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Discard Survival and Condition in Orkney Brown Crabs (*Cancer pagurus*)

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This report presents the results of marine and freshwater scientific work carried out for Marine Scotland under external commission.

Abstract

A major problem faced in commercial crustacean fisheries, and the research and management of such fisheries, is the potential effect of discarding practices on survival and condition of non-retained catch. This study combined RAMP (reflex action mortality predictors) with vitality scores and the likelihood of survival for each vitality category to estimate survival rates of discards in the Orkney brown crab fishery. The vitality reflexes used in this study were similar to those established by Stoner (2012) and based upon behavioural responses. The study was divided in two phases: Phase I considered crabs smaller than the then-current (2016) 140 mm carapace width MLS (Minimum Landing Size) and Phase II considered legal-sized crabs. Two experimental set-ups were used, namely creels and tanks, each comparing control and treatment groups. Four categories of treatments were considered: missing limbs, recently moulted crabs, black spot and berried females were tested against a control group. In total, 265 brown crabs were collected for observation, of which 162 were females and 103 were males. Reflex impairment was closely related with vitality and damage scores showed more crabs died when scored 3 than when scored 2/1. Tank trials excluded all individuals that died when temperatures exceeded 16.2^{o}C. Results obtained from the creel trials, exposed to ambient environmental temperature, were considered to show a clearer picture of the fate of brown crab discarded - an overall estimated survival rate of 92.7% across all groups in comparison with tanks with 90.3%.

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Discard Survival and Condition in Orkney Brown Crabs (*Cancer pagurus*)

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Introduction

Brown crab (*Cancer pagurus*) is heavily exploited throughout Scotland and England, and from the south of France to the north of Norway (Tully, 2006; Woll, 2010). It is one of the most important targets of the Scottish inshore fisheries and the second most important species of crustacean landed in Scotland in terms of value at first landings. Scottish fleet landings into Scotland accounted for 10,806 tonnes and a value of £14,837 million in 2016 (Scottish Government, 2016). This study occurred in Orkney where total landings amounted to 3,404 tonnes and a value of £4,769 million in 2016 (Scottish Government, 2016). According to OSF (Orkney Sustainable Fisheries Ltd), voluntary logbook records of brown crab comprise 80% of the Orkney landings (Coleman & Rodrigues, 2016).

The brown crab fishery has been growing over the past 30 years. Gear improvements and more modern fishing vessels allow fishermen to target areas that have not been previously exploited within the 12 nm limit (nautical miles).

The Orkney brown crab fishery is long established around the islands and it has provided income for many families. The fleet is comprised mainly of small vessels; currently there are 120 vessels registered within Orkney that hold a shellfish licence with the assumption that all at some point target brown crab. Scottish Sea Fisheries Statistics (2015) reported 110 active registered vessels, of which 82 are under 10 m, and 28 over 10 m. Most vessels are operated by two fishermen on one-day trips, and often combine brown crab with other species such as European lobster and velvet crab. Some of these vessels may be able to stay out for longer periods at sea. Additionally, the Orkney shellfish fleet has two large vivier vessels with live storage facilities, which catch crab offshore.

Traditionally, the fishery has been essentially inshore in nature encompassing coastal waters mainly between 6 nm and 12 nm. Fishing occurs throughout the year with a landings peak starting in late April and ending between October and November. Outside this period, landings are substantially reduced when compared with the summer months. The species lives on soft bottom sediments at depths ranging from 15 to 120 m. Fishermen use creels to catch brown crab, a stationary passive gear type that captures animals that range from sizes above and below the minimum target size and holds them in a common space. Creels are baited with either or both fish frames and/or whole oily fish and are set on strings with an average of 25 creels connected.

A major problem faced in commercial crustacean fisheries, and the research and management of such fisheries is the potential effect of discarding practices on survival and condition of non-retained catch. The discarded catch includes those individuals that are outside size and/or sex restrictions imposed by fisheries managers. In Orkney, discarded brown crab comprise individuals that do not meet the new MLS (Minimum Landing Size) of 150 mm carapace width (CW) as well as soft shelled individuals (recently moulted individuals), bacterial shell diseased brown crab (known as black spot), berried females and individuals missing both claws.

Observer trips and a voluntary logbook scheme undertaken by OSF showed 47% (by number) of the catch was discarded within the last four years. In 2016, the average discard rate was reported as 27% of the total catch, comprising both undersized and unmarketable crabs (Coleman & Rodrigues, 2016). The survival of these discarded individuals is important to the future status of the target fishery and may be essential for the success of any measures restricting landings by size and sex. The incidental mortality of a fishing method can represent a loss of potential income and a human food source (Kelleher, 2005; Stoner, 2012; Urban, 2015). It is recognised that discarding non-retained catch over many years may also play a significant role in affecting reproductive success and future harvests (Murphy, 1995).

Currently, discard data are not routinely collected for brown crab in Scotland and any mortality from discarding practices is not taken into account in stock assessments (Mesquita et al., 2016). The mortality of discarded crustacean species has been assumed low and some papers suggest that a number of crustacean species (crabs, lobsters) are relatively robust and likely to survive when discarded, especially those caught in creel fisheries (Stevens, 1990, Mesnil, 1996). However, even though crabs are returned to sea alive it is important to consider unaccounted mortality as a feature in the overall assessment of a fishery (Krafft, 2015). Further, survival rates can vary greatly between crustacean species (Tallack, 2007).

Stress in crabs can be caused by various cumulative factors that influence survival rates. Anthropogenic changes and fishing pressure combined can influence long-term effects on biological processes such as spawning, egg attachment, growth, maturity reproductive capability and feeding (Davis, 1980; Murphy et al., 1995; Brouwer et al., 2006; Leland et al., 2013; He, 2016). Many of the fishery practices can cause crabs injuries, limb loss, and can induce mortality as results of capture and handling (Barber et al., 2007; Patterson et al., 2009; Duermit et al., 2017). Discarded animals in poor condition are shown to be less successful in competing for food and shelter compared to apparently undamaged conspecifics. However, estimating relevant discard mortality rates is rather challenging because it is difficult to replicate the effects of the various factors that influence it and to assess the long-term fate of individuals (Murphy, 1995; Benoit, 2012). The main factors usually recognized to affect the survival of discards are the species and size, depth of capture, gear type, volume and composition of the catch, method of sorting and handling, season, air temperature (Mesnil, 1996). It is vital to account for all sources of mortality if sustained yield management is to be effective.

Over the years, some research regarding the fate of discarded crustaceans has been undertaken and further studies have been carried on potential physiological stress caused by the fishing gear and on the importance of understanding potential discards mortality for stock assessment purposes. A great emphasis has been given to mobile gears regarding mortality and damage rates of discarded crustaceans. By comparison, mortality of discarded crustaceans in creel fisheries has been less fully studied and for just a few species (*Cancer magister* (Kruse et al 1994); *Paralithodes camtschaticus* (Zhou and Shirley 1995); *Chionoecetes opilio* (Grant 2003; Urban 2015); *Panulirus cygnus* (Paterson et al 2005); *Chaceon quinquedens* (Tallack 2007); *Scylla serrata* (Butcher et al 2012); *Sagmariasus verreauxi* (Leland et al 2013)). Some of this research undertaken in situ (control tanks) and ex situ (control creels/pots) showed low rates of discard mortality. For example, Butcher et al (2012) studied the survival and physiology of Indo-Pacific swamp crab (*Scylla serrata*) discards. This study did not record any mortality, but suggested that further research is required to determine the long-term consequences of physical damage on growth, limb regeneration, reproductive output, competiveness, infection and mortality; Leland et al (2013) has demonstrated 100% survival of juvenile eastern rock lobster (*Jasus verreauxi*) discarded after trapping.

Despite the need to investigate the fate of discarded brown crab, only one study published as a poster by Dawson and Northridge (2010) has assessed the impacts of discard mortality in brown crab, estimating 24% mortality overall on the west coast of Scotland, including undersized, sick and soft-shelled individuals. A drawback in many studies that estimated crustacean discard mortality is that they do not take into account predation by either fish or seabirds following discarding from the deck and sinking back onto the seafloor (Harris et al., 2003), as most of these experiments occurred in protected conditions (seabed cages or onshore tanks).

Determining discard mortality requires information not only on capture but also on release. However, formal estimates of discard mortality can be costly and technically difficult to obtain, and are therefore only available for a limited number of species and fisheries. There are three main approaches based on direct observations to estimate species mortality rates: (i) tagging, (ii) acoustic telemetry and (iii) captive holding studies. Mortality rates estimated by indirect observations are usually based on physiological parameters. The facilities and time available in this study, sought as the best approach to combine captive direct observations with RAMP (Reflex Action Mortality Predictors) with vitality scores with the likelihood of survival for each vitality category to estimate a survival rate for the brown crab fishery.

RAMPs could be used to quantify some types of unaccounted fishing mortality. Reflex impairment imposed on fish and crab from fishing practices has been correlated with stress and mortality outcomes both in the laboratory and in field (Hammond, 2013). The process for validating reflex impairment as a research tool in crabs is to identify reflex responses, such as aggressive display; leg tension; chelae grip; response to abdomen simulation; mouthpart strong and eyestalks responsive (Stoner, 2012; Urban 2015). Impairment of an individual's reflexes link RAMPs to vitality indicators that usually involve the degree of injury sustained, which have been found to be good predictors of survival (Morfin, 2017) and representative of the conditions experienced by discards (Benoit, 2012). There is often a direct relationship between losses in reflex actions and delayed mortality (Paterson, 2005), and when multiple reflexes are tested, estimates can be made for the probability of mortality. Once a reflex impairment model is validated, it can then be used for real-time assessment to predict mortality (Hammond, 2013). There are many advantages of using RAMP to estimate discards mortality rates which made it an increasingly used methodology over the years: it can be applied regardless of environmental and/or biological factors, it is relatively inexpensive and assessments can be easily done with little training with results been generated rapidly (Stoner, 2012, Yochum, 2015).

Stoner (2012) has published the second study testing whether mortality predictions could be made accurately for crustaceans from a reflex-based score applied to two *Chionoecetes* species. He identified and tested six reflex actions to provide a seven-tiered reflex impairment scale ranging from zero (all reflexes present) to six (all reflexes absent). This impairment score was directly related to observed patterns of delayed mortality for the two species. Further studies using vitality reflex demonstrated efficiency on this method to analyse delayed mortality. Urban (2015) applied RAMP to snow crab discarded under actual fishing conditions with the goal of evaluating estimates of discard mortality rates. Hammond (2013) used RAMP relationship developed to estimate snow and tanner cab mortality using different fishing gears, showing a positive correlation between reflex and delayed mortality for each gear tested. Barrento et al. (2009) examined the relationship between haemolymph chemistry and a behavioural vigour index on survivorship for *C. pagurus* during crab transport processes. Woll et al. (2010) provided other insight of how handling-related shifts in haemolymph chemistry was related to crab condition, expressed as a vitality index. Benoit et al. (2012) studied short-term fish survival using vitality scores and his results supported that there is relationship between vitality score and survival.

The RAMP approach does have certain inherent limitations because it does not take into account some of the indirect and delayed effects of the discarding and handling stress. Some of the following indirect sources of mortality not built into RAMP are the ability to avoid predation, feeding, growth, moulting, and reproduction. The hypothesis is that mortality in the field will be directly proportional to the values predicted from RAMP-based holding experiments across a wide range of crab sizes, gender, and fishing practices. Despite some limitations, the advantages of RAMP in mortality prediction are large. Reflex actions can be evaluated quickly, inexpensively, and quantitatively, and the method can easily be adapted to test a large number of individuals (size and sex) over a wide range of different conditions (Stoner, 2012).

Objective

The discard mortality component of fishing is often under researched, a fact recognised by OSF. This study was designed to obtain survival rate estimates of discarded brown crab considering biological parameters, size, sex and injury from the first day of captivity to the end of the monitoring period.

Given the above, the two key aims of this study were (i) to describe any possible damage caused to discarded brown crabs by creels during fishing operations, and (ii) estimate mortality of intact and damaged brown crab discards.

Methods

Study area

This study was undertaken on the west of Orkney Mainland with the participation of two commercial fishing vessels. Both vessels fished inshore grounds to the north of Orkney Mainland and to the south off Hoy (Figure 1), with depths ranging between 19 and 40 m. Both vessels in the study used creels of 26 inches D shaped with two roped soft eye side entrances and a bait bag between the entrances; the base was rubbered, the steel enforced with a second rope, and the door was held with a hook and elastic. Some differences were however noted between vessels: one of the vessels tied each creel to a tail of 1.5 m, and then attached to 35 m string rope, separated with 2.5 m between each creel. A 15 kg weight attached to each end of the string, to keep the creels on the seafloor and two presence buoys attached with 40 m rope to each end of the string; creels number varies from fifteen up to forty-five in each string. The second vessel used a tail of 1 m attached to 40m string rope, separated with 3 m between each creel. The number of creels varied from thirty up to forty creels in each string, and each string of 40 pots had a distance of 90 m between each twenty creels. A 20 kg weight and two presence buoys were attached with 43 m rope to each end of the string.

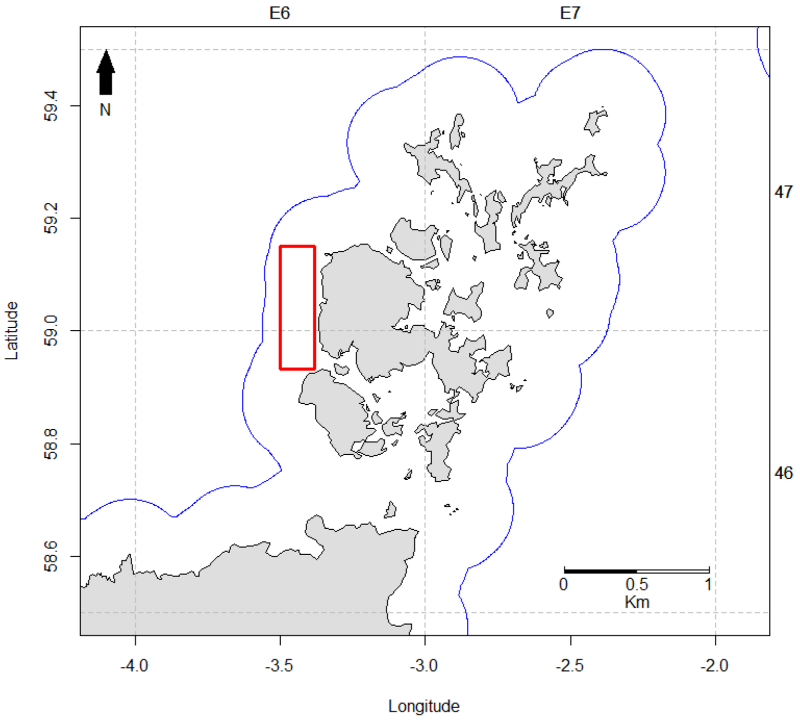

Figure 1: Map of the study area with blue line showing the 6 nm limit. The red rectangle corresponds to the area where the brown crab were collected for observation of survival and condition.

The study started in 2016 ending in September 2017. Dates of observer trips during which crabs were collected for research are shown in Table 1.

Table 1

Number of brown crab collected for each observer trip by date.

Date	Individuals collected
10/08/2016	30
22/08/2016	30
01/06/2017	30
27/06/2017	30
11/07/2017	30
29/07/2017	30
17/08/2017	30
01/09/2017	28
13/09/2017	30

Experimental design

The experimental protocol was divided in two phases: Phase I, crabs smaller than 140 mm carapace width (the Minimum Landing Size (MLS) at the time); and Phase II, crabs larger than 140 mm carapace width. Two experimental trials were chosen for this study: creels and tanks, with two groups (control and treatment) and four categories of treatment.

Treatments selected to represent brown crab discards in the most plausible commercial fishing procedures were based on previous observations undertaken by OSF staff members. Brown crab injuries such as broken or lost appendages were the most common. Damage of carapace and/or abdomen was not observed during standard fishing practices. Therefore, the treatments designated to study brown crab survival rate were missing limbs, recently moulted crabs, black spot and berried females (Table 2). Undamaged crabs were used as the control and tested against the four treatments, with a replicate of treatment for each occasion. Crabs were assessed using a vitality index based on injuries, missing appendages or mouthparts, and strength of movement, and scored by the presence or absence of specific behavioural reflexes and injuries. The vitality reflexes used in this study were similar to the one established by Stoner (2012) and based upon behavioural responses (Annex, Table A.1). Moribund individuals were left under observation for a possible recovery or until dead. Dead individuals were removed from the tanks/creels upon each recorded observation.

Table 2

Description of treatment for discarded individuals selected alongside with vitality index.

Treatment individuals		Reflex Description	Reflex	Vitality Index
Missing Limbs	Absence of all pereiopods	Mouthpart strong movement and eyestalks responsive	Yes	Weak
	Absence of one or both chelae	Leg tension Response to abdomen simulation (defensive movements) Mouthpart strong and eyestalks responsive Aggressive display (if one of chelae present) Chelae grip (if present)	Yes	Weak
	Absence of walking legs	Aggressive display Chelae grip Mouthpart strong and eyestalks responsive	Yes	Weak
	Absence of one or more walking legs or one or both chelae	Leg tension Response to abdomen simulation (defensive movements) Mouthpart strong and eyestalks responsive Aggressive display (if one of chelae present) Chelae grip (if present)	Yes	Healthy
Recently moulted		Leg tension Response to abdomen simulation (defensive movements) Mouthpart strong and eyestalks responsive Aggressive Chelae grip	Yes	Strong
Black spotted		Leg tension Response to abdomen simulation (defensive movements) Mouthpart strong and eyestalks responsive Aggressive	Yes	Strong

	Chelae grip		
Berried females	Leg tension Response to abdomen simulation (defensive movements) Mouthpart strong and eyestalks responsive Aggressive Chelae grip	Yes	Strong

Vitality was assessed based upon a five-point scale with one being strong individuals and five dead (Table 3). Vitality was visually assessed by the same observer to avoid bias, based on the five vitality levels and recorded for each brown crab individual.

Table 3

Vitality codes assessment based on RAMP reflex.

Vitality	Code	Description
Strong	1	Total positive response Prompt, strong, aggressive response or defensive position unable to access the abdominal area; Cling to hand when held upside down; Eyestalk response; Mouthpart Strong.
Healthy	2	Total positive response Like index 1 however the aggressive/defensive response is slower.
Weak	3	Partial positive/lost response Weak legs and claws, no aggressive response; Slow reaction when touched in the abdominal area; Loosen the grip when held upside down Eyestalk response; Mouthpart strong.
Moribund	4	Almost lost response No claw response; No reaction when touched in the abdominal area; No grip when held upside down; Slow eyestalk response;

		Mouthpart slack
Dead	5	Total lost response Like index 4 but no movement in antennae and mouthparts when touched

Damage criteria were also applied in this study with a four-level index (no damage-0, no damage but white/berried-1, slight damage-2, severe damage-3) adapted from Ridgway et al. (2006). The damage index for each crab in the survival trial was recorded just after the selection. Table 4 describes the damage index and criteria.

Table 4

Damage index and criteria (adapted from Ridgway et al. (2006)).

Damage Index	Description
Damage 0	Intact crab; no visible damage of the carapace or loss of limbs
Damage 1	Intact moulted crab; no visible damage of the carapace or loss of limbs
Damage 2	Missing one claw or/and up two walking legs; slightly damage of carapace/thorax
Damage 3	Missing both claw or/and more than two walking legs; severe damage of carapace/thorax

At sea data collection

Collection of brown crab individuals took place during fishermen’s normal fishing operations in their usual fishing grounds. Sampling of control and treatments was conducted on the same day of each observer trip undertaken (Table 5). The fisherman was asked to put all the discards obtained during the trip in a basket and the observer selected the crabs fit for the study.

For each treatment group (Table 5), a subset of 30 crabs was randomly selected from the discards box. Each individual was sexed, measured with callipers (to the nearest 1 mm below) for CW (carapace width) and numbered with non-toxic Chalk Marker D60.

Observations of the degree of injuries (missing limbs and carapace damage) and physiology (recently moulted crab and black spot disease) was recorded for each treatment at the time of selection and a vitality score was given according to the response they were displaying during selection.

The individuals were stored in separated ventilated plastic boxes (L 36 x W 26 x H 9 cm) (Annex B, Figure B.1). Each plastic box was immersed in a 200 Litre static plastic storage tub (L 74 x W 41 x H 64.7 cm) (Annex B, Figure B.2) on the deck with a continuous sea water supply to minimize stress to the individuals.

Table 5

Description of sampling occasions using two distinctive groups (creels and tanks) with the total number of individuals collected per trip.

Occasion	Trial	Control individuals	Number of Control individuals	Treatment individuals	Number of Treatment individuals
10.08.2016	Tanks	Sub-legal intact individuals	5	Sub-legal missing limbs (legs & claws) individuals	10
	Creels	Sub-legal intact individuals	5	Sub-legal missing limbs (legs & claws) individuals	10
22.08.2016	Tanks	Sub-legal intact individuals	5	Sub-legal recently moulted individuals	10
	Creels	Sub-legal intact individuals	5	Sub-legal recently moulted individuals	10
01.06.2017	Tanks	Sub-legal intact individuals	5	Sub-legal black spot individuals	10
	Creels	Sub-legal intact individuals	5	Sub-legal black spot individuals	10
27.06.2017	Tanks	Legal intact individuals	5	Legal berried females individuals	10
	Creels	Legal intact individuals	5	Legal berried females individuals	10
11.07.2017	Tanks	Sub-legal intact individuals	5	Sub-legal mixed treatments	10
	Creels	Sub-legal intact individuals	5	Sub-legal mixed treatments	10
29.07.2017	Tanks	Legal intact individuals	5	Legal missing limbs (legs & claws) individuals	10
	Creels	Legal intact individuals	5	Legal missing limbs (legs & claws) individuals	10
17.08.2017	Tanks	Legal intact individuals	5	Legal recently moulted individuals	10
	Creels	Legal intact individuals	5	Legal recently moulted individuals	10
01.09.2017	Tanks	Legal intact individuals	5	Legal black spot individuals	8

	Creels	Legal intact individuals	5	Legal black spot individuals	10
13.09.2017	Tanks	Legal intact individuals	5	Legal mixed treatment	10
	Creels	Legal intact individuals	5	Legal mixed treatment	10

Creel trials

The control creels used in this experiment were 26 inches D shaped creels used by the fisherman (Annex B, Figure B.4). Three creels had both entrances closed. Each creel was baited and placed with five individuals ranging with different sizes and sexes selected for each treatment. Creel 1 (C1) was the control creel with only intact brown crab individuals and C2 and C3 were the treatment creels.

Creels were monitored a week after deployment, rebaited to avoid cannibalism between the individuals and checked for vitality reflex. In total, during the two weeks period, creels were hauled up to three times during each treatment. Dead individuals were recorded and removed from the creels. Every two weeks samples were substituted with five new individuals and a different treatment was analysed for vitality reflex. A data temperature logger was placed in one of the creels for temperature control.

Tank trials

The onshore holding facilities were located in the pier Orkney Fisherman Society “Ponds”, so air exposure during the transport from the vessel to the onshore tanks was very reduced lasting only a few minutes. Control and treatment tanks were placed alongside with one tank for control and two for treatment (with approximately 35cm height) provided with continuous seawater inflow through a filtration system from the Stromness Harbour. (Annex B, Figure B.3). Control tank (T1) had five intact brown crab individuals, and T2 and T3 (treatment tanks) had each five damaged brown crab individuals. The individuals were monitored if possible on a daily basis, recording any alterations or/and possible damage. Every two weeks crabs were substituted with new individuals at the same time as the creel treatments. Temperature was also recorded throughout the experiment.

Data analysis

General additive model (GAMs)

Generalised Additive Models (GAMs) were used to compare RAMP predictors contributing to survival of the crabs, using six independent variables (i) size, (ii) sex, (iii) treatment type, (iv) vitality score, (v) damage score and (vi) temperature. GAMs were fitted with a binomial distribution and a logit link function to the survival from the first day of captivity to the end of experimentation. The binomial response variable was survival, coded as 1 for live crabs and 0 for dead crabs.
The best model was determined by minimum value of the Akaike Information Criteria (AIC; Akaike 1973) selecting the simplest adequate model for the data.

Results

In total, 265 individuals were collected for observation, of which 162 were female and 103 were male brown crab. The table below shows the number of individuals collected for each treatment during 2016 and 2017 (Table 6), of which 90 were intact crabs (40<MLS; 50>MLS) and 175 treatment crabs (78<MLS; 97>MLS).
Temperature conditions in the study area were typical of seasonal variation for the region. Mean bottom water temperature through the collection months were 11.7^{0}C with average air temperature of 14^{0}C. Females were more common in each collection and the overall sex ratio was 0.6M:1F.

During the collection, crabs were exposed incidentally to handling and stress through the process of selection. On a normal fishing day crabs are subject to minimal air exposure and very little handling (pers. obs. Rodrigues (OSF)) with sorting time not taking longer than one minute per creel, thus any bias in this study is likely to be in the precautionary direction of overestimating mortality.

For a short period (approximately two weeks) crabs in the tank trials were occasionally subjected to higher temperatures, which were not possible to control, suffering sudden mortality. Therefore, days where temperatures were recorded above 16.2^{0}C were removed from the study as it is assumed that high temperatures have a negative effect on survivability, and this is not representative of the conditions to which individuals are exposed during fishing operations. Furthermore, any crabs that escaped or were eaten by other crabs were also removed from the data analysis.

Table 6

Number of individuals collected per treatment and damage index during the project.

Treatment	Damage criteria	Number of individuals	Total
Berried Females	1	8	19
	2	10	
	3	1	
Black spots crab	1	31	50
	2	17	
	3	2	
Intact	0	90	90
Missing limbs	2	41	52
	3	11	
Soft crab	1	26	54
	2	23	
	3	5	
Overall			**265**

Creel trials

Creel trials included a total of 134 individuals, 51 males and 83 female brown crab individuals, with carapace width ranging from 80 to 199mm (Figure 2). During the trials two individuals escaped from the creels and nine were eaten (two undersized and seven above 140 mm CW), within the treatments of missing limbs, soft crab, black spot crab and intact.

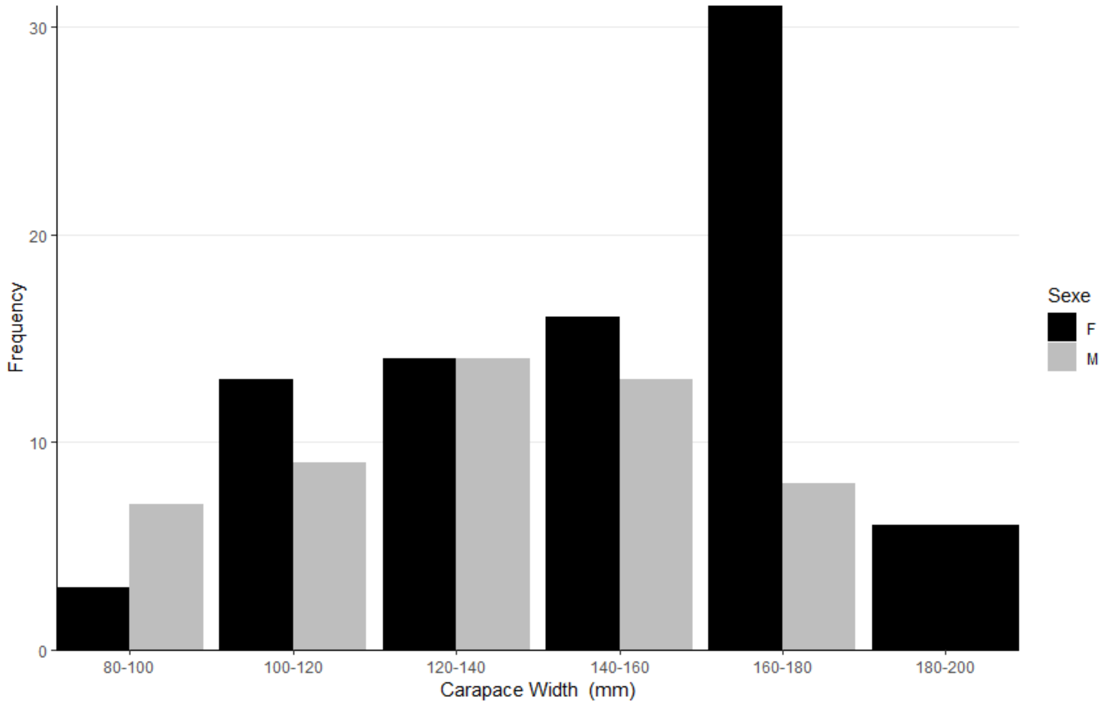

Figure 2: Length frequency of brown crab held in the creels for observation during the study.

Creel estimated survival using observations for score, treatment, damage and CW

Table 7

Model fit statistics for GLM/GAM models of survival of brown crabs in creels. The preferred model (smallest value of Akaike Information Criterion, AIC) is indicated in bold. Model terms: score, vitality index; damage, damage index; treatment, experimental group; s(CW), spline smooth terms for carapace width.

Model	AIC	% Deviance Explained
Vitality score + s(CW)	45.51	53.5
Damage + s(CW)	48.10	52.6
Treatment + s(CW)	43.36	60.8
Score	59.28	17.3
Damage	63.08	14.5
Treatment	58.57	24.6
s(CW)	55.20	32.1
Constant	66.39	0.0

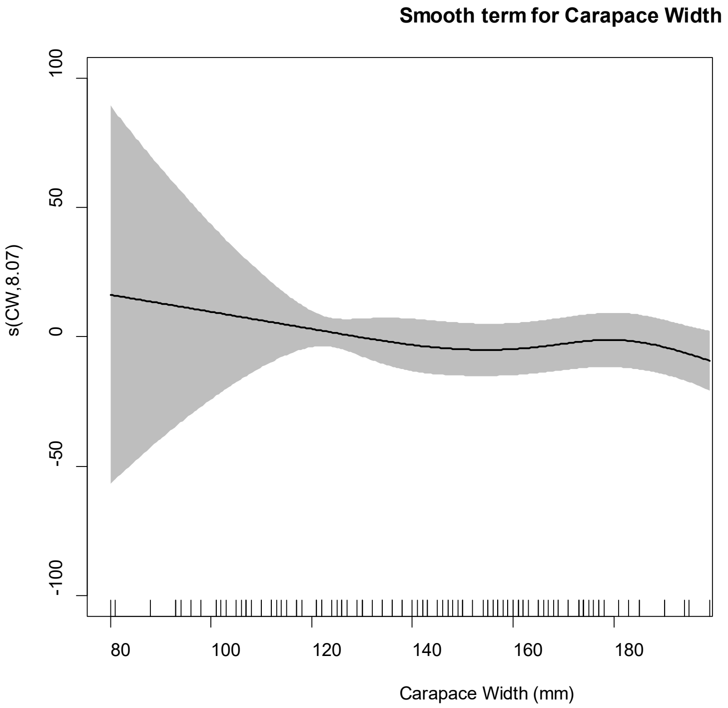

Figure 3: Partial effect of carapace width in a GAM model for survival of crabs in creels, modelled as a spline smooth.

The most parsimonious model for the creel survival data (minimum AIC value) included experimental treatment and a smooth term for carapace width (Table 7), indicating a decline in survival with increasing size of crab (Figure 3). Given 100% survival was achieved for some experimental treatments, standard errors of GAM model estimates are not well determined, hence survival rates for legal and sub-legal crabs are summarised based on raw data rather than model estimates, using the inverse beta distribution to calculate exact 95% confidence intervals (Table 8). The results show 100% survival of crabs smaller than 140 mm CW, and of larger intact crabs, including berried females. Some mortality was observed for larger soft and black spot crabs but the lowest survival rate (50%) was found for larger crabs with missing limbs (Figure 4). Overall survival across all crabs was 92.7% (86.6-96.6%, 95% C.I.). In addition, survival decreased for animals with a higher damage and vitality index score (Figure 5 and 6).

Table 8:

Estimated survival rates of crabs in creels.

Size (mm CW)	Treatment	No. crabs	No. survivors	% survival		
				Average	Lower 95% CL	Upper 95% CL
80-139	Intact	18	18	100	81.5	100
	Berried female	0	0	n/a	n/a	n/a
	Black spot	15	15	100	78.2	100
	Soft	12	12	100	73.5	100
	Missing limbs	11	11	100	71.5	100
	All	56	56	100	93.6	100
140-199	Intact	24	24	100	85.8	100
	Berried female	9	9	100	66.4	100
	Black spot	10	9	90.0	55.5	99.7
	Soft	12	10	83.3	51.6	97.8
	Missing limbs	12	6	50.0	21.1	79.0
	All	67	58	86.6	76.0	93.7
All sizes	Intact	42	42	100	91.6	100
	Berried female	9	9	100	66.4	100
	Black spot	25	24	96.0	79.6	99.9
	Soft	24	22	91.7	73.0	99.0
	Missing limbs	23	17	73.9	51.6	89.8
	All	123	114	92.7	86.6	96.6

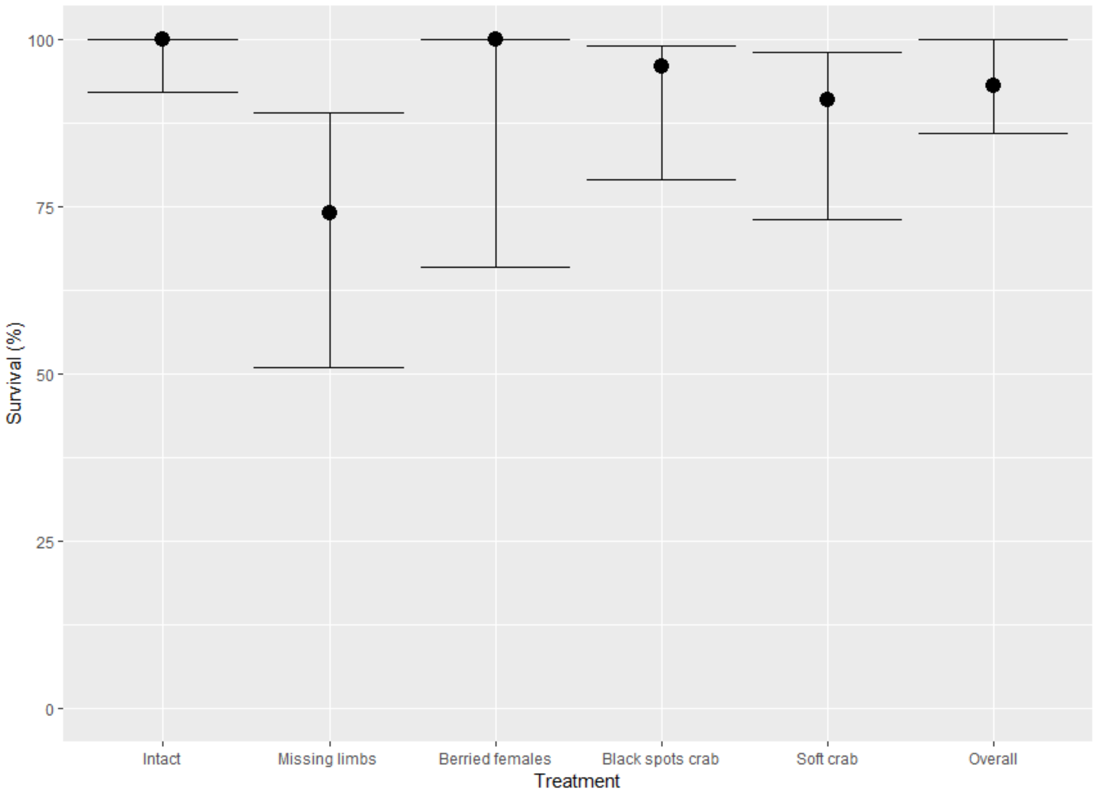

Figure 4: Survival rates of brown crab in creels according to different treatments. Error bars represents 95% confidence intervals.

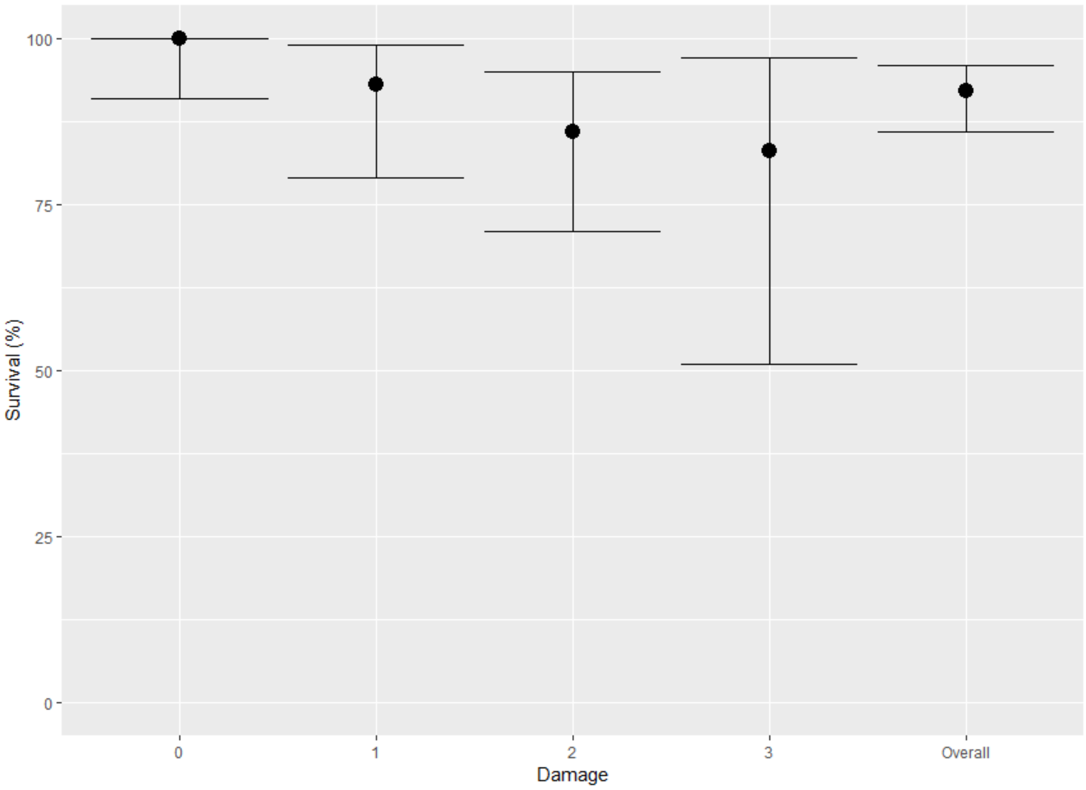

Figure 5: Survival rates of brown crab in creels according to initial damage index values. Error bars represent 95% confidence intervals.

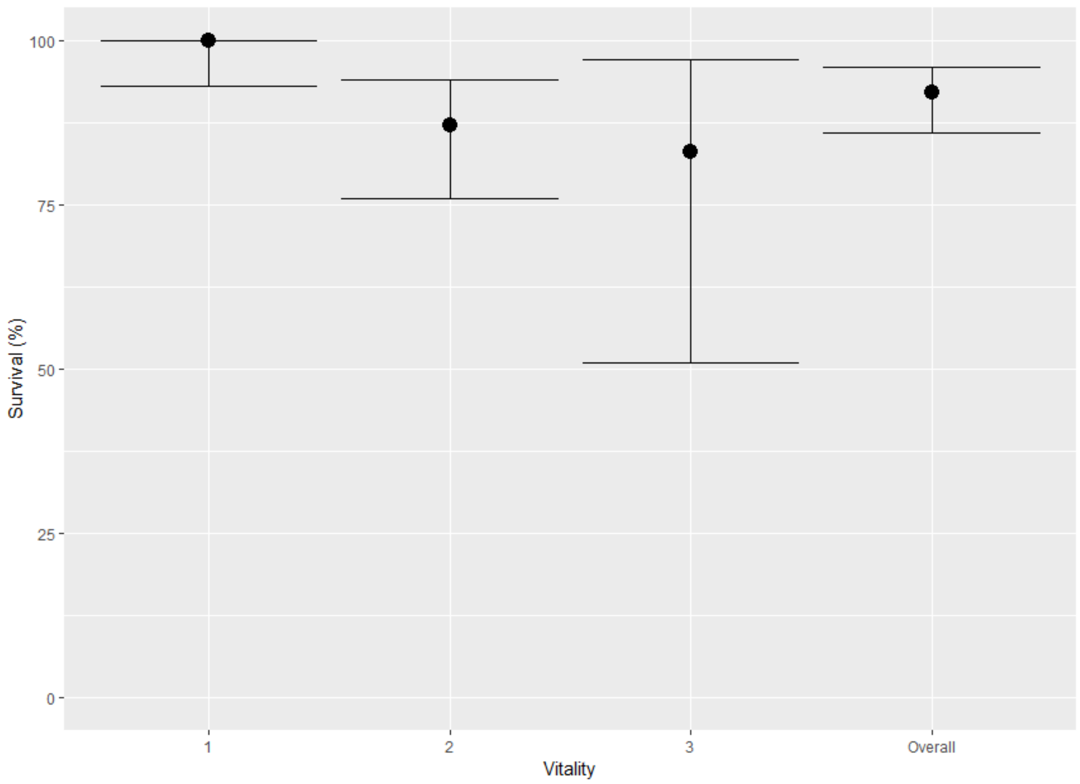

Figure 6: Survival rates of brown crab in creels according to initial vitality index values. No initial scores higher than three were observed. Error bars represent 95% confidence intervals.

Tank trials

Overall, 131 crabs were placed in tanks and observed for survival, 79 females and 52 males brown crab individuals. The length frequency ranged between 70 and 201mm carapace width (Figure 7). During the trials one undersized soft crab was eaten.

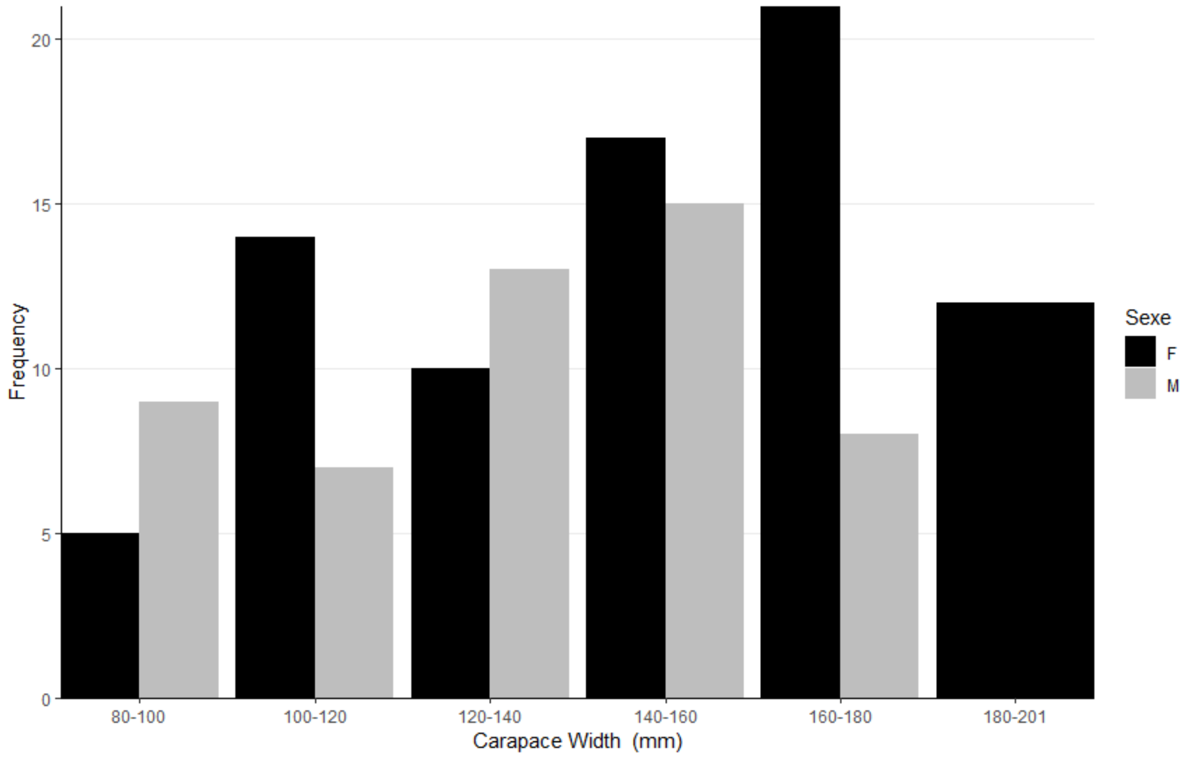

Figure 7: Length frequency of brown crab held in the tanks for observation during the study.

Tanks estimated survival using observations for survival, score and treatment

GAM models were fitted to individual survival data from the tank experiments in the same way as for the creel experiments. In addition to terms for carapace width (smooth term), vitality index, damage index and experimental treatment (factor terms), a spline smooth term for maximum water temperature recorded for each batch of crabs and a factor term for crab sex were included. After high mortality (33 out of 58 crabs, 44.2%) was recorded at elevated water temperatures (16.9-19.0°C) in the tank experiments, the analysis was restricted to data recorded for crabs held at 16.2°C or less.

Table 9

Model fit statistics for GLM/GAM models of survival of brown crabs in tanks. Given 32 separate models considered for the data, results are shown only for the top five (minimum AIC). The preferred model (smallest value of Akaike Information Criterion, AIC) is indicated in bold. Model terms: s(CW), spline smooth term for carapace width; sex, male or female; s(temperature), spline smooth terms for maximum tank water temperature experienced by each crab.

Model	AIC	% Deviance Explained
Constant	32.55	0
s(CW)	33.32	4.0
Sex	33.83	2.4
s(Temperature)	34.04	1.7
s(CW) + Sex	35.06	4.8

The results show that survival in the tank experiments was effectively constant at 90.3% (81.0-96.0%, 95% C.I.). However, good alternative models (within 2 AIC units of the minimum AIC model) describe pattern in relation to carapace width, sex or temperature (in descending order of importance) (Table 9). These marginal effects (not shown) are slight declines in survival with increasing carapace width or decreasing water temperature, and slightly higher survival in males than females. These effects are very minor, however, and the summary of survival rates in Table 10 shows differences according to experimental treatment only, for comparison with the creel experiments (Figure 8). Lower survival rates in the tanks compared with the creel experiments, particularly at high water temperatures, demonstrates the importance of ‘natural’ environmental conditions for determining survival.

Table 10

Estimated survival rates of crabs in tanks.

Water temperature (°C)	Treatment	No. crabs	No. survivors	% survival		
				Average	Lower 95% CL	Upper 95% CL
13.0-16.2	Intact	25	23	92.0	74.0	99.0
	Berried female	0	0	n/a	n/a	n/a
	Black spot	11	11	100	71.5	100
	Soft	23	21	91.3	72.0	98.9
	Missing limbs	13	10	76.9	46.2	95.0
	All	72	65	90.3	81.0	96.0
16.9-19.0	Intact	20	9	45.0	23.1	68.5
	Berried female	10	7	70.0	34.8	93.3
	Black spot	11	6	54.5	23.4	83.3
	Soft	4	1	25.0	0.6	80.6
	Missing limbs	13	2	15.4	1.9	45.4
	All	58	25	43.1	30.2	56.8

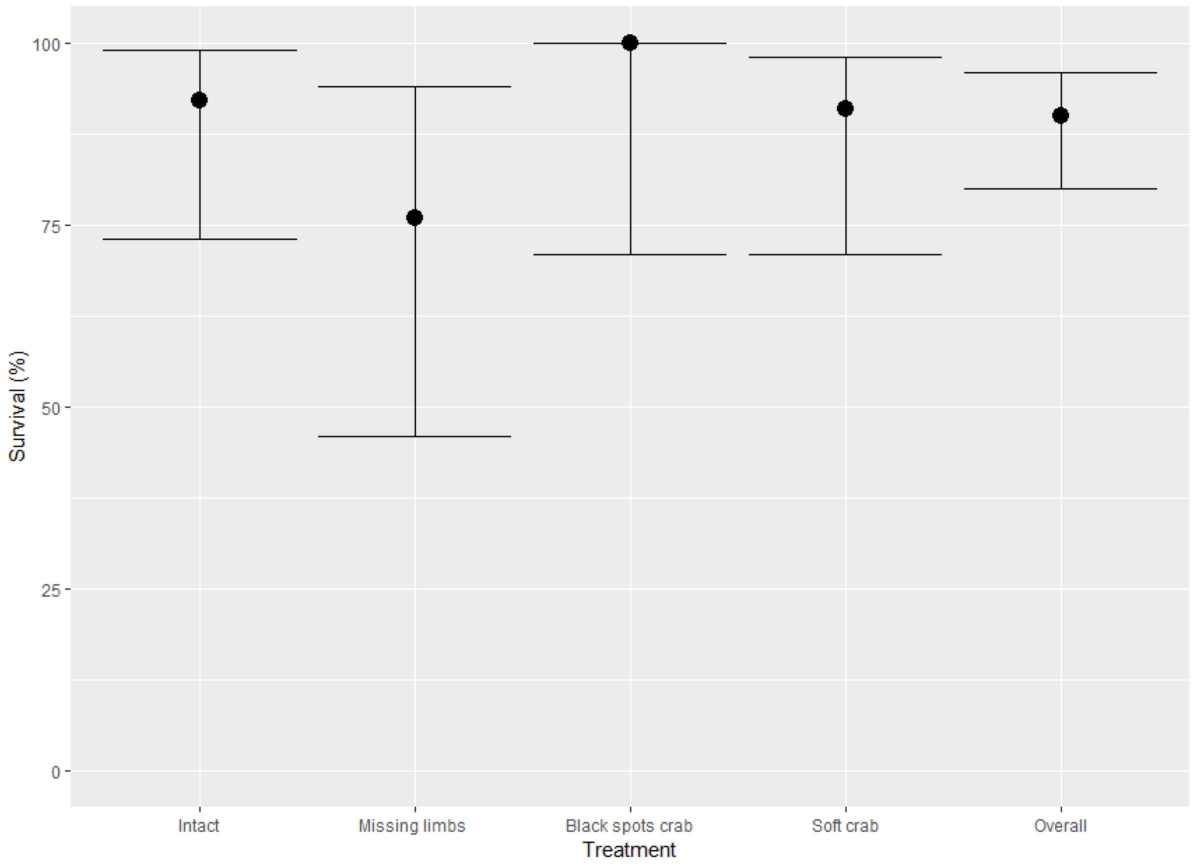

Figure 8: Survival rates of brown crab in tanks according to different treatments. Error bars represent 95% confidence intervals.

Discussion

This project used two experimental trials to study brown crab survival rate. The methodology applied demonstrated that vitality codes associated to reflex impairment were overall good indicators of direct observations of delayed mortality. The two-week period was sufficient to observe delayed mortality, with mortality occurring within the first three days of crabs being held for observation. Variables, such as animal size, sex, and shell damage/limbs injuries may potentially influence the cumulative mortality in discarded brown crab. The model used to analyse the dataset from each trial showed slightly different variables influencing the overall estimated survival rate for discarded brown crab. Survival estimates are conservative because in a normal fishing day crabs have a minimal handling and exposure (Rodrigues (OSF) pers. obs.). Although the experiments do not take into account effects of exposure to predation whilst sinking, or whilst seeking suitable habitat, brown crab are known to be robust and are capable of living in a wide variety of habitats (Edwards, 1979). Whilst data on sinking rates are lacking, informal observations indicate that their transit of the water column is generally rapid, such that exposure to additional predation is likely to be minimal. Tallack (2007) assumed sinking rates in the order of 0.5 $m.s^{-1}$ for deep-water red crab (*Chaceon quinquedens*) discarded in the New England fishery, representing transit times of 20-26 minutes in water depths of 600-800 m. Comparable figures for Orkney brown crab in waters of 30-90 m would be 1-3 minutes. Thus, given available information on likely risks of exposure to predation and unsuitable habitat, we consider that the estimated survival rates are conservative with respect to the overall discarding process.

Initially creel experimental trials were set up to validate the results obtained on tanks experiments, as it is difficult to control natural environmental conditions in onshore experiments (Kennedy et al., 1990). In order to record crab mortality during different stages of the experiment, creels were hauled up to three times during each treatment, implying that individual crabs were exposed to multiple fishing processes including being left in the creels (soak time), hauling, deployment and extra handling. Exposure of crabs to these extra variables also serves to show the potential for cumulative impacts that fishing practices from recapture of previously discarded crabs. This further supports the notion that brown crab is relatively robust and very likely to survive consecutive recaptures.

Holding animals in tanks is a common approach for making direct observations on delayed mortality and generally, crustaceans are more adaptable to tank holding than many fish species (Stoner, 2012). However, the facilities and set up of the tanks made it difficult to keep the ideal temperature and the air pump failed for a whole week negatively influencing the survival of the crabs during that time. For this reason a set of individuals were removed from data analyses after sudden mortality across all treatments when temperatures rose over 16.2^{0}C. Increased temperatures can cause increased oxygen consumption, especially in larger crabs like the berried females, and thus cause crabs to be more susceptible to suffering from impaired respiration (Murphy, 1995).

The GAM models showed a decrease in survival with increasing CW; similar results were obtained by Stevens (1990) that also showed a marked increase in mortality with sizes above 120mm for king crabs and Yochum (2015) obtained similar results for tanner and snow crabs regardless of the vitality score given. It is unclear why larger crabs were more vulnerable but it may be related with physiological responses of cumulative stressors, however there is no studies supporting this and further research should look into physiological differences between small and larger crabs.

Reflex impairments were closely related with vitality and damage scores showing more crabs died when scored three than when scored 2/1, highlighting that survival is strongly associated to strong/healthy crabs with a low degree of damage. Treatments breakdown showed that crabs missing limbs for both trials were less likely to survive. It has been suggested in various studies that lost limbs can have an effect on the overall survival (Stevens, 1990; Méhault, 2011; Lelanda, 2013; Yochum, 2015), and also make them more susceptible to predation.

The results suggested that creel trials were better than tank trials in providing insight into the fate of discarded brown crab. As already noted (see Results), it was extremely difficult at certain times to control water temperature in the onshore tanks, impacting on observed survival rates (90.3% overall in the tank trials, compared with 92.7% in the creels). Subject to our assumptions about low risks from predation mortality and displacement from suitable habitat (see above), the estimated survival rate obtained in this study seems to represent discard survival in the fishery, despite the fact that the study did not account for induced experimental mortality (handling and air exposure) and excluded marine predation (Morfi 2007; Mérillet 2018). The analyses presented suggest that vitality is a dependable and important predictor of survival across a broad range of environmental conditions.

Conclusion

In the context of ecological management of marine resources, knowledge on the survival of discards is important to estimate the status of fishery stocks. This study provided new data on the survival rate of brown crab in Orkney. The estimate of 92.7% survival is higher than the 76% estimated by Dawson & Northridge (2010), and we consider that this estimate is conservative in relation to the fishery, since damaged individuals were over-represented in the experiments when compared with fishery catches. The comparison between creel and tank experiments also highlights the importance of measuring survival under natural conditions, particularly in relation to water temperature, and it is possible that this accounts for at least some of the differences between this study and that of Dawson & Northridge (2010). The initial vitality and reflex impairment assessments showed that crabs in healthy condition had higher survival than those classified as weak. Injuries caused by the fishery occurred at very low levels and therefore should have a minimal effect on overall discard mortality rates.

The results obtained give a good insight into the fate of discards in the brown crab fishery, nevertheless it is recommended that further research should be taken to support these findings such as long term data collection of damage in catches over a time period. The estimate of survival rates for the fishery should take into account data on reflex assessments gathered during a representative number of trips that incorporate the variability of the fishery. This can be assessed by sampling vitality values from the fishery by at-sea observers as implemented in this study. Additionally, we suggest that in each observer trip undertaken by members of OSF whenever possible, the level of damage in the crabs during the discard process should be recorded so that a full survival rate could be applied to the whole fishing operation within Orkney.

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Annexes

Annex A

Table A.1

Identified reflexes for predicting discard survival in brown crab (reviewed in Stoner, 2012; Urban 2015) for assessing vitality.

Reflex	Test	Positive response	Lost response
Leg flare	Lift crab by the carapace, dorsum up	Legs spread wide and to near horizontal orientation in strong crabs	Legs droop below horizontal with no attempt to raise them
Leg retraction	While held as above, draw the forward-most walking legs in the anterior direction	Legs retract in the posterior direction or present resistance to the motion in weakened crab	No resistance to the manipulation occurs
Chela close	Observe for motion or hold the chelae in the fingers	Chelae open and close with or without manipulation; in weakened crabs, the chelae may close slowly or show low resistance to manual opening	No motion is detected in the chelae under manipulation
Eye retraction	Touch the eyestalk with a blunt probe, or lift the eyestalk from its retracted position	Eyestalk retracts in the lateral direction below the carapace hood or shows resistance to lifting	No motion or resistance to manipulation occurs in the eyestalk
Mouth close	If closed, attempt to open (extend) the third maxillipeds with a sharp dissecting probe; if open, draw the maxillipeds downward	Third maxillipeds retract to cover the smaller mouth parts; maxillipeds droop open or move in an agitated manner in weakened crabs	No motion in the maxillipeds occurs
Kick	With the crab in ventrum-up position, use a sharp dissecting probe to lift the abdominal flap away from the body	One or more legs or chelipeds move quickly in the ventral direction, particularly in males; motion in hind-most legs is retained in weakened crabs	No motion in the legs or chelipeds occurs

Annex B

Figure B.1: Ventilated plastic box, L 36 x W 26 x H 9 cm.

Figure B.2: Static plastic storage tub (200 Litre), L 74 x W 41 x H 64.7 cm.

Figure B.3: Set up of the three tanks to storage brown crab individuals.

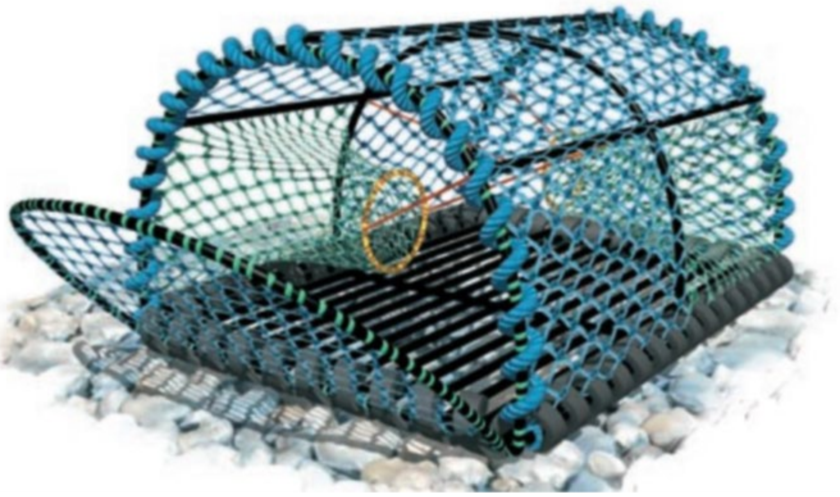

Figure B.4: Example of a D shaped creel. (Source: Scottish Fisheries Information Pamphlet No. 25 (2004))

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