Unaccounted mortality and overview of the Hawaiian Kona crab *Ranina ranina* (Linnaeus) fishery

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Abstract

Injuries sustained by Kona crabs *Ranina ranina* (Linnaeus) through tangle-nets were quantified during 17 fishing trips on 4 of the Main Hawaiian Islands: Oahu, Hawaii, Maui, and Niihau. Of the 1,160 crabs assessed by onboard observers, 30% were damaged via the fishing process, either through predation of crabs stuck to the tangle-nets or disentanglement by the fishermen. Effects of the most common injuries on crab mortality were then evaluated during a laboratory experiment. Aquaria were used to hold damaged crabs along with undamaged controls to compare the resulting mortalities during two rounds of experiments. The loss of one or more dactyli resulted in 0-8.7% mortality; one limb pulled off resulted in 62.5% mortality; one limb cut cleanly off resulted in 8.3% mortality; and crabs kept out of water under the sun for two hours resulted in 16.7% mortality. The demonstrated care in aquarium husbandry underscores that estimated mortality rates are potentially very sensitive to aquarium setup, explaining differences between similar studies. Additionally, predation on crabs stuck to the tangle-nets and on those sinking back to the sea floor after release were monitored via small high definition cameras. Post-release mortality was calculated by multiplying the number of injuries observed in the field by the corresponding mortality rate from the lab. Unaccounted mortality, the combined rates of post-release mortality and total predation, was calculated at 10.9% for the Hawaiian Kona crab fishery. Using the ratio of landed and released crabs this results in the deaths of an additional 38.9% of landed crabs. However, when catch rates are high, care in handling crabs is compromised, therefore unaccounted mortality is likely a minimum estimate.

Key Words

Captive observation; Discard survival; Injuries; Tangle-net; Brachuyra

1. Introduction

Ranina ranina (Linnaeus) is a Brachuyran crab found throughout the tropical and subtropical Indo-Pacific region. *R. ranina* bury themselves in sandy substrate at depths between 2 and 200 m. The crabs emerge from the sand to scavenge on dead marine fauna, small fish, and invertebrates (Onizuka, 1972; Fielding and Haley, 1976; Kennelly et al., 1990). *R. ranina* are considered a delicacy and are fished throughout their range. The crabs are captured using strings of baited tangle-nets positioned on sandy seafloor. Crabs emerge from the sand and walk across the netting to eat the bait and become entangled in the mesh.

In Hawaii, *R. ranina* are known as Kona crabs, and are a highly prized food crab on the islands. Currently, several catch regulations are in place to protect the Kona crab population. The fishery is closed from May through August to protect the crabs during their breeding season (§HAR 13-95, 2010). During the open season, regulations restrict the harvest to males with at least a 10.2 cm (4 in) carapace length (§HAR 13-95, 2010; HI REV Stat §188-58.5, 2011). These regulations have contributed to a high percentage of Kona crab catch discarded due to size and sex restrictions.

Post-release mortality is an important factor for any stock assessment, and for the management of the Hawaiian Kona crab fishery due to the massive amount of undersized and female crabs released back into the water. Surveyed fishers from Hawaii report that they are careful when disentangling the crabs from tangle-nets (Wiley, 2017). However, injuries to the crabs still occur with the most common being the loss of the dactyl (last segment) of a walking leg. Studies on other crustaceans found that disentanglement injuries decrease growth after molting and can increase mortality based on blood loss from unsealed injuries (Brouwer et al., 2006; Uhlmann et al., 2009; Leland et al., 2013). An Australian study determined that 60-100%

of *R. ranina* with injuries due to disentanglement (loss of one or more dactyli or the loss of a whole limb) died within 50 days (Kennelly et al., 1990).

Predation may be another factor for post-release mortality. Released animals often experience an impaired physiological capacity and altered behavior, which may result in an increased susceptibility to predators (Raby et al., 2014). The predation of animals still stuck to traps (referred to as "depredation" hereafter) is also a common source of mortality within fisheries, distinct from post-release mortality (Clark and Agnew, 2010). Depredation can have both economic and ecological impacts to valuable fisheries (Briceño et al., 2014).

Depredation occurs on *R. ranina* while the crabs are stuck to the tangle-nets before being hauled to the surface. Crabs are unable to bury in the sand to avoid detection and are thus easy targets for various predators (Onizuka, 1972; Kirkwood and Brown, 1998; Brown et al., 2001). Kona crabs are pulled up with missing chunks out of the carapace, missing chelae, and entire bodies missing with only limbs still attached to the net. Hawaiian fishermen estimate that depredation can increase the total percent of injured crabs by up to 40% (Wiley, 2017). Some fishers do make efforts to minimize depredation by limiting soak time and using less bloody bait such as tuna and billfish bones to attract fewer predators.

The purpose of this study was to categorize and quantify injuries to Kona crabs caused by normal fishing activities for the Hawaiian fishery, and to determine the rate of unaccounted mortality within the fishery including both post-release mortality and depredation. This project was conducted in two portions: a field assessment and a laboratory experiment.

2. Materials and Methods

2.1 Field Work

A total of 17 fishing trips were conducted between November 2017 and April 2018. Seven different local fishing boats and crews with experience capturing Kona crabs were contracted to fish for crabs on four of the Main Hawaiian Islands: Oahu, Hawaii, Maui, and Niihau (Figure 1). Fishing boats ranged in length from 23 to 34 feet and in engine power from a single 200 horsepower engine to twin 315 horsepower engines.

Figure 1. Commercial fishing grids for the Main Hawaiian Islands. Fished areas highlighted orange.

Typical fishing practices included setting strings of tangle-net traps with bait attached to the middle over sandy substrate 10-90 m deep. Fishermen attached traps 3-5 m apart to a set line with weights at the ends connected to buoys and enough rope for the buoys to float freely. Traps were about 1 m in diameter and covered with one or two layers of small mesh netting which entangled the limbs of the crabs as they walked across the net to the bait (Figure 2). Operational characteristics – including traps per string, number of sets, soak time, depth, and bait (typically fish scraps such as mahi, tuna, and billfish skin and bones) – varied between fishermen.

Figure 2. Tangle-net used to capture the attached Kona crabs. Metal ring measures roughly 1 m in diameter with either one or two (pictured here) layers of mesh netting.

The number of traps, soak time, location, and water depth were recorded for each set. Upon retrieval of the crabs, carapace length, trap number, time out of water, sex, and any injuries were recorded for each captured crab. Injuries which occurred before being handled by fishermen were classified as depredation injuries while those which occurred directly from fishermen pulling crabs off the nets were classified as disentanglement.

Cameras were utilized throughout the fishing and release process to observe crab behavior and predator interactions. Ten high definition GoPro Hero Session cameras were attached to random nets in order to capture bottom type, crab arrival times, trap efficiency (number of crabs walking over the trap that were captured), and predator interactions and arrival times. A live-feed splash camera (Deep Blue Pro from Ocean Systems Inc.) and a Garmin VIRB 360° camera were used to observe the crabs upon release. Underwater housing was made by the National Oceanic and Atmospheric Administration Pacific Islands Fisheries Science Center Advanced Tech Program and used to allow recordings of the entire descent of the crabs. These cameras captured the average time it took to sink to the bottom, behavior of the crabs after release, and any predator interactions.

2.2 Lab Experiment

Crabs used in the mortality experiment were captured on the west side of Oahu and placed in a live-well aboard the fishing boat. The crabs were then transferred into aerated 100 L bins filled with seawater and driven by truck to the Waikiki Aquarium (approximately 1 hour). After acclimating with the aquarium water, the crabs were placed into one of four identical 680 L (1.0 x 1.5 x 0.6 m) tanks, each containing 20 cm of sand. Crabs were held in these aquaria for 3-9 weeks before beginning the experiment. Crabs kept from each specific fishing trip were randomly, yet equally, assigned to each treatment group to ensure no group had a disproportionate amount of older crabs to newer.

The experiment consisted of two unique rounds, which tested the effect of common injuries observed during the fishing process on the mortality of the crabs. Based on Kennelly et al. (1990), each round lasted a total of 50 days. Crabs were sexed, measured, and weighed prior to the start of the experiment. The length weight relationships for both males and females were calculated using these measurements. Cable ties labeled with unique numbers by permanent marker were used as simple loop-tags and attached to the chela of each crab for identification. The four aquaria represented replicate experiments for each round, with all treatment groups represented in each tank (Table 1). Limbs or segments were removed according to the crabs' assigned group. The choice of which limb was to be injured within each treatment group was determined randomly. Crabs were then placed back in their designated tanks. They were cared for in the same manner as the holding period and otherwise left alone for the 50-day experimental period.

Round 1 began June 20, 2017 with 88 crabs. The crabs were randomly assigned to one of five treatments: control (no injury), removal of one dactyl from one walking leg, removal of one dactyl from two walking legs, removal of one whole walking leg (cut cleanly off with wire cutters), and preexisting (old) injuries (acquired during holding period). Old injuries ranged from a single missing dactyl to multiple whole limbs missing.

Round 2 began February 2, 2018, with 95 crabs. Round 2 had four treatments: control (no injury), one dactyl removed from four legs, removal of one whole walking leg (pulled off), and two hours sitting out of water in a bin exposed to the sun (similar to extreme cases observed on fishing trips). Crabs from Round 2 were held in bins half-filled with standing aquaria water for 40 minutes after sustaining their injury to better simulate the most common fishing practices observed before releasing crabs in the field.

Table 1: Treatment groups for Kona crabs present in each of the four experimental tanks.

	Treatment Group	# crabs per tank	# crabs per treatment
Round 1	Control (no injury)	5	20
	Removed 1 dactyl from 1 limb	5	20
	Removed 1 dactyl from 2 limbs	5	20
	Removed 1 whole limb (cut)	3	12
	Old injuries	4	16
	Total	**22**	**88**
Round 2	Control (no injury)	6	24
	Removed 1 dactyl from 4 limbs	6 (one tank w/ 5)	23
	Removed 1 whole limb (pulled)	6	24
	2 hours out of water	6	24
	Total	**24 (one tank w/ 23)**	**95**

The aquaria used an open system of seawater flowing continuously into each tank. Round 1 used the Waikiki Aquarium's well saltwater, which flowed at a rate of 300 L/hr resulting in a residence time of about 1.5 hours. Round 2 used the Aquarium's natural seawater (filtered surface ocean water) in accordance to their water usage needs at the time. The natural seawater flowed at a rate of 900 L/hr resulting in a residence time of about 0.5 hours. The same tanks were used in both rounds and were located outside, providing natural sun cycles, and fitted with layered mesh covers to block direct heat from the sun and keep crabs within the tanks.

Crabs were fed daily with pieces of herring, night smelt, or white crab. The tanks were also cleaned daily by pulling out excess food from the previous day and using a gravel vacuum to clean smaller food particles and detritus from the sand. Additionally, water overflowed down a stove-pipe (opposite the in-flow) which removed floating debris. Water quality was tested weekly to ensure parameters such as temperature, salinity, pH, dissolved oxygen, and nitrogen levels (NH_3, NO_3^-, NO_2^-) were maintained throughout the trials. All mortalities were removed and recorded daily.

Annual Fishing Mortality

One of the primary foci of this study was to estimate the post-release mortality of those crabs being released back into the ocean. Probable post-release mortality was calculated based on the number and type of injury witnessed in the field and the mortality rate of injuries observed in the laboratory experiment. The percent mortality for multiple injuries was calculated as the mean of the average mortality rates of all other injuries (1 dactyl/2 dactyli, 3+ dactyli, limb/chela). Injury specific post-release mortality was calculated by multiplying the number of injuries observed in the field by the corresponding mortality rate calculated in the lab.

Depredation events were not included with post-release mortality. These instances assumed 100% mortality to be conservative based on the severity of injuries observed. Thus, depredation mortality equaled the number of field observations.

Annual fishing mortality can be calculated by using the rates of crab retention and unaccounted mortality (combined post-release and depredation mortality). Fishing mortality (F) is equal to the amount of crabs landed (L) plus the unaccounted mortality (U) as seen in Equation 1.

$$F = L + U \quad (1)$$

U is determined by Equation 2, where a = mortality rate from the experiment for a specific injury, b = observed number crabs with the corresponding injury in the field, d = deaths from depredations, c = total captured crabs in the field, and T = total released crabs within the fishery.

$$U = \left\lfloor \frac{\left(\sum_{i=1}^{n} a_i b_i\right) + d}{c} \right\rfloor * T \quad (2)$$

Then, the amount of L crabs can be expressed in terms of T by some factor of x (determined by fishing), as in Equation 3.

$$T = L * x \qquad (3)$$

F can then be calculated from the amount of L crabs as Equation 4.

$$F = L + \left(\left\lfloor \frac{(\sum_{i=1}^{n} a_i b_i) + d}{c} \right\rfloor * L * x \right) \qquad (4)$$

3. Results

3.1 Fishing Summary

The number of nets per set ranged from 10 to 100. Soak time varied from 23 minutes to a maximum soak time of just over 3 hours; the mean soak time was 74 minutes (SE = 2.9 min). A total of 1,337 crabs were captured with 1,160 crabs measured and assessed for injuries (Table 2). The Niihau trip had the highest catch with 473 total crabs. During this trip, the amount and rate of crabs captured was so high complete data could only be captured for the first 40 crabs per set. The remaining catch per set were quickly counted based on sex and size.

A basic catch-per-unit effort (CPUE: total crabs/traps) was calculated per island. Niihau and Hawaii had the highest CPUE (Table 2). Niihau also had the highest percentage of legal sized males at 25.6% of the total catch. Oahu had the most trips resulting in the highest total catch yet had the lowest CPUE. Coordinating logistics with suitable weather windows limited the opportunities to sample neighboring islands as the researchers were based on Oahu.

Table 2: Summary of trips and catch by island platform. Trips were performed during fishing season November 2017-April 2018. Ratio of males to females is expressed as M:F. Catch per unit effort (CPUE) expressed as both legal crabs kept per trap and total crabs caught per trap.

	Trips (N)	Female	Male (<4 in)	Male (>4 in)	Total	M:F	% Kept	# sets	# traps	CPUE (kept/traps)	CPUE (total/traps)
Niihau	1	208	144	121	473	1.27	25.6%	8	800	0.15	0.59
Oahu	14	345	165	129	639	0.85	20.2%	97	2690	0.05	0.24
Maui	1	24	27	14	65	1.71	21.5%	15	186	0.08	0.35
Hawaii	1	104	27	29	160	0.54	18.1%	16	240	0.12	0.67
Total	**17**	**681**	**363**	**293**	**1,337**	**0.96**	**21.9%**	**136**	**3,916**	**0.07**	**0.34**

A total of 512 video observations from the GoPros mounted to the traps were analyzed. These videos represented 130 traps, from 81 sets on 16 different fishing trips. The GoPro video footage revealed that crabs reached the trap a mean of 22 minutes (SE = 1.33 min) after setting. The maximum time it took for a crab to come to the nets was 71 minutes. About 75% of crabs were at the trap within 30 minutes of it settling on the bottom. Crabs were often observed walking on and off the traps without capture. Of the 140 crabs observed on the nets, 39% were able to escape. Crabs walking off the net typically appeared smaller than the legal size. Their walking legs stepped more easily between the mesh to avoid entanglement.

Total catch was comprised of 49% male and 51% female crabs, which was not significantly different than a 1:1 sex ratio ($\chi^2 = 0.20$, df = 1, $p > 0.1$). Male carapace length differed significantly with female carapace length ($z = 8.17$, df = 1142, $p < 0.001$). The largest male had a carapace length of 15.2 cm while the largest female carapace length was 12.7 cm. Males and females had a mean carapace length of 9.78 cm (SE = 0.09 cm) and 8.86 cm (SE = 0.06 cm) respectively.

Kona crab size across islands was similar. The largest males were caught in Niihau and Oahu. Maui had the highest percentage of non-mature males (20%) and females (43%). The length weight equation is $W = 3.9 \times 10^{-3} L^{2.454}$ ($R^2 = 0.80$; n = 42) for males and $W = 2.7 \times 10^{-3} L^{2.5316}$ ($R^2 = 0.82$; n = 53) for females.

In total, 25.4% of captured crabs were injured in some way due to disentanglement. The most common observable injury was the loss of a single dactyl from one limb, followed by the loss of two dactyli (43% and 15% of injured crabs respectively) (Figure 3). Crabs captured in Niihau and Hawaii had the most injuries due to disentanglement (40.6% and 53% respectively). These trips had the highest catch rates (Table 2), resulting in less careful disentanglement by the fishermen and a higher injury rate for the crabs.

Figure 3: Percentage of type of injuries sustained from disentanglement and depredation by island.

Additionally, 4.8% of crabs caught were injured through depredation. Maui had the highest proportion of depredation while Niihau had the lowest proportion of depredation. More depredated crabs may have gone unnoticed during the Niihau trip; the higher rate of catch made it difficult for researchers to closely inspect each crab and net. Unquantified mortality from depredation for which there was no video evidence, nor evidence left on the net, is also likely.

The most common injury attributed to depredation was the loss of one or both chelae (58%). Other common results from depredation included a missing chunk out of the carapace (28%) and retrieval of only limbs or pieces of crab (14%). Video footage revealed the spotted burrfish *Chilomycterus reticulatus* (Linnaeus) was responsible for eating the crabs' chelae once the crab was captured on the net. The spotted eagle ray *Aetobatus narinari* (Euphrasen) sucked the crab off the net and left only legs and pieces of the abdomen. Of the 140 crabs caught on camera, 11 depredation events were observed (7.9%). All 11 of these depredation events were from either the spotted burrfish or the spotted eagle ray. Other predators did approach the nets (sharks, rays, jacks), but they were only interested in the bait and didn't harm the crabs even after multiple passes. Predators (including those that attacked only the bait) reached the traps a mean of 35 minutes (SE = 2.73 min) into the soak time.

The combination of a live-feed splash camera and a 360° camera provided a view of the water column and sinking crabs. Bottom current combined with surface winds made it difficult to follow crabs all the way to the bottom on several releases. However, upon successful camera drops, predators were never witnessed consuming a sinking crab or a crab off of the sand. A scrawled filefish *Aluterus scriptus* (Osbeck) was observed pecking at a sinking crab in one video and pecking at a crab laying ventral side up on the sand in another video. It was unclear if these instances caused any real damage to the crabs. Most crabs landed on their back before burying after a few minutes or more.

3.2 Aquarium Mortality Experiment

Temperature within the aquaria typically varied between 23° and 25° C between the morning and heat of the day, although one day did have a spike up to 27° C. No negative effects were observed during this temperature peak. Salinity remained close to 34. The pH was maintained closely around 8.0. Dissolved oxygen was kept above 85%. Values for NH_3, NO_3^-, and NO_2^- were kept below 0.13 ppm, 0.05 ppm, and 0.02 ppm, respectively.

Four (4.5%) Kona crabs died during Round 1 while 23 (24.2%) died during Round 2. Daily mortality percentages are shown in Figure 4. Only the one limb removed treatments (pulled and cut) and four dactyli treatment had crabs die quickly (1-5 days) after injuries were induced. The remaining mortalities all occurred after day 40 during Round 1 and day 19 in Round 2. No significant differences in mortality were observed between males and females or specific tanks allowing all the data from both rounds to be pooled together, which yielded a significant difference between treatment groups ($\chi^2 = 53.3$, df = 7, $p < 0.01$).

Figure 4: Mortality of Kona crabs over the 50-day experimental periods for Round 1 (A) and Round 2 (B). The “Control” and “2 dactyli removed” groups had zero mortality throughout.

The treatment group with one whole limb removed by pulling yielded the highest mortality percentage by nearly four times that of the next treatment group (two hours out of water) and nearly eight times the third highest mortality group (four dactyli removed). When the pulled whole limb group was removed from the treatment comparison, no significant difference in mortality was detected across all other treatment groups ($\chi^2 = 6.7$, df = 6, $p > 0.3$). Thus, the whole limb group was the clear driver in the initial comparison and had a significantly different mortality rate than the other treatment groups.

Limbs pulled off resulted in an increased mortality rate nearly eight times greater than when limbs were cut cleanly. Pulling off limbs caused a small amount of connected inner tissue loss for some of the crabs. Each of the eight crabs (33.3%) that lost any inner tissue when the limb was pulled died within two days of limb loss.

Zero crabs molted during Round 1 (June-Aug) while 27 crabs molted during Round 2 (Feb-March). No difference in number of molts was observed between males and females, but there was a significant difference between crabs that molted and their treatment group ($\chi^2 = 11.1$, df = 3, $p < 0.05$). The control group had the highest amount of molts.

Regeneration was also observed in the lab following each round of experiments. Crabs were kept on display at the Waikiki Aquarium following the first round of experiments. Three months after the first round concluded molting occurred in the display tanks and the crabs were reexamined. Each of the previously injured crabs (n = 11) had clear signs of regeneration following this molt. After the second round, 20 crabs from injured groups were maintained in one experimental tank. Two crabs, each with four dactyli removed, successfully molted after the experiment. Molts occurred 76 and 84 days after injuries were first induced. Each crab successfully regenerated all four dactyli following this single molt.

3.3 Post-Release Mortality

Field observations revealed nearly 80% of the total crabs caught are released due to the size and sex restrictions (Table 2). The unaccounted mortality rate (including depredation on the nets) was 10.9%; post-release mortality caused by disentanglement alone was 6.1% (Table 3)

Table 3: Post-release and total unaccounted mortality based on observed field injuries and mortality from laboratory experiment.

Injuries	**# Observed (in field)**	**% mortality (+/- 1 SE)**	**Estimated deaths**
1 dactyl/ 2 dactyli	205	2.5% (+/- 2.5 %)	5.1
3+ dactyli	31	8.7% (+/- 5.9%)	2.7
limb/chela	16	62.5% (+/- 9.9%)	10.0
out of water > 2 hrs	50	16.7% (+/- 7.6%)	8.3
multiple injuries	43	24.6% (+/- 4.6%)	10.6
depredation	56	100%	56.0
non-injuries	759	4.5% (+/- 3.1%)	34.5
TOTAL OBSERVED	1160		
Post-release mortality		6.1% (+/- 3.3%)	71
Unaccounted mortality		10.9% (+/- 3.3%)	127

Applying the results to Equations 1-4:

$$F = L + [0.109 * L * 3.57] = 1.389L$$

Thus, annual fishing mortality (*F*) for any given year can be easily calculated by multiplying the number of landed crabs (*L*) by 1.389.

4. Discussion

We have quantified the components of and estimated total unaccounted mortality for the Kona crab fishery using both field observations and aquarium studies. Previous studies conducted similar experiments testing injury effects on the mortality of *R. ranina* in Hawaii (Onizuka, 1972) and Australia (Kennelly et al., 1990; Kirkwood and Brown, 1998). The results from each study are provided in Table 4.

Table 4: Comparison of mortality percentages (sample size in parentheses) of injured Kona crabs from four studies.

Injury	Onizuka (1972)	Kennelly et al. (1990)	Kirkwood and Brown (1998)	Present Study
None	6.4 (94)	12.5 (16)	5.0 (20)	4.5 (44)
1 Dactyl	7.7 (13)	62.5 (16)	20.0 (20)	5.0 (20)
2 Dactyli	-	-	-	0.0 (20)
3 Dactyli	-	-	25.0 (20)	-
4 Dactyli	9.3 (54)	62.5 (16)	-	8.7 (23)
8 Dactyli	20.0 (15)	-	-	-
1 Limb (pulled off)	70.0 (10)	-	55 (20)	62.5 (24)
1 Limb (cut off)	-	-	-	8.3 (12)
2 Limbs	-	100.0 (16)	-	-
1 Chela	-	-	90 (20)	-
2 Hours sitting out	-	-	-	16.7 (24)

The mortality results achieved for this study are similar to Onizuka (1972) and Kirkwood and Brown (1998) even with an experimental time twice that of Kirkwood and Brown (1998) and an unknown time for Onizuka (1972). The mortality rates observed by Kennelly et al. (1990) were far higher than the other studies for comparable injuries: 3 to 12 times higher with one dactyl removed and about 7 times higher with four dactyli removed.

The loss of one or more dactyli does not appear to have a major impact on mortality for crabs studied in Hawaii. However, the loss of an entire limb does appear to have a drastic impact on Kona crab survival. All studies testing this injury showed a mortality rate of at least 55%. An interesting caveat, when the limb was cut cleanly off at the base, the mortality rate drastically dropped over 7 times that of pulling off the limb.

Limb autotomy was observed on four instances when crabs were handled by people – three times while fishing and once while preparing crabs for the experiment (resulting in the exclusion of the crab) – and may explain why cutting the limb cleanly was far less likely to result in mortality. The autotomy response of *R. ranina* was also documented by Kirkwood and Brown (1998). However, Kennelly et al. (1990) suggested *R. ranina* exhibited a weak autotomy reflex possibly because they spend most of their time buried in the sand where limbs could be easily lost while digging.

Increased survival rate for cleanly injured crabs has meaningful implications to the Kona crab fishery. Fishermen could take extra precaution not to remove any inner tissue deeper than the limbs of the crabs to increase chances of survival. A last resort for particularly stuck crabs could be to cut the crabs off the nets rather than pulling. Even better for the crabs would be to cut the mesh point of the net to avoid any damage to the crab. However, higher catches can cause a hurried response in fishermen to quickly remove crabs from the tangle-nets to keep pace with the rate of fishing. Such instances were observed while fishing around the islands of Niihau and

Hawaii resulting in rougher detachment and more injuries; asking fishermen to increase handling time to limit injuries may not prove to be practical.

The aquarium husbandry techniques used to hold the crabs play a vital role in their possible mortality. Providing enough space and sand to allow crabs safety from each other likely decreases their stress levels and intraspecific aggression, while allowing damaged crabs enough protection to safely heal their wound(s). Kirkwood and Brown (1998) noted crowded conditions (12-16 crabs m^{-2}) frequently resulted in greater aggression between crabs causing more injuries and possibly death. Our study had initial crab densities upwards of 14.76 m^{-2} and minimal effect on mortality even with 27 molted crabs during the experiment. The 20 cm of sand greatly helped by providing more 3-dimensional space for crabs to hide. Kennelly et al. (1990) had double the initial crab density of our study (30.30 crabs m^{-2}), which could be a large factor in why such high mortality was observed. Maintaining consistent water quality is also crucial to prevent mortalities not directly caused by the injuries. Kennelly et al. (1990) noted a breakdown in the aeration system which caused a 12.5% increase in mortality across treatment groups.

Kirkwood and Brown (1998) was the only study to effectively use cages buried in situ rather than aquaria (despite forced early termination due to collision with a fishing vessel). Kennelly et al. (1990) achieved one day of in situ testing before cages were pulled from the substrate. Regardless, no study currently accounts for potential increased mortalities caused by decreased competitive ability, foraging efficiency, and increased predator vulnerability in injured crabs (Juanes and Smith, 1995). Laboratory results can be validated by tagging injured crabs and recapturing them in situ. Previous work shows high site fidelity and successful recaptures of tagged Kona crabs in Hawaii (Onizuka, 1972).

In addition to physical injury from the fishing process, post-release mortalities may occur immediately as the crabs are vulnerable to predators as they sink and sit on the sand before burying. Other studies have observed loggerhead turtles *Caretta caretta* (Linnaeus) feeding on *R. ranina* after they were released from the boat (Kirkwood and Brown 1998). Most crabs take at least 68 seconds to bury upon reaching the sandy substrate, while some crabs may take up to 20 minutes to fully bury (Kirkwood and Brown, 1998). Crabs remaining on their backs are far more vulnerable to predators.

The female and undersized crabs in the present study were usually released as a group after several sets of nets had been picked up. Fishermen tend to keep crabs on the boat in order to deter predators from entering fishing areas. The fishermen then drive to a different location with suitable habitat to drop the crabs away from the nets still soaking. Such practices seem to be proficient in deterring predator interactions with sinking crabs as the drop cameras never witnessed a crab taken in the water column or on the substrate.

Crab depredation while on the traps varied between island and fishing trip. Injuries attributed to depredations accounted for 14% of the total injuries observed. Fishermen must allow enough time to attract the crabs but too much time may increase depredation on the trapped crabs. Based on the average time it took for crabs to reach the trap, fishers could limit their soak time to 45 minutes and would still catch 90% of the crabs while reducing predator interactions. Though sharks, stingrays, and jacks were never observed eating the trapped crabs on the net videos, it still may occur.

One indicator that crabs are surviving fishing injuries post-release was the field observation of 50 captured crabs with clear signs of regenerated dactyli, legs, and chelae.

Regenerated limbs observed in the field appear noticeably different than normal appendages; they are often smaller, rougher, and discolored.

Regeneration and limb loss are common for crustaceans (Skinner, 1985) and have been studied on other benthic crabs (Niwa and Kurata, 1964; Edwards, 1972). However, several papers have stated that *R. ranina* may not have the same repair mechanisms observed in other marine crabs (Kennelly et al. 1990, Juanes and Smith 1995, Brown et al. 2001). We document clear evidence that Hawaiian Kona crabs can seal wounds and regenerate lost limbs after breakage caused by fishing or predation. However, based on studies of other decapods, injuries sustained during fishing practices as well as blood loss could affect their survival in the wild and growth rate after molting (Brouwer et al., 2006; Leland et al., 2013; Urban 2015). Additionally, limb loss can have an effect on mating success (Abello et al., 1994).

Due to the large amount of undersized crabs and female crabs thrown back, unaccounted fishing mortality is an important factor for any stock assessment and management of the Hawaiian Kona crab fishery. This study calculated the actual annual fishing mortality for Kona crabs in the Hawaiian fishery to be 1.4 times that of the reported landed crabs. The additional deaths are caused by injuries to released crabs during disentanglement and depredation. Additional onboard observations to better quantify Kona crab injuries, especially for the top fishers in the commercial fishery, would allow for a more representative correction factor. Managers can use this information to evaluate the efficacy of current regulations such as the annual catch limit and the prohibition of female crab retention.

Of further interest, size and sex structure for the Hawaiian Kona crab fishery were determined. Kona crabs are sexually dimorphic with males attaining a larger size than females

(Fielding and Haley, 1976; Minagawa, 1993). Based on size at maturity (Fielding and Haley, 1976), 91% of males and 83% of females captured in our study were sexually mature.

Prior studies determined the sex ratio of Hawaiian Kona crabs to be more skewed than the current study. Sites including Waimea Bay and Wailua Bay on the North shore of Oahu and Penguin Banks off the coast of Molokai consisted of 55% male and 45% female (Onizuka, 1972; Fielding and Haley, 1976). However, a different study at Penguin Banks observed the opposite sex ratio of 45% male and 55% female (Vansant, 1978). Our study falls in between these estimates with 49% male and 51% female. The difference in ratios might be attributed to varying study area, depth, or sampling season. The current study included a broader range of locations than the other three studies, thus may be a closer representation of the statewide population. Additionally, this study was conducted after the 2006 regulation that prohibits the take of females (HI REV Stat §188-58.5, 2011), which suggests the regulation has had a minimal impact on the sex ratio.

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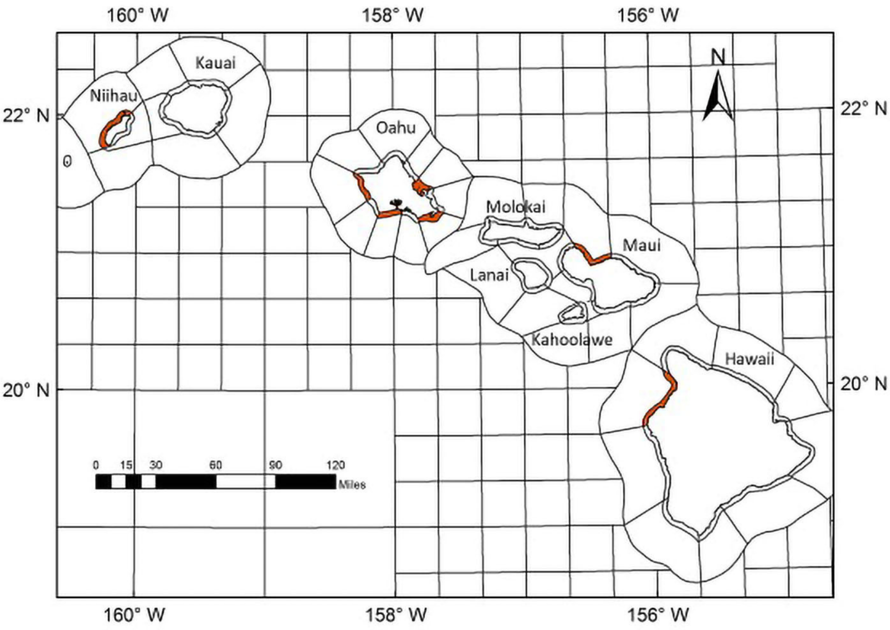

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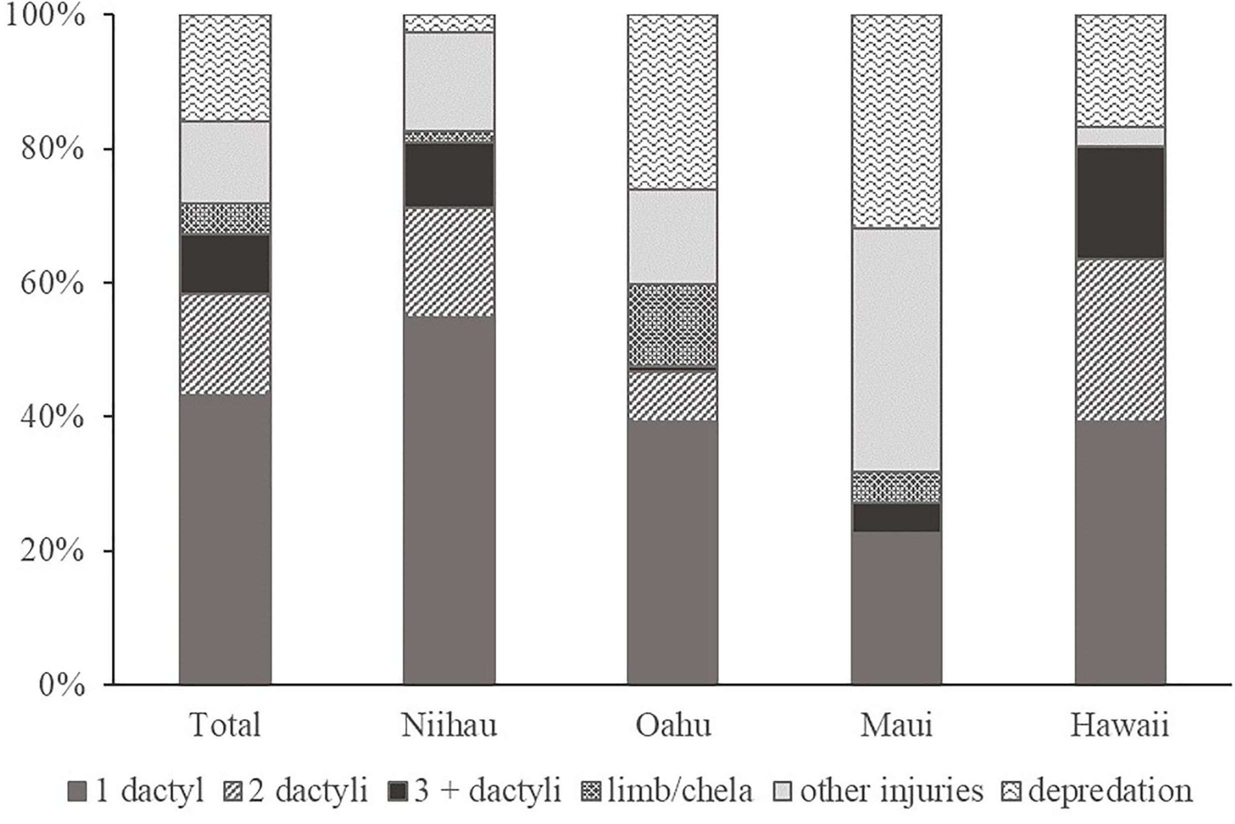
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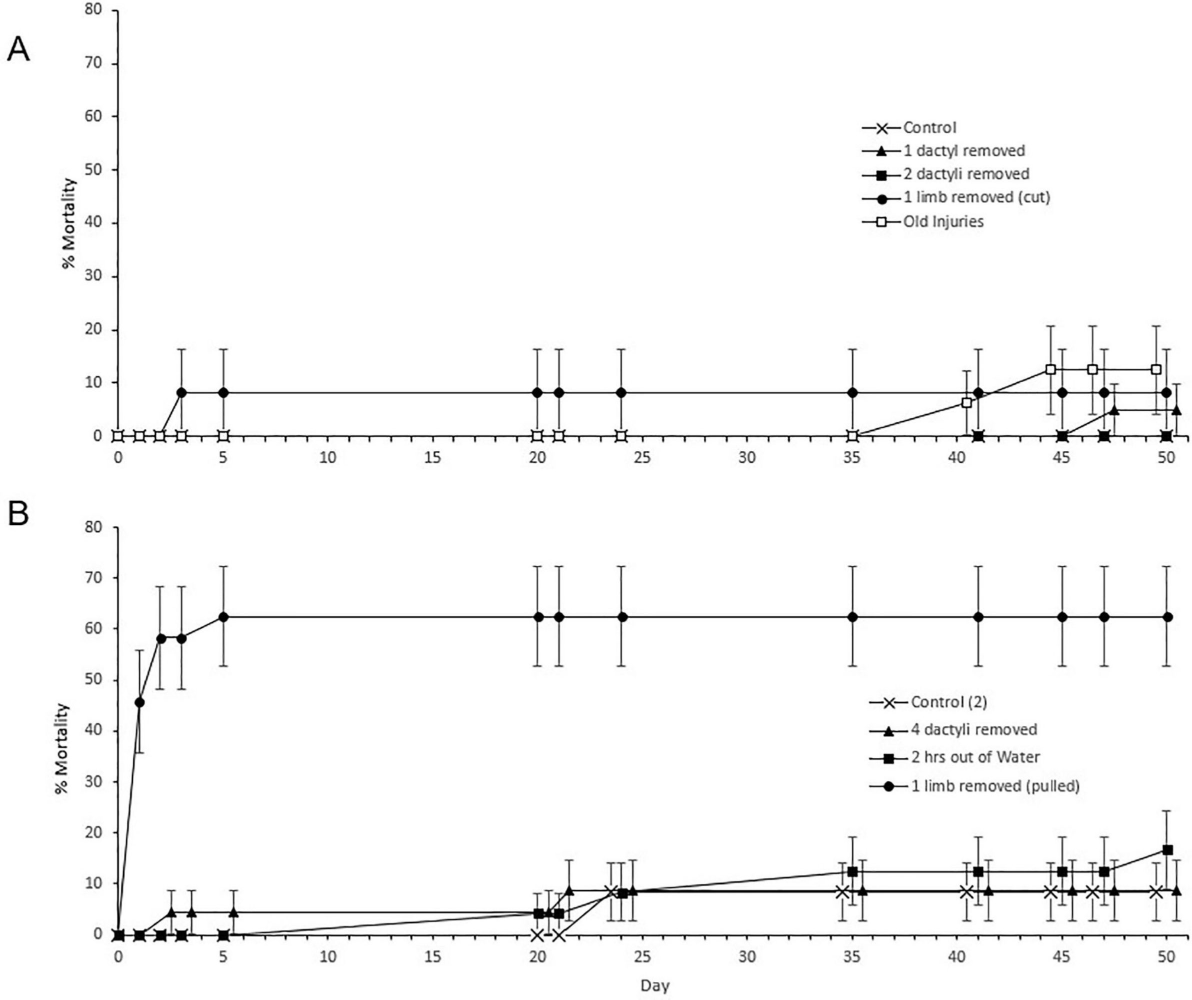
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