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#4- Red Crab

Escape ring selectivity, bycatch, and discard survivability in the New England fishery for deep-water red crab, *Chaceon quinquedens*

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The trap fishery for red crab, *Chaceon quinquedens*, occurs at depths of 600–800 m along the continental slope of New England. The target product is a male crab with a carapace width of ~105 mm or greater. Selectivity was tested at two discrete depths (600 and 800 m), for four different escape ring scenarios: control trap with no escape rings, and escape rings with internal diameters of 9, 10, and 11 cm. Proportions of non-marketable *C. quinquedens* were large (71–100%) at both depths for all traps, but were smallest in traps with escape rings. Discard mortality was estimated at ~5% through caging experiments across three haul frequency conditions (every 24 h, every 4 d, and after 8 d), which represented the likely reality of multiple recaptures during a commercial trip. The impact of discarding techniques (low and high impact) was also assessed. If discard proportion estimates of >71% are realistic, and if an estimated ~5% of these discards die, the recommendation must be made for fishery participants to improve gear selectivity, and thereby to minimize discard mortality rates. On the management side, stock assessments will be more accurate if estimates of discard mortality are incorporated.

Keywords: *Chaceon quinquedens*, deep-sea red crab, discard mortality, escape rings, gear selectivity, trap fishery.

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Introduction

The commercial trap fishery for deep-water red crab, *Chaceon quinquedens*, takes place at depths of ~600–800 m along the continental shelf from Georges Bank south to waters off Virginia (NEFSC, 2006). Landings have risen steadily since 1995, peaking at ~4000 t in 2001; as such, this species is increasingly valuable for the diversified New England fisheries. The market for red crab originally required a carapace width (CW) of ~115 mm, which encouraged a male-only fishery because few females reach this size; more recently this market size has been reduced to ~105 mm CW in response to decreased catches of large male crabs. In 2002, legislation was enacted prohibiting red crab vessels from landing more than "one standard US fish tote" of females from any directed red crab trip (CFR, 2002). No legal size limit is currently in place.

The deep-water nature of this fishery poses a challenge for fishers and researchers alike. Research on *C. quinquedens* in the Northwest Atlantic began during the 1970s (Wigley *et al.*, 1975; Haefner, 1978) and progressed into the 1980s focusing on shell disease (Feeley, 1993), reproduction (Haefner, 1977; Elner *et al.*, 1987; Hines, 1988; Hinsch, 1988), and growth (Perkins, 1973; Lux *et al.*, 1982; Van Heukelem *et al.*, 1983), but soon waned in the face of reduced fishing effort and research difficulties. Since the establishment of a target fishery in more recent years, the need for contemporary research on *C. quinquedens* is topical again. Data have been collected to furnish stock assessments and abundance estimates, in addition to estimates of movement and growth (Keith, 2003, 2005; Weinberg *et al.*, 2003; Wahle *et al.*, 2006).

Currently, the fishery for *C. quinquedens* is not subject to gear restrictions other than a trap capacity limit (18 cubic feet or 0.51 m^3), gear line and marking requirements, and a 600 pot trap limit (CFR, 2002). Operators can choose trap designs according to desired performance in terms of catchability, durability, and space efficiency on deck, all of which are important considerations for the safe and economical operation of any fishery. In recent years, many of the traps have been fitted with 9 cm diameter escape rings, though no evaluation was undertaken to assess the most efficient escape ring size. The current study assesses the relative selectivity of different sized escape rings incorporated into the industry's standard nylon mesh traps. This is important because maximizing the selectivity of gear often translates into minimizing the capture of non-target animals, and in turn, reduces the impact of discard mortality.

Discard mortality is a component of fishing mortality (F) which, combined with natural mortality (M), gives an estimate of total mortality (Z); all three are vital parameters for stock assessments. Traditionally, the mortality of discarded crustacean species has been assumed to be low, but more recent assessments on various crustaceans discarded from both mobile (Stevens, 1990; Wileman *et al.*, 1999; Lancaster and Frid, 2002) and fixed (Grant *et al.*, 2002; Grant, 2003; Harris and Ulmestrand, 2004) gears suggest that crustacean discard mortality can be high. A summary of mortality estimates for major commercial crab species makes clear that findings vary greatly (0–100%) between gear types, species, and intermoult conditions (Alverson *et al.*, 1994). Recent research on the snow crab, *Chionoecetes opilio*, documented high rates of discard mortality (up to 51%; Winger and Walsh, 2005) for a trap fishery, which takes place in 170–380 m; that stock is now considered to be in decline (DFO, 2003). However, the discard mortality component of fishing effort is often under-researched (Alverson *et al.*, 1994), a fact recognized by the New England Fisheries Management Council in its recent documentation of prioritized research needs (NEFMC, 2004). Currently, there is no information regarding the survival rate of *C. quinquedens*, which are hauled to the surface from considerable depth and exposed to air and sunlight, before being discarded.

Multiple factors are likely to affect discard mortality in *C. quinquedens*, including the physiological capacity of the species to survive the significant change in environment experienced during the haul and discard process. In the red crab fishery, traps are typically emptied, re-baited, and reset immediately in nearby grounds (pers. obs.), so it is probable that surviving discarded crabs will be recaptured (possibly multiple times) during the course of a single commercial trip. The potential cumulative impact of fishing procedures is rarely investigated in discard mortality studies, but it was identified as key to this fishery and, as such, is investigated by undertaking caging studies at different haul frequencies to represent recapture events. In addition, different components of the actual discard process will influence the mortality levels of discarded crabs; for example, the "drop" (or height) between the trap emptying and sorting locations, and the discard location and the water surface have been shown to have a considerable impact on other crab species (Grant *et al.*, 2002; Grant, 2003; Purves *et al.*, 2003). In the red crab fishery, the drop of relevance is that from the sorting location to the water surface (~2–3 m), which could prove significant if vulnerability of red crabs to injury is high, as was proposed by Gray (1970). Additional factors influencing survival in other crab fisheries relate to aerial exposure and extreme changes in temperature (Zhou and Shirley, 1995, 1996; MacIntosh *et al.*, 1996; Tracy and Byersdorfer, 2000, 2002; Zhou and Kruse, 2000a, 2000b; Suuronen, 2005; Warrenchuk and Shirley, 2002) or salinity (Harris and Ulmestrand, 2004). The current study investigates discard mortality, focusing on (i) ascent/descent survival, and (ii) the effects of handling during the discard process.

Material and methods

Fishery-independent sampling took place in May 2006 on the red crab fishing grounds near Block Canyon (39°50′N 71°20′W). The 10-d research trip was aboard the FV "Hannah Boden" (26 m), one of the primary commercial red crab vessels. A variety of experiments was conducted to estimate trap selectivity and discard mortality.

Trap selectivity and escape ring trials

The standard industry trap was used; this is a conical crab trap (120 cm diameter × 60 cm height), rigged with ~7.6 cm nylon mesh and a top bucket-entry (25 cm). Two depths were targeted: ~600 m (typically associated with smaller and female red crab) and ~800 m (typically associated with larger male crabs). At both target depths, three strings were set, each consisting of 15 sequentially attached traps, three traps for each of the four escape ring conditions: (C) control, with no escape rings, and escape rings with internal diameters of 9 cm (S), 10 cm (M), and 11 cm (L).

The entire catch of every trap was sampled, including non-target species. *C. quinquedens* were sexed and their CW measured. These data were used to calculate estimates of catch per unit effort (cpue) and were also used to generate selectivity curves for each escape ring scenario. Selectivity curves were calculated using logistic curve analysis:

$$P = \frac{1}{(1 + \exp^{-r(\mathrm{CW}-\mathrm{CW}_{50})})}, \tag{1}$$

where P is the proportion of the total catch of the size CW caught in the trap, r a constant, and CW_{50} the mean length at which 50% of the crabs are retained (King, 1995; Jennings *et al.*, 2001).

A VEMCO temperature-depth recorder (rated to 1000 m) was attached inside a trap on the 800 m string and sampled at a rate of 30 readings per hour; this yielded temperature–depth data throughout the trip, and the live well was chilled according to this *in situ* information.

Bycatch data collection

The bycatch component of the red crab fishery was determined through frequency analysis of target and non-target species data collected during the escape ring trials.

Survival of ascent and descent: crab "hotels"

The physiological capacity of red crab to survive the variable environment associated with the haul and return to the seabed was assessed through a caging experiment. Crabs were captured using commercial traps and, from the sorting table, were placed directly into compartmentalized cages (hotels) for return to the sea floor. Each hotel took ~5 min to fill and, because hotels could not be deployed individually (owing to the operating depth of ~600 m), hotels were submerged in the vessel's chilled (5°C) and aerated live well to minimize non-typical aeration on board the vessel. The total hotel loading/deployment duration was ~50 min. Data on crab size and sex were collected at the end of the experiment to avoid burdening the findings with additional, non-typical handling procedures gathered during the course of the experiment.

The hotels were made from 2.5 cm Aquamesh and measured 90 cm × 120 cm × 45 cm; each hotel provided a total of 36 individual compartments, each measuring 30 cm × 30 cm × 15 cm. The hotels were hauled at different frequencies to simulate three different recapture scenarios: (i) every day after initial capture, (ii) every 4 d, and (iii) 8 d after initial capture. During the course of the experiment, the survival of each crab was monitored using a stamina index (SI)′where:

0 = dead;

1 = weak, slow movement of mouthparts, limp legs, little sign of life, but alive;

2 = slow movement of mouthparts, slight tension in legs;

3 = fast movement of mouthparts, tension in legs, fast reaction to touch stimuli on abdomen;

4 = fast movement of mouthparts, tension in legs, fast reaction to touch stimuli on abdomen, aggressive display.

Drop effects

The vessel's aerated live well was filled with seawater and chilled to the *in situ* temperature (5°C), as indicated by the temperature data collected during gear selectivity trials. The impact of the discard drop was assessed by creating two discard conditions:

(i) Control—dropped: 100 crabs discarded using the typical fishery practice, i.e. sorted on a table and dropped into the live well from the same height as would happen if a crab entered the sea via the vessel's discard shoot (~2 m);

(ii) Treatment—slid: 100 crabs sorted on the sorting table and slid down a plastic slide that delivered the crab into the live well with minimal impact.

This experiment was repeated for five consecutive days using separate, non-compartmentalized cages (90 cm × 120 cm × 45 cm) for each day and each discard condition. At the end of 5 d, cages were retrieved from the live well and the following data were collected: sex, size, injury, shell condition, SI, and holding duration.

Results

Trap selectivity and escape ring trials

Cpue data indicate a significantly higher mean catch rate at 600 m ($\mu = 35.06$) than at 800 m ($\mu = 16.24$; $\chi^2 = 6.927$, d.f. = 1, $p < 0.01$). Sex ratio differences in crab distribution between 600 m and 800 m were dramatic and significant. By the end of the gear trial experiment, 225 traps had been hauled at each depth. The total catch of females was significantly higher at 600 m ($n = 4369$) than at 800 m ($n = 94$), whereas males were caught in almost equal numbers at 600 m ($n = 3374$) and 800 m ($n = 3420$; $\chi^2 = 2918.371$, d.f. = 1, $p < 0.001$).

Table 1 shows that, at both 600 and 800 m, there is also a significant difference in cpue between trap conditions. All three traps with escape rings retained considerably fewer crabs than the control trap (Figure 1), with the smallest number of crabs being caught by the traps with 11 cm (L) escape rings (Table 1).

The size range of crabs captured by each trap condition is presented in Figure 2. Size-frequency analysis of the catch for each trap condition indicates that undersized crabs represent between 71.7% and 98.4% of the catch at the 10 mm CW market size (and 93.6–100% at the original market size of 115 mm CW). Two-sample Kolmogorov–Smirnov analysis (Table 2) on size-frequency distributions by trap treatment indicated that the catch compositions differed significantly at both depths; the only exception was at 800 m between the 10 cm (M) and 11 cm (L) escape rings. Gear selectivity curves (Figure 3) reveal that, for all gear conditions, the size at which the probability of capture is 50% (CW_{50}) is well below both the current market size (105 mm CW) and the previous market size (115 mm CW).

Table 1. Cpue data (average number of crabs $trap^{-1}$) by trap treatment across two depths (600 and 800 m).

Depth	Control cpue	Small cpue	Medium cpue	Large cpue	χ^2 statistic	*p*-value
600 m	85.99	40.31	24.67	18.11	66.471	<0.001
800 m	36.62	19.44	12.32	9.62	22.734	<0.001
% empty	1.1%	1.1%	0.0%	1.1%	–	–

Chi-squared analysis (χ^2) revealed significant differences both between depth and between trap treatments. The total proportion of empty trap hauls by trap treatment is also presented.

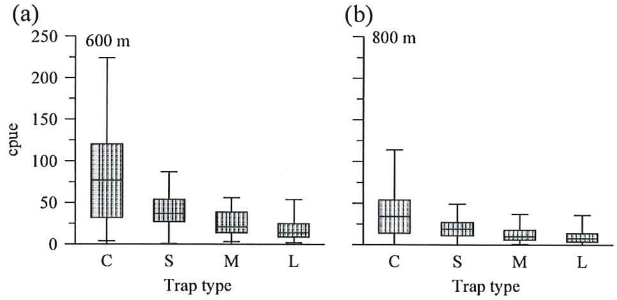

Figure 1. Mean cpue of *C. quinquedens* by trap treatment at target depths of (a) 600 m, and (b) 800 m. C = no escape rings, S = 9 cm escape rings, M = 10 cm escape rings, and L = 11 cm escape rings. Whiskers depict the minimum and maximum; upper and lower quartiles are represented by the box; and the line through the box represents the median.

Although the incorporation of escape rings did increase the size composition of the catch overall, particularly at 800 m, no significant differences in CW_{50} were found between gear treatments at either depth (Table 3).

The proportions of marketable vs. non-marketable catch by trap condition are presented in Table 4; at the current 105 mm CW market size, the smallest mean proportion of undersized crabs (72.4% at 600 m and 81.3% at 800 m) and the greatest number of marketable crabs (57 at 600 m and 36 at 800 m) are observed for the 9 cm (S) escape ring. If the 115 mm CW market size were imposed again, the combination of smallest mean proportion of discards and greatest number of marketable crabs would be achieved by the 10 cm ring (M). If the number of marketable (>105 mm CW) crabs and discard crabs are considered as a ratio, the 9 cm (S) escape ring is favoured relative to other escape ring options; 22:57 at 600 m, and 8:36 at 800 m (Table 4). Box plot visualizations (Figure 2) also demonstrate that the 9 and 10 cm escape rings retain a more restricted and larger size range of crabs.

Bycatch data collection

From 450 gear trial trap hauls, a total of 16 non-target organisms were recorded; this equates to 0.001% of the total catch of target species ($n = 11\,257$). The organisms captured included golden crab (*C. fenneri*, $n = 2$), Jonah crab (*Cancer borealis*, $n = 8$), unidentified whelk spp. ($n = 3$), ocean pout (*Macrozoarces americanus*, $n = 1$), and wrymouth (*Cryptacanthodes maculatus*, $n = 1$). Too few non-target organisms were recorded to discover any relationship with escape rings. All other bycatch consisted of undersized and/or female *C. quinquedens* and represented 85.7% of the total catch ($n = 9650$).

Physiological survival of ascent and descent: crab hotels

A total of seven hotels ($n = 252$ crabs) were filled and set for each condition. The total proportion of red crab that survived the descent/ascent hotel experiments was 93.8% (Table 5). Comparisons of the three hauling conditions (i.e. crabs hauled every 24 h, after 4 d intervals, or after 8 d) revealed that crabs that undergo the ascent/aeration/descent procedure regularly (i.e. every 24 h) demonstrate significantly greater mortality than crabs retrieved after either 4 d or 8 d ($\chi^2 = 18.092$, d.f. = 2, $p < 0.001$; data pooled when observations were <5). There was no evidence of effects related to crab sex (Table 5) or crab size.

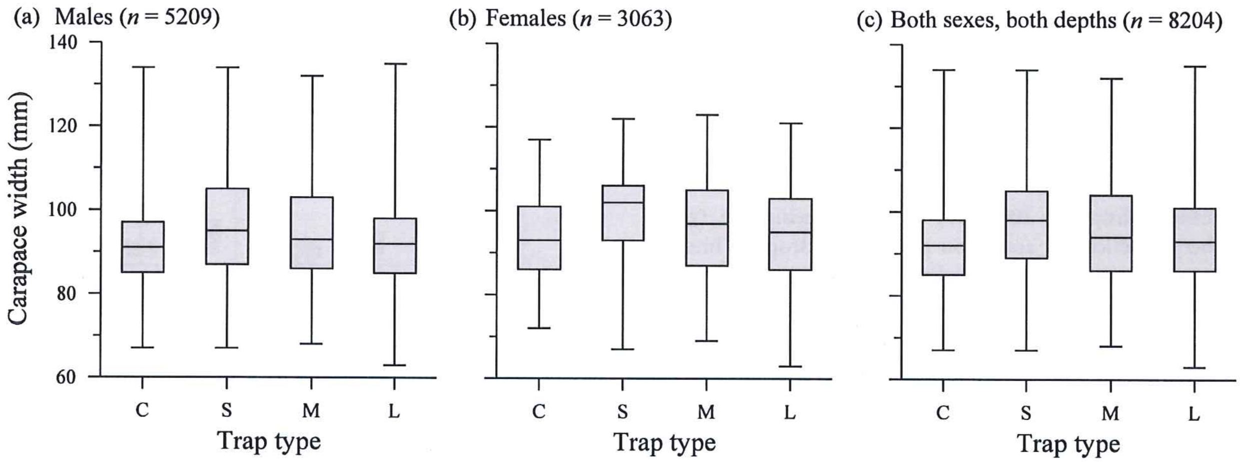

Figure 2. The total size composition (depths combined) of *C. quinquedens* for each trap treatment. C = no escape rings, S = 9 cm escape rings, M = 10 cm escape rings, and L = 11 cm escape rings. Whiskers depict the minimum and maximum; upper and lower quartiles are represented by the box; and the line through the box represents the median.

Drop effects

The discard handling technique had a strong impact on SI and the overall survival of crabs. Chi-squared analysis (categories pooled when observations were <5) indicated that crabs that had been slid into the water (i.e. no surface impact) were significantly more likely to be recorded as strong (SI3 or SI4), and crabs that had been dropped into the water were significantly more likely to be categorized as dead (SI0) or weak (SI1 or SI2; $\chi^2 = 12.738$, d.f. = 2, $p < 0.01$). Table 6 shows the relative frequencies for each SI for males and females exposed to the two conditions. Overall, mortality was greater (4.3%) for dropped crabs than for slid crabs (0.8%). No sex differences were observed.

Fresh limb loss was considered a possible impact of fishing/handling and was observed in 25 females (4.3%) and 13 males

Table 2. Two-sample Kolmogorov–Smirnov analysis on the size-frequency distributions of catch compositions across different escape ring treatments.

Trap comparisons	600 m			800 m		
	Z statistic	*n*	*p*-value	Z statistic	*n*	*p*-value
C: S (9 cm)	8.457	3 110	<0.0001	9.501	1 529	<0.0001
C: M (10 cm)	3.697	2 761	<0.0001	7.885	1 319	<0.0001
C: L (11 cm)	1.829	2 398	<0.01	6.901	1 183	<0.0001
S (9 cm): M (10 cm)	4.048	2 545	<0.0001	1.841	1 328	<0.01
S (9 cm): L (11 cm)	5.264	2 272	<0.0001	1.752	1 192	<0.01
M (10 cm): L (11 cm)	1.795	1 833	<0.05	1.197	982	NS

NS, not significant.

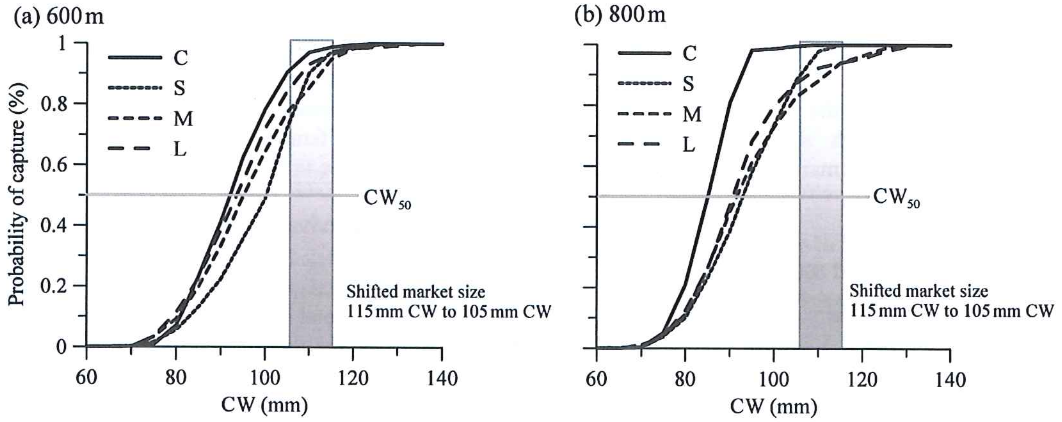

Figure 3. *Chaceon quinquedens* selectivity curves for different escape ring treatments at (a) 600 m and (b) 800 m. C = no escape rings, S = 9 cm escape rings, M = 10 cm escape rings, and L = 11 cm escape rings. The size at which the probability of capture is 50% (CW_{50}) is indicated by the grey horizontal line. The vertical bar represents the shift in market size from ~115 mm CW to ~105 mm CW.

Table 3. The CW_{50} values obtained for each trap treatment across two depths (600 and 800 m).

Depth	Control CW_{50}	Small CW_{50}	Medium CW_{50}	Large CW_{50}	χ^2 statistic	*p*-value
600 m	92	101	96	94	0.478	N. S.
800 m	86	93	92	92	0.350	N. S.

Chi-square analysis (χ^2) revealed no significant differences in the size at which the probability of capture is 50% (CW_{50}) between trap treatments at either depth. N. S. = not significant.

(2.8%), although this difference was not significant ($\chi^2 = 3.789$, d.f. = 1, $p > 0.05$). For males, fresh limb loss was equally frequent between dropped crabs ($n = 6$, 2.8%) and slid crabs ($n = 7$, 2.9%). However, females that had been dropped into the live well were significantly more likely to exhibit fresh limb loss ($n = 18$, 6.6%) than those that had been slid ($n = 7$, 2.8%; $\chi^2 = 4.840$, d.f. = 1, $p < 0.05$).

Discussion

Although traditional fisheries have diversified to include deep-water fisheries, there is a paucity of information available regarding the impact that changing fishing practices is having on these deep-water communities. From the current study, it would

Table 4. The relative selectivity (at both current and original market sizes) of each trap condition at 600 and 800 m depth for *C. quinquedens*; because females are not legally marketable, they are considered as 100% discards, so marketable numbers for females is always 0, even if females of market size were caught in the trap.

Depth, ring size, and sex	Average number in trap	At market size 105 mm CW			At market size 115 mm CW		
		Undersized (%)	Marketable[a] (n)	Discards[a] (n)	Undersized(%)	Marketable[a] (n)	Discards[a] (n)
600 m							
Control							
Males	84	91.7	7	77	96.6	3	81
Females	93	89.6	0	93	97.5	0	93
Total	177	90.6	17	160	97.1	5	172
Small (9 cm)							
Males	39	73.1	10	29	87.9	5	35
Females	40	71.8	0	40	100.0	0	40
Total	79	72.4	22	57	90.3	8	71
Medium (10 cm)							
Males	24	77.7	5	19	82.5	4	20
Females	27	77.2	0	27	100.0	0	27
Total	51	77.4	12	39	85.5	7	44
Large (11 cm)							
Males	18	86.0	3	15	90.5	2	17
Females	18	82.9	0	18	95.3	0	18
Total	37	84.4	6	30	93.2	3	34
800 m							
Control							
Males	37	92.4	3	34	95.6	2	35
Females	0	87.5	0	0	100.0	0	0
Total	37	90.0	4	33	96.4	1	36
Small (9 cm)							
Males	20	80.8	4	16	89.2	2	17
Females	24	81.8	0	24	100.0	0	24
Total	43	81.3	8	36	90.6	4	38
Medium (10 cm)							
Males	12	82.8	2	10	87.9	1	11
Females	0	92.9	0	0	100.0	0	0
Total	12	87.8	1	11	87.7	2	10
Large (11 cm)							
Males	10	87.2	1	9	92.1	1	9
Females	11	93.8	0	11	100.0	0	11
Total	20	90.5	2	19	93.8	1	19

[a] Of key interest is the ratio of marketable:discard crabs.

[a] To the nearest whole crab.

Table 5. The overall proportions of *C. quinquedens* that survived, died, or escaped during the course of the hotel experiment.

Haul frequency	Female			Male			Totals		
	n	Alive (%)	Dead (%)	*n*	Alive (%)	Dead (%)	*n*	Alive (%)	Dead (%)
Every 24 h	138	85.5	13.2	114	83.3	12.3	252	84.5	11.5
Every 4 d	136	99.3	0.9	116	97.4	1.7	252	98.4	1.2
After 8 d	113	100.0	0.0	139	97.1	2.2	252	98.4	1.2
Totals	387	94.6	4.3	369	93.0	5.1	756	93.8	4.6

In all, 12 crabs were lost as a result of cage damage. Thus, when proportions sum to less than 100%, the difference represents "missing" crabs.

appear that the deep-water red crab fishery's impact on non-target species (as evidenced by capture frequencies) is low; the most abundant bycatch for this fishery is undersized and female *C. quinquedens*. Very few non-target species were observed in the current study, consistent with observations during commercial sampling trips (pers. obs.; R.A. Wahle, pers. comm.).

Gear trial experiments demonstrated significant differences in both the cpue and the size structure of the crabs retained in each of the trap conditions. The control traps (without escape rings) had the highest mean cpue (~86 and ~36 crabs trap^{-1} at 600 and 800 m, respectively), with undersized (<105 mm CW) crabs averaging >90% of the catch. The mean cpues for traps with escape rings were considerably lower (18–40 crabs trap^{-1} at 600 m and 9–20 crabs trap^{-1} at 800 m), and the proportions of discards were also smaller. This suggests that vessels using the 9 cm escape ring have probably reduced their catch rates of undersized crabs considerably. Although no escape ring was found that completely eliminates undersized animals, if minimizing capture of non-marketable (<105 mm CW) crabs is the aim, then the industry's current 9 cm escape ring appears most effective in achieving this goal, and also retaining a good catch of marketable crabs. If, however, a larger market size (e.g. 115 mm CW) were required, the 10 cm (M) ring would be recommended. Although the size range of retained crabs differs little from the 9 cm ring, the cpue of the 10 cm ring is lower, so the number of non-marketable crabs impacted is also lower. The relative benefit of either size escape ring is best seen by comparing the ratio of marketable:discard crabs, with the goal of maximizing the mean number of marketable (large male) crabs relative to the numbers of discards. If industry also increased the soak time (20–24 h is currently typical), crabs that are small enough to escape may also leave the trap once the bait supply has been exhausted.

Table 6. The proportion of *C. quinquedens* recorded at different stamina indices after being dropped vs. slid into the holding facility; stamina index 0 = dead.

Discard method by sex	*n*	Stamina index (per cent)				
		0	1	2	3	4
Drop						
Female	275	4.4	0.4	0.4	5.8	89.1
Male	216	4.2	0.9	0.0	1.4	93.5
Total	491	4.3	0.6	0.2	3.9	91.0
Slide						
Female	255	0.4	0.0	0.0	3.9	95.7
Male	254	1.2	0.0	0.8	1.2	96.9
Total	509	0.8	0.0	0.4	2.6	96.3

The findings in this study are not necessarily representative of the catch composition during all commercial operations, because fishers will target an area where larger, male crabs are anticipated. Setting traps at 600 m ensured that the gear was tested in a zone where females and smaller crabs were likely to be abundant. Even when sampling at depths most typically associated with marketable males (i.e. ~800 m), the catch was heavily skewed towards undersized crabs (>71%). Because the fishery tends not to operate during May, it is possible that this effect is less typical during the peak fishing season. However, fishery-dependent sampling during commercial trips in 2002 (pers. obs.; R.A. Wahle, pers. comm.) revealed that catches of non-marketable crabs can be very large, particularly at the start of the season when fishers are prospecting for the crabs.

The mortality rates estimated from the caging (hotel) experiment suggest that discard mortality may be ~5% in deep-sea red crab. No significant differences were found between mortality rates associated with sex or size. Mortality was greatest in crabs that experienced multiple ascents and descents (11.5%), suggesting that if crabs are recaptured multiple times in a short period of time, their susceptibility to mortality is increased. Key influences on discard mortality are thought to be thermal shock (Suuronen, 2005) associated with extreme air and surface water temperatures (Tracy and Byersdorfer, 2000; Warrenchuk and Shirley, 2002), and changes in salinity (Harris and Ulmestrand, 2004). The variations in air and water temperatures are less extreme during May (the sampling period) than during summer and fall (primary fishing months), when air and surface water temperatures are at a maximum, and the water column is most stratified. Because the fishery operates at a time when discarded crabs will experience the greatest difference between *in situ* and surface environments, it is recommended that future work investigates how discard mortality varies over the course of the fishing season.

This study demonstrated that the impact associated with discard methods can result in higher levels of crab damage, particularly for females. Mortality was also ~5× higher for dropped vs. slid crabs, suggesting that the impact associated with discard procedures can cause discard mortality, and this finding is in line with other observations on drop effects during handling (Grant *et al.*, 2002; Grant, 2003). The distance from the discard chute to the water's surface is ~2–3 m for most red crab vessels, and modifications to the chute so that crabs are dropped closer to the water's surface would reduce the potential for discard-associated damage.

Additional factors likely to affect the survival rate of discarded crabs are predation *en route* to the sea floor and displacement from their preferred habitat (Brown and Caputi, 1983). A discarded crab must fall through the water column to return to the sea floor. At a hypothetical fast sinking speed estimate of 0.5 m s^{-1}, and a water depth of 600–800 m, this journey may take 20–26 min. Crabs may be exposed to a variety of predators during this period, although assessment of predation rates throughout the 800 m water column presents a considerable logistical research challenge. Sinking rate is another component of the discard process that is likewise difficult to observe, but that also might prove crucial to the survival of crabs returning to the seafloor. Because *C. quinquedens* is a species that demonstrates strong, sex-specific depth preferences, if sinking rates are slow or currents are strong, discarded crabs may be displaced outside their narrow band of preferred habitat along the continental slope, and thus, survival may be impeded.

In summary, these findings represent the first attempt to quantify discard mortality for *C. quinquedens*, and the accuracy of future stock assessments for *C. quinquedens* might be improved if these estimates of discard mortality were incorporated into the estimates of fishing-related and total mortality. If the estimates calculated are truly representative of this species' resilience to fishing procedures, then discard mortality may be a minor issue for this resource, but further investigations into the effects of season, predation, and displacement are recommended. The fact that discard mortality occurs means that the large proportions of undersized and non-marketable catch observed are far from ideal. Both the industry and the crab resource would benefit from further gear research to improve the selectivity of the traps. Recommended gear research foci for the future include gear design (e.g. entry disincentives for smaller crabs) and soak time studies.

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References

Alverson, D. L., Freeberg, M. H., Pope, J. G., and Murawski, S. A. 1994. A global assessment of fisheries bycatch and discards. FAO Fisheries Technical Paper, 339. 233 pp.

Brown, R. S., and Caputi, N. 1983. Factors affecting the recapture of undersized western rock lobster *Panulirus cygnus* George returned by fishermen to the sea. Fisheries Research, 2: 103–128.

CFR. 2002. Electronic Code of Federal Regulations (e-CFR). Title 50: Wildlife and Fisheries: Subpart M – Management Measures for the Atlantic Deep-Sea Red Crab Fishery. 67 FR 63233, Oct. 10, 2002. http://ecfr.gpoaccess.gov/.

DFO. 2003. Newfoundland and Labrador snow crab. DFO Science Stock Status Report, 2003/021.

Elner, R. W., Koshio, S., and Hurley, G. V. 1987. Mating behavior of the deep-sea red crab, *Geryon quinquedens* Smith (Decapoda, Brachyura, Geryonidae). Crustaceana, 52: 194–202.

Feeley, M. W. 1993. The distribution of shell disease and analysis of contaminant loads in the deep-sea red crab, *Chaceon quinquedens*, along the continental slope of the northeast and mid-Atlantic United States. MSc thesis, University of Connecticut, Storrs, CT.

Grant, S. M. 2003. Mortality of snow crab discarded in Newfoundland and Labrador's trap fishery: at-sea experiments on the effect of drop height and air exposure duration. Canadian Technical Report of Fisheries and Aquatic Sciences, 2481. 25 pp.

Grant, S. M., Keats, C., and Blackwood, G. 2002. Survivability of snow crab discarded from the pot fishery: experimental cage design and preliminary drop experiments. A report submitted to the Canadian Center for Fisheries Innovation and the Fisheries Diversification Program, Environmental Awareness and Conservation Technology Component. Department of Fisheries and Oceans, St Johns, Newfoundland. 30 pp.

Gray, G. W. 1970. Investigation of the basic life history of the red crab (*Geryon quinquedens*). Rhode Island Deparment of Natural Resources: Completion Report, NOAA-74062714. 32 pp.

Haefner, P. A. 1977. Reproductive biology of the female deep-sea red crab, *Geryon quinquedens*, from the Chesapeake Bight. Fishery Bulletin US, 75: 91–102.

Haefner, P. A. 1978. Seasonal aspects of the biology, distribution and relative abundance of the crab, *Geryon quinquedens* (Smith) in the vicinity of the Norfolk Canyon, western North Atlantic. Proceedings of the National Shellfisheries Association, 68: 49–62.

Harris, R. R., and Ulmestrand, M. 2004. Discarding Norway lobster (*Nephrops norvegicus* L.) through low salinity layers—mortality and damage seen in simulation experiments. ICES Journal of Marine Science, 61: 127–139.

Hines, A. H. 1988. Fecundity and reproductive output in two species of deep-sea crabs, *Geryon fenneri* and *G. quinquedens* (Decapoda: Brachyura). Journal of Crustacean Biology, 8: 557–562.

Hinsch, G. W. 1988. Ultrastructure of the sperm and spermatophores of the golden crab *Geryon fenneri* and a closely related species, the red crab *G. quinquedens*, from the eastern Gulf of Mexico. Journal of Crustacean Biology, 8: 340–345.

Jennings, S., Kaiser, M. F., and Reynolds, J. D. 2001. Marine Fisheries Ecology. Blackwell Science, Oxford.

King, M. 1995. Fisheries Biology, Assessment and Management. Fishing News Books, Oxford.

Lancaster, J., and Frid, C. 2002. The fate of discarded juvenile brown shrimps (*Crangon crangon*) in the Solway Firth UK fishery. Fisheries Research, 58: 95–107.

Lux, F. E., Ganz, A. R., and Rathjen, W. F. 1982. Marking studies on the red crab *Geryon quinquedens* Smith off southern New England. Journal of Shellfish Research, 2: 71–80.

MacIntosh, R. A., Stevens, B. G., Haaga, J. A., and Johnson, A. B. 1996. Effects of handling and discarding on mortality of tanner crabs (*Chioneocetes bairdi*). *In* The 13th Lowell Wakefield Fisheries Symposium: International Symposium on Biology, Management, and Economics of Crabs from High Latitude Habitats, pp. 577–590. University of Alaska, Fairbanks.

NEFMC. 2004. New England Fisheries Management Council Research Priorities 2005.

NEFSC. 2006. 43rd Northeast Regional Stock Assessment Workshop: 43rd SAW assessment summary report. The US Department of Commerce, Northeast Fisheries Science Center. Northeast Fisheries Science Center Reference Document 06–14. Available from: National Marine Fisheries Service, 166 Water, Street, Woods Hole, MA 02543-1026. 46 pp.

Perkins, H. C. 1973. The larval stages of the deep sea crab, *Geryon quinquedens* Smith, reared under laboratory conditions (Decapoda:Brachyura). Fishery Bulletin US, 71: 69–82.

Purves, M. G., Agnew, D. J., Moreno, G., Daw, T., Yau, C., and Pilling, G. 2003. Distribution, demography, and discard mortality of crabs caught as bycatch in an experimental pot fishery for toothfish in the South Atlantic—*Dissostichus eleginoides*. Fishery Bulletin US, 101: 874–888.

Stevens, B. G. 1990. Survival of king and tanner crabs captured by commercial sole trawls. Fishery Bulletin US, 88: 731–744.

Suuronen, P. 2005. Mortality of fish escaping trawl gears. FAO Fisheries Technical Paper, 478. 72 pp.

Tracy, D., and Byersdorfer, S. C. 2000. Summary of crab injury assessment and aerial exposure sample results from selected 1997/1998 Bering Sea/Aleutian Islands king and tanner crab fisheries and the 1998 Pribilof Islands hair crab fishery. Alaska Department of Fish and Game Regional Information Report No. 4K00-52. 90 pp.

Tracy, D. A., and Byersdorfer, S. C. 2002. Injuries and aerial exposure to crabs during handling in Bering Sea fisheries. *In* The 19th Lowell Wakefield Symposium. Crabs in Cold Water Regions: Biology, Management and Economics, pp. 211–212. Ed. by A. J. Paul, E. G. Dawe, R. W. Elner, G. S. Jamieson, G. H. Kruse, R. S. Otto, B. Sainte-Marie *et al.* University of Alaska Sea Grant College Program, Fairbanks.

Van Heukelem, W., Christman, M. C., Epifanio, C. E., and Sulkin, S. D. 1983. Growth of *Geryon quinquedens* (Brachyura: Geryonidae) juveniles in the laboratory. Fishery Bulletin US, 81: 903–905.

Wahle, R. A., Williams, J., and Chen, Y. 2006. Final Report Submitted to the Northeast Consortium: developing stock assessment methods for the New England deep sea red crab fishery (Award #04–815) and evaluating beam trawls in stock assessment of the New England deep sea red crab fishery (Project Development Award #PD PUZE043). Bigelow Laboratory for Ocean Sciences, West Boothbay, ME. 28 pp.

Warrenchuk, J. J., and Shirley, T. C. 2002. Effects of windchill on the snow crab (*Chionoecetes opilio*). *In* The 19th Lowell Wakefield Symposium. Crabs in Cold Water Regions: Biology, Management and Economics, pp. 81–96. Ed. by A. J. Paul, E. G. Dawe, R. W. Elner, G. S. Jamieson, G. H. Kruse, R. S. Otto, B. Sainte-Marie *et al.* University of Alaska Sea Grant College Program, Fairbanks.

Weinberg, J. R., Dahlgren, T. G., Trowbridge, N., and Halanych, K. M. 2003. Genetic differences within and between species of deep-sea crabs (*Chaceon*) from the North Atlantic Ocean. Biological Bulletin, 204: 318–326.

Weinberg, J. R., and Keith, C. 2003. Population size-structure of harvested deep-sea red crabs (*Chaceon quinquedens*) in the Northwest Atlantic Ocean. Crustaceana, 76: 819–833.

Weinberg, J. R., and Keith, C. 2005. Revisiting population size-structure of the deep-sea red crab, *Chaceon quinquedens*. Crustaceana, 78: 245–246.

Wigley, R. L., Theroux, R. B., and Murray, H. E. 1975. Deep-sea red crab, *Gueryon quinquedens*, survey off Northeastern United States. Marine Fisheries Review, 37: 1–21.

Wileman, D. A., Sangster, G. I., Breen, M., Ulmestrand, M., Soldal, A. V., and Harris, R. R. 1999. Roundfish and *Nephrops* survival after escape from commercial fishing gear. Final report. EC Contract FAIR-CT95–0753. Brussels.

Winger, P. D., and Walsh, P. 2005. Evaluating the feasibility of escape mechanisms in conical snow crab traps—laboratory observations of snow crab behavior. Final report. Center for Sustainable Aquatic Resources, Fisheries and Marine Institute of Memorial University, St Johns, Newfoundland. 16 pp.

Zhou, S., and Shirley, T. C. 1995. Effects of handling on feeding, activity and survival of red king crabs, *Paralithodes camtschaticus* (Tilesius, 1815). Journal of Shellfish Research, 14: 173–177.

Zhou, S., and Shirley, T. C. 1996. Is handling responsible for the decline of the red king crab fishery? *In* The 13th Lowell Wakefield Fisheries Symposium: International Symposium on Biology, Management, and Economics of Crabs from High Latitude Habitats, pp. 591–612. University of Alaska, Fairbanks.

Zhou, S., and Kruse, G. H. 2000a. Modifications of cod pots to reduce tanner crab bycatch. North American Journal of Fisheries Management, 20: 897–907.

Zhou, S., and Kruse, G. H. 2000b. Capture efficiency and size selectivity of two types of pots for red king crabs in the Bering Sea. Alaska Fishery Research Bulletin, 6: 94–103.

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