment, then use of vitality alone might be the best choice, as it indicated similar survival (92.5%) for the top category and could be assessed adequately in seconds, whereas a comprehensive assessment for injuries required a deliberate, systematic examination, consuming more time than may be available, given the priority of the task. Even then, some injuries, such as minor cracks in the carapace, were easy to miss.

Despite the quantity of data collected on injury types and severity, there was no clear, unambiguous relationship between injuries and mortality. The overall physical condition of crabs, which could be assessed by activity level, was a better indicator of future survival than injuries. Leg injuries were only slightly more fatal than bodily injuries to king crabs. Both immediate and delayed mortality increased with the number of legs injured, and proximal injuries to legs were more fatal than distal injuries, which was not unexpected since bleeding from the coxa or basi-ischium (leg segments which are proximal to the autotomy plane) would likely be more difficult for the crab to stop than bleeding from a more distal segment, which could be autotomized at a later time. In our experience, though, it was uncommon for crabs that had injured legs at the time they were examined to autotomize them in the live tanks. If autotomy had not occurred soon after the injury, and prior to examination, it was less likely to do so after a day or two. However, this is a subjective observation and was not documented, because injuries were not reassessed prior to release. The poor relationship between injuries and death suggests that other factors, such as exposure or suffocation, may have played a significant role in determining survival of crabs.

In an attempt to simulate the effects of culling crabs in the directed, winter-season pot fisheries, Carls and O'Clair (1990) documented the effects of exposure of ovigerous female king and Tanner crabs to various combinations of time and air temperature (max. 40 min. at −19°C). They found that both mortality and righting time were inversely proportional to exposure, expressed in terms of degree-hours, but neither response occurred in air temperatures above 0°C. Their conditions contrasted with this experiment; although water and air temperatures were not recorded, 30-year mean August seawater temperatures in the area where this experiment was conducted have been 2–5°C on bottom and 8–9°C at surface (Ingraham 1983), and air temperatures were probably above 10°C, so no negative degree exposures occurred. However, during the winter trawl fishery such exposures might occur, although most crabs would be insulated by the surrounding catch in the net or processing bins.

Carls and O'Clair (1990) also found that exposure-related mortality of king crabs was delayed, occurring 16–128 days after exposure, and was usually associated with ecdysis; in contrast, 50% of their Tanner crab mortality occurred within the first 24 hours. Although crabs were not retained over 48 hours in the present experiment, and no ecdysis occurred, exposures were not as severe either.

Location of leg breaks was found to be related to mortality of stone crabs *Menippe mercenaria* by Simonson and Hochberg (1986). They studied the effects of exposure and claw breakage on survival of stone crabs and found that breakage on either side of the breakage plane resulted in significantly higher mortality than breaks on the plane. Mortality also increased with severity of the break, and length of exposure, from 2 to 6 hours. Severity of breaks also increased with exposure time prior to breakage. In their study, claw breakage was intentional rather than accidental, as fishermen remove the claws for sale and return the live, clawless crab to the sea.

Crabs subjected to trawl capture and subsequent release probably also suffer some sublethal effects, but they could not be documented in this study. Brown and Caputi (1985) studied the effects of exposure and leg loss on growth of sublegal rock lobsters *Panulirus cygnus*, and found that exposure for periods of 15, 30, and 60 minutes resulted in decreased growth at the next molt of 0.8–2.3 mm, or 1.2–3.3% of carapace length. In addition, the growth increment was reduced by 0.48 mm, or about 0.7%, for each appendage missing. Carls and O'Clair (1990) also found that female king crabs exposed to subzero air temperatures showed decreased growth at subsequent molts. Other sublethal effects included reduced feeding rates and increased limb autotomy by female Tanner crabs.

The recapture of a tagged and released crab indicates that such multiple captures of discarded crabs may be common in this type of intensive fishery. Recaptured crabs would probably have lower survival rates than crabs captured and released only once, due to the cumulative effects of stress and injuries. However, there is no evidence suggesting that the rate of recapture during the experiment differed from the normal conditions of the commercial fishery, so the calculated survival rates may adequately incorporate any effects of recapture.

Smith and Howell (1987) studied the effects of trawl capture on American lobsters *Homarus americanus* in Long Island Sound and found that the incidence of damage varied seasonally from 0 to 14%, and was greater during months when molting was occurring. Immediate plus delayed mortality ranged from 1% to 21%, depending upon season also. In contrast to this report, they found that uninjured lobsters, and those with autotomized claws rarely experienced delayed mortality, and that seasonally warm seawater temperatures were associated with increased delayed mortality independent of damage. The conditions to which lobsters were exposed differed greatly from those encountered by king crabs, however, as the lobsters were commonly sorted out of the catch in less than an hour, as opposed to times of 3–17 hours for crabs in this study.

The effect of discarding crab via conveyor belts and discard chutes from the factory was not examined, and could inflict further injury upon crabs via entanglement in machinery or damage upon impact with the water surface, 3–6 m below the discard chute.

The estimated catch of 88000 red king crabs and 751000 Tanner crabs *C. bairdi* by the Bering Sea JV fishery in 1988 (Berger and Weikart 1989) amounted to 0.22% and 0.11% of the total estimated abundance of those two species, respectively, in the Bering Sea that year (Stevens et al. 1988). Even though the amount of bycatch in the domestic fishery is unknown, it is unlikely that the total bycatch exceeded 0.5% of the population for either species, largely as a result of restrictions on bycatch. Removals of this magnitude are well below the ability of the NMFS crab survey to detect, and probably have no significant biological impact. The possibility of additional, unseen mortality of crabs due to trawling has largely been discounted by submersible studies (West 1987, Highliners Association 1988) in which the observed trawls made little or no contact with the sea bottom, caused no observable injuries to crabs contacted, and no injured or dead animals were observed in the wake of the net.

Nevertheless, the issue of bycatch mortality is of great concern to the fishing industry, and the North Pacific Fishery Management Council has developed a policy of reducing bycatch mortality as much as possible. To that end, the most useful results of this study were, first, that crab mortality increased with CAPTIME, so reduction of CAPTIME should be a high priority. Second, reduction of king (and probably Tanner) crab mortality could be achieved by conducting the trawl fishery during periods of the year when molting activity is at a minimum.

Summary

1 Over 50000 crabs were measured during the study. Vitality was recorded for over 10000, injuries for 3353, and delayed mortality for 691.
2 Overall survival was estimated to be 21% (±2.0%) for king crabs and 22% (±3.6%) for Tanner crabs.
3 Overall survival of king crabs declined at sizes above 120 mm CL. Overall survival could not be determined for Tanner crabs, but immediate survival showed a slight increase with size.
4 Immediate mortality of king and tanner crabs increased in direct proportion to time in captivity, but was poorly related to weight of the catch.
5 Immediate survival odds for king crabs increased significantly with shell age.
6 No clear difference in survival was apparent between the net types for either king or Tanner crabs.
7 Delayed mortality was shown to be dependent on both vitality and injuries, with vitality being the best predictor. Observation of injuries did not contribute substantial additional information concerning future (48-hour) survival.
8 Leg and body injuries contributed about the same amount to immediate mortality, but mortality increased with number of legs injured, and injuries to leg segments proximal to the autotomy plane were more serious for king crabs but not for Tanner crabs.

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