# Using underwater video to evaluate the performance of the Fukui trap as a mitigation tool for the invasive European green crab (*Carcinus maenas*) in Newfoundland, Canada (#20010)



First submission

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Donald Kramer / 4 Oct 2017

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# Using underwater video to evaluate the performance of the Fukui trap as a mitigation tool for the invasive European green crab (*Carcinus maenas*) in Newfoundland, Canada

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## ABSTRACT

The European green crab (*Carcinus maenas*) is a destructive marine invader that was first discovered in Newfoundland waters in 2007 and has since become established in nearshore ecosystems on the south and west coast of the island. Targeted fishing programs aimed at removing green crab from invaded Newfoundland ecosystems use Fukui traps, but the capture efficiency of these traps has not been previously assessed. We assessed Fukui traps using *in situ* observation with underwater video cameras as they actively fished for green crab. From these videos, we recorded the number of green crab that approached the trap, the outcome of each entry attempt (success or failure), and the number of exits from the trap. Across all videos, we observed 1,226 green crab entry attempts, with only a 16% rate of success from these attempts. Based on these observations we believe there is scope to improve the performance of the Fukui trap through modifications in order to achieve a higher catch per unit effort (CPUE), maximizing trap usage for mitigation. Ultimately, a more efficient Fukui trap will help to control green crab populations in order to preserve the function and integrity of ecosystems invaded by the green crab.

## 1. Introduction

The European green crab, *Carcinus maenas* (Linnaeus, 1758) is a crustacean species native to European and North African coastlines (Williams, 1984). It has been ranked among 100 of the world's 'worst invasive alien species' by the International Union for Conservation of Nature (Lowe et al., 2000). The European green crab (hereafter green crab) was first discovered in the nearshore waters of Newfoundland in 2007 and has since become established across the southern and western coasts of the island (DFO, 2011a). This invasion is concerning because green crab destroy eelgrass beds (DFO, 2011a; Matheson et al., 2016), are voracious predators of bivalves (Ropes, 1968; Cohen, Carlton & Fountain, 1995; Klassen & Locke, 2007; Matheson & McKenzie, 2014), and compete with native species and other crustaceans for food and habitat (Cohen, Carlton & Fountain, 1995; Matheson & Gagnon, 2012). The impact of green crab on eelgrass beds is particularly threatening as invasive species are one of the multiple stressors contributing to a global trend in seagrass decline (Orth et al., 2006). Eelgrass serves as important habitat for commercial species such as cod, herring, and lobster, therefore green crab invasions pose both an ecological and economic threat (Joseph, Schmidt & Gregory, 2013; Matheson et al., 2016).

The complete eradication of an invasive species in an aquatic environment is virtually impossible once the organism has become established, unless the invasion is addressed shortly after arrival and in a confined area (Bax et al., 2003; Lodge et al., 2006). In Newfoundland, the complete eradication of green crab is no longer considered an option. Therefore, efforts are now focused on mitigation to suppress invasive populations to slow their spread and minimize their negative effects (DFO, 2011b). These mitigation studies have found that the direct removal of green crabs through focussed trapping is one effective control technique, and has become the current method of conducting targeted removals of green crab on both the east and west coast of Canada (DFO, 2011a,b; Duncombe & Therriault, 2017). Green crab removal efforts in Canada usually utilize Fukui traps (60 x 45 x 20 cm, 12 mm bar length square mesh, 45 cm expandable entry slit) which are practical for mitigation efforts as they are light-weight, collapsible, durable, and can be easily deployed from small boats or from shore.

Despite the widespread use of the Fukui trap for research, monitoring, and mitigation, there have been no formal investigations of the interactions between green crab and the standard Fukui trap, and substantial knowledge gaps exist surrounding the trap's overall efficiency. In addition, it has been shown that green crab aggression and feeding behaviour can vary across sites, which may influence catch rates and the performance of the trap ~~from~~ between areas (Rossong et al., 2012). The main objective of this study was to evaluate the performance and efficiency of the Fukui trap in terms of its ability to catch green crab, and to gain a better understanding of this capture process and how it may differ across sites in Newfoundland.

In this study, we used underwater video cameras to record footage of the traps as they actively fished for green crab *in situ* across Newfoundland. Underwater video is the best way to understand the interactions between an animal and a piece of fishing gear, and is beneficial in determining the optimal design and use of this fishing gear (Favaro et al., 2012; Underwood, Winger & Legge, 2012). There is a growing body of literature on the use of cameras to better understand various types of fishing gears, including traps (alternatively referred to as pots) (Bacheler et al., 2013; Favaro et al., 2013; Jury et al., 2001; Meintzer et al., 2017), trawls (Nguyen et al., 2014; Underwood et al., 2015), and hooks (He, 2003; Robbins et al., 2013). In the case of the Fukui trap, underwater video is an effective method to accurately assess the number of green crab that approach the trap, the outcome of each attempt to enter the trap, and the likelihood that a green crab will remain inside the trap before it is retrieved.

Six steps have to be completed successfully for green crabs to be caught in a trap (Fig. 1) (Favaro, Duff & Côté, 2014). First, they must be present in the area where the Fukui trap has been deployed. Second, they must be able to detect the presence of the trap, either visually or by detecting olfactory cues of the bait plume. Third, green crab must approach the Fukui trap. Fourth, they must locate one of the entrances and make an entry attempt. Fifth, they must successfully complete that entry attempt in order to become captured. Sixth, they must remain in the trap until the gear is hauled (i.e. they must not exit). The use of underwater video cameras in this study enabled us to accurately evaluate steps three through six of the capture process (number of approaches to the trap, proportion of successful entry attempts, number of exits) in order to determine the effectiveness of the Fukui trap at catching green crab. Furthermore, the use of underwater video allowed us to identify barriers that were inhibiting the capture process. This information will enable us to identify inefficiencies in the capture process that could be addressed through modifications to the fishing gear, so that future removal programs can be conducted more efficiently.

## 2. Methods

### *2.1 – Camera apparatus and equipment*

We used custom-built camera housings with Sony HDR-AS20 Action Cameras capable of recording 13-hour high-definition underwater videos (as described in Bergshoeff et al., 2017). We mounted each camera system to a wooden frame built around a standard Fukui trap. Using a large 114–165 mm diameter gear-clamp, the camera housing was centred above the trap, with the camera pointing downward to provide a top-down view of the trap and surrounding area (Fig. 2). The camera was positioned at a height of 53 cm above the top of the trap and 74 cm above the ocean floor, creating a field-of-view (FOV) of approximately 81 cm by 150 cm when filming underwater. The wide-angle lens of the camera made it possible to view the entire trap, in addition to a buffer surrounding all edges of the trap (45 cm to the left and right edge of the trap, and 18 cm from the top and bottom edge). The wooden frame was weighted down with four 2.8 kg cement bricks in order to make it negatively buoyant and to prevent shifting due to currents and wave action. Finally, the rope attaching the trap to the surface float was marked in half-metre increments in order to determine the approximate depth of deployment.

An external lighting system was necessary for overnight trap deployments; therefore each camera apparatus was equipped with two Light and Motion (Marina, California, USA) Gobe Plus flashlights with red LED light attachments (Gobe Focus Head). On low-power mode these flashlights had sufficient battery life to illuminate the entire night cycle. Many crustaceans are insensitive to wavelengths greater than 620 nm, therefore we used red lights with the goal of minimizing the behavioural impacts that may accompany full-spectrum light (Goldsmith & Fernandez, 1968).

*2.2 – Field methods*

We recorded underwater videos at six sites across Newfoundland during the summer of 2015 and one site during the summer of 2016 (Fig. 3) (Kahle & Wickham, 2013). These sites were as follows: 1. Fair Haven (FH), Placentia Bay (June 9-11, 2015 & August 18-20, 2015) 2. Boat Harbour (BH), Placentia Bay (June 23-26, 2015) 3. Little Harbour East (LHE), Fortune Bay (June 22-23, 2015) 4. Little Port Harmon (PH), St. George's Bay (July 7-10, 2015) 5. Penguin

Arm (PA), Bay of Islands (July 14-15, 2015) 6. Deer Arm (BB), Bonne Bay (July 11-14, 2015) 7. Fox Harbour (FX), Placentia Bay (June 30 – July 1, 2016). Each of these sites has known green crab populations. The video data collected during June 2016 in Fox Harbour, NL was collected as part of a complementary study that followed the same methodology for recording videos, and therefore we ~~incorporated the results into this manuscript~~.

At each site we followed a set procedure for deploying the camera traps. Prior to each trap deployment the Fukui traps were baited with equal amounts of herring, the standard bait used by Fisheries and Oceans Canada (hereafter, DFO) for green crab mitigation projects, in a perforated plastic bait container (Gillespie et al., 2007; DFO, 2011b). Once the traps were baited, the camera equipment was secured inside the camera housing and mounted to the frame surrounding the Fukui trap. We used a wireless Sony RM-LVR1 Live View Remote to ensure that the camera and FOV were oriented correctly, and to initiate recording prior to each trap deployment.

We typically deployed the traps close to shore (<50 m) using a small Zodiac boat. When we placed the traps in the water, we made sure that the camera housing entered the water horizontally in order to prevent air bubbles from becoming trapped on the housing's acrylic viewport. We deployed each trap no less than 1 m below the low tide water depth to prevent the camera apparatus from breaching the surface with the changing tides. Each camera trap was paired with a Fukui trap without an attached camera to examine whether the camera itself affected catch rates. The two traps within each pair were placed approximately 10 m apart based on other studies involving the Fukui traps (Gillespie et al., 2007; Yamada et al., 2008; Curtis et al., 2015). In total, two camera traps and two non-camera traps were set at each deployment. Sampling location, global positioning system (GPS) coordinates, time of day, depth, and weather information were recorded for each deployment. Traps were either deployed early in the day and retrieved in the evening (termed ‘daytime deployments’), or deployed before sunset and retrieved the next morning (termed ‘overnight deployments’). We aimed for each trap to be deployed for 12 hours, but logistical factors such as weather sometimes affected trap retrieval time adding variation to total soak time.

When the traps were retrieved the catch was sorted, counted, and sexed. All bycatch species were visually identified to the lowest possible taxonomic level, recorded and released as soon as possible. As per DFO recommendations, all captured green crabs were euthanized by freezing and disposed of. Once the catch was processed the camera equipment was reset and the traps were prepared for re-deployment. We re-baited the traps with fresh herring before each new deployment.

The project was approved as a ‘Category A’ study by the Institutional Animal Care Committee at Memorial University as it only involved invertebrates (project # 15-02-BF), and all field research was conducted under experimental licenses NL-3133-15 and NL-3271-16 issued by DFO.

*2.3 – Determining the effect of camera presence on catch*

We built two linear mixed-effects models using the nlme package (Pinhero et al., 2017) in R (R Core Team, 2015) in order to test whether the presence of the camera had an effect on green crab catch. We ~~performed analysis on~~ analysed a subset of the green crab catch data which included only Fair Haven, NL and Little Port Harmon, NL because all other sites had a mean catch per deployment that was below our elimination threshold of 10 (Table 1). We did not see any meaningful relationship between deployment duration and catch (Fig. 4A, 4B), however due to logistical reasons the soak times were not consistent between Fair Haven (range: 21.8 – 24.3 h) and Little Port Harmon (range: 7.4 – 14.5 h) (Fig. 4C). To account for this we created a separate model for each location, because the underlying effect of soak time on catch was potentially unique to each site (Fig. 4D). These two models tested the fixed effects of camera presence (i.e. camera present, camera not present) and duration on catch-per-deployment. Due to the paired nature of our design we designated each camera and non-camera pair as a single deployment, which were included in the models as a random effect. The residuals for both the Fair Haven and Little Port Harmon models met the assumptions for homogeneity, normality, and independence.

*2.4 – Video analysis*

*2.4.1 – Video selection*

In order to determine which videos to analyze in-full, we first reviewed them according to a selection key (Fig. S1). This process involved evaluating the level of green crab activity in each video, as well as an assessment of the overall image quality of the video. The activity level of each video was determined by counting the approximate number of green crab present in the field of view (FOV) at 35 minute intervals, and calculating the overall mean across those intervals. The average number of green crab in the FOV corresponded to the following activity levels: 0 = 'none'; 0.1 – 5.0 = 'low'; 5.1 – 10.0 = 'medium'; 10.0 and above = 'high'. If the activity level of the green crab was determined to be 'none' or 'low' the video was disqualified. Our assessment of video quality was based on visibility of the trap due to particulate matter and lighting conditions. If the lower panel (i.e. the floor) of the Fukui trap was clearly visible, as well as the entire periphery of the FOV, then the video quality was classified as 'good'. If the lower panel of the Fukui trap was clearly visible, but the periphery of the FOV was poorly lit, then the video quality was classified as ‘fair’. Finally, if the lower panel of the Fukui trap was not visible due to lighting or particulate matter the video quality was classified as ‘poor’. If the video quality was determined to be ‘poor’ the video was disqualified. Overall, in order to qualify for analysis each video required ‘medium’ or ‘high’ activity levels, as well as ‘fair’ or ‘good’ video quality.

*2.4.2 – Video analysis procedure*

We used a standardized procedure to evaluate the video obtained during the 2015 and 2016 field seasons. Video files were viewed using VLC Media Player 2.2.4 on a 27-inch 16:9 (widescreen) flat screen monitor. For night videos, we used the sepia colour setting in VLC to reduce glare and eye-strain caused by the red lighting. Data was recorded in a spreadsheet using Microsoft Excel 2013. The spreadsheet was broken down into different sheets to store video metadata, video analysis data, and indexes which explained the video analysis data (e.g. species code index, event index). The analysis procedure involved characterizing the video by “events” (both qualitative and quantitative) and recording the time during the video at which each event occurred.

We began analyzing the video as soon as the trap settled on the ocean floor after deployment. The FOV was divided into four sections in a clockwise manner (top = 1, right = 2, bottom = 3, left = 4). Every time an animal entered the FOV, we recorded the direction of approach (e.g. APP1, APP2), the species (e.g. GC for green crab, RC for rock crab), and the time as indicated by the VLC time counter. A rough estimate of size was made for each species (small, medium, or large), however, limited emphasis was placed on this information due to the potential for biases and size distortion depending on the distance of a green crab from the camera.

We recorded each attempt to enter the trap, along with the time taken to complete or fail the attempt. For green crab, an attempt was defined as when the entire body of the crab was inside the entry tunnel of either entrance 1 or entrance 2 (Fig. 5). The time for each attempt was recorded until the entry was either successful (e.g. a green crab fully entered the trap) or failed (e.g. a green crab fully left the entrance tunnel). If an entry attempt failed, the predominant reason for failure was noted according to four common, reoccurring situations: 1) Agonism (AGON): some form of intraspecific or interspecific agonistic behaviour deterred or prevented the green crab from entering the trap, 2) Partial entry (PE): the green crab entered the entrance tunnel, but turned around and exited before contacting the trap entry slit, 3) Full entry (FE): the green crab fully entered the entrance tunnel and contacted the trap entry slit, but subsequently turned around and exited, or 4) Difficulty completing entry (DCE): the green crab fully entered the entrance tunnel, but was unable to get through the trap entry slit in order to successfully complete the entry, and subsequently turned around and exited. Additionally, if a green crab was able to escape the trap after it had successfully entered, this was recorded as an exit.

If a notable behaviour occurred that was not part of our core observation framework (e.g. predation) we recorded the time and context of the event. We focused on behavioural interactions outside of the trap instead of green crab already inside the trap, which could be seen as an artificial environment influencing behaviour.

*2.5 – Regional performance of the Fukui trap*

Recently, it has been shown that genetically different green crab populations exist within Newfoundland (Jeffery et al., 2017). We compared video analysis results between St. George's Bay (i.e. Little Port Harmon) on the west coast of Newfoundland, and Placentia Bay (i.e. Fair

Haven and Fox Harbour) on the southeast coast in order to examine regional differences in the performance of the Fukui trap. When comparing these regional differences we focused on parameters related directly to the interactions of green crab with the Fukui trap. This allowed us to evaluate whether variations in regional green crab behaviour had an impact on Fukui trap performance. The parameters we examined included the average time to make an entry attempt and the proportion of each entry attempt type. Furthermore, we compared the effect of increasing trap density on entry attempt proportions between each region. We defined a new density bin for every 10 green crab that were successfully captured (e.g. 0-10, 11-20).

## 3. Results

### *3.1 – Field deployment results*

During the 2015 field season, a total of 39 camera traps and 40 traps without cameras were deployed (total n = 79) across the six field sites. Trap deployment times ranged from 2.7 to 24.4 hours (mean ± S.E. = 14.2 ± 0.7). We collected 37 videos in total (Table S1: two of the 39 videos failed due to partial flooding of the camera housing). Recording duration of videos ranged from 2.7 to 13.0 hours (mean ± S.E. = 11.2 ± 0.4). The inconsistency in deployment durations can be attributed to a combination of logistical challenges getting to-and-from the site and inclement weather preventing retrieval of the gear.

Both the fishing effort and the number of green crab caught per trap varied across the six study sites visited in 2015, with all but two of the sites (Fair Haven, NL and Little Port Harmon, NL) exhibiting a mean catch of less than 10 green crab per deployment (Table 1). Generally, bycatch using the Fukui trap was minimal. The most common occurrence of bycatch was rock crab (*Cancer irroratus*) in Boat Harbour, NL and Bonne Bay, NL (Table 2).

*3.2 – Camera effect results*

We found the presence of the camera had no significant impact on green crab catch at both Fair Haven, NL ($\beta 1 = 19.409$, S.E. = 46.797, $t = 0.415$, $p = 0.693$) and Little Port Harmon, NL ($\beta 1 = -21.526$, S.E. = 16.970, $t = -1.268$, $p = 0.273$). The effect size, $\beta 1$, can be interpreted as an increase of 19 crabs per trap when a camera is present at Fair Haven, and a decrease in 22 crabs per trap when the camera is present at Little Port Harmon, both relative to non-camera traps. Camera traps fished in Fair Haven caught between 10 and 299 green crabs (Fig. 6, mean ± S.E. = 140.88 ± 35.22, n = 8), and non-camera traps fished in Fair Haven caught between 18 and 232 green crabs (mean ± S.E. = 122.62 ± 28.6, n = 8). Camera traps fished in Little Port Harmon caught between 3 and 74 green crabs (mean ± S.E. = 26.33 ± 10.77, n = 6), and non-camera traps fished in Little Port Harmon caught between 0 and 102 green crabs (mean ± S.E. = 49.29 ± 13.66, n = 7).

*3.3 – Video analysis results*

Using the video selection key (Fig. S1), we filtered through the video recordings and determined that 8 of the 37 collected videos were suitable for complete analysis (Table S2). The majority of the videos that were rejected from the analysis process showed no or 'low' green crab activity, and were therefore disqualified. Overall, videos were clear and well illuminated, however videos collected at night under red illumination were dim around the periphery of the FOV (Fig. 2). Additionally, videos collected in Fair Haven in late-August, 2015 were disqualified due to 'poor' quality caused by excessive turbidity and suspended particulate in the shallow bay in which we were trapping.

Results from the eight videos that were analyzed can be examined in Table 3. The variability between each video and the range of green crab activity levels across each site is illustrated in Figure 7. In total, we observed 2,373 green crab approaches to the trap over the course of eight camera deployments (73.0 hours) (Fig. 7A) and 351 approaches to the trap by other species. Green crabs comprised 86.0% (± 1 S.E. = 3.6) of all approaches to the trap and it took 3.5 min on average for the first green crab to approach the trap (N = 8, S.E. = 1.2 min, range: 0.9 – 11.1 min). We observed an average of 35.7 ± 6.4 green crab approaches per hour across all eight videos. Only 8.0 ± 1.8% of the 2,373 green crab approaches resulted in a successful entry into the Fukui trap. No green crab exits were observed during any of the videos.

We observed a total of 1,226 green crabs make an attempt to enter the Fukui trap across all sites (Fig. 7B), as well as 30 attempts by other species. 52.5 ± 3.8% of green crabs that approached the trap made entry attempts and on average there were 18.0 ± 3.2 entry attempts per hour. Across all sites, 181 green crabs made successful entry attempts (Fig. 7C), which equates to an average success rate of 16.0 ± 4.0%. As seen in Figure 8, the proportion of successful entries into the Fukui trap was not necessarily linked with the number of entry attempts made. On average, it took a green crab 140.3 ± 11.0 seconds (range: 8 – 837 seconds) to successfully enter the Fukui trap during an entry attempt, while a failed entry attempt took an average of 126.1 ± 6.2 seconds.

The proportion of failed entry attempts (84.0 ± 4.0%) can be further broken down according to the four most common reasons for failure (Fig. 9). First, 4.0 ± 0.8% (n = 51) of all entry attempts failed due to some sort of agonistic behaviour (AGON) preventing the green crab from entering the trap after an average of 41.9 ± 7.8 seconds. Second, 20.0 ± 4.3% (n = 209) of all entry attempts failed because the green crab entered the entry tunnel, but only made a partial entry (PE) and exited after an average of 41.1 ± 2.4 seconds. Third, 15.5 ± 2.6% (n = 215) of all entry attempts failed after the green crab fully entered the entrance tunnel and contacted the entry slit, but subsequently turned around (FE) after an average of 47.5 ± 2.0 seconds. Finally, 44.5 ± 5.1% (n = 570) of all entry attempts failed because the green crab had difficulty getting through the trap entry slit in order to complete the entry (DCE). On average, a green crab would struggle to pass through the entry slit for 195.4 ± 10.4 seconds before failing the attempt.

### *3.4 – Regional performance of the Fukui trap*

The performance of the Fukui trap remained consistent across Newfoundland, regardless of study site and region (i.e. Fox Harbour and Fair Haven in eastern Newfoundland, Little Port Harmon in western Newfoundland). The proportion of successful and failed entry attempts, as well as the average time taken for each type of entry attempt, revealed no clear site-specific trends (Fig. 10). Based on all entry attempts at each site, the proportion of successful entry attempts was 15%, 17% and 14% at Fair Haven, Fox Harbour, and Little Port Harmon, respectively. As the density of green crabs within the Fukui trap increased there was no obvious site-specific effect on the outcome of an entry attempt (Fig. 11). We did not observe any saturation of the Fukui traps during this study.

## 4. Discussion

### *4.1 – Video quality*

In this study, we found underwater video to be an effective means of evaluating the Fukui trap as it actively fishes for invasive green crab *in situ*, providing information that could not be inferred from catch data alone. However, there are inherent challenges associated with the collection of data from video recordings.

First, ~~as mentioned in the results~~, the illumination during nighttime deployments was dim around the periphery of the FOV and the use of red lights had an impact on image quality due to high absorption of this frequency in water (Williams et al., 2014). Therefore, the number of approaches recorded during these deployments may have been less accurate than daytime deployments. This is a common issue when recording video in low-light environments (Underwood, Winger & Legge, 2012; Favaro, Duff & Côté, 2014). However, both of the entry tunnels and the trap entry slits were clearly illuminated during nighttime deployments, therefore the accuracy of entry attempt data remained consistent across all deployments. Second, we were limited to videos collected in June and July due to poor visibility caused by increased water temperature in mid-August. The videos collected in Fair Haven, NL in August 2015 had to be disqualified due to excessive turbidity and suspended particulate. Finally, as green crab accumulated inside the Fukui trap it became more difficult to track individual crabs as they made entry attempts, as the line-of-sight was often obstructed by green crabs already inside the trap. This may have had an effect on the number of entry attempts recorded in videos with high green crab densities, which could have ultimately influenced our calculations of entry attempt proportions.

*4.2 – Evaluation of the six-step capture process*

Through our video analysis we have gained considerable insight into the performance of the standard Fukui trap as a tool for green crab mitigation, as well as the behaviour of the green crab in relation to the trap itself, other species, and other green crab. These findings can be summarized using the framework of the six-step capture process (Fig. 1).

*Step 1 – Green crab must be present in the ecosystem*

We found varying numbers of green crab present in the areas where we deployed Fukui traps. As demonstrated in Table 1, effective trapping requires that green crab be present in sufficient numbers within the area being fished. Despite anecdotal evidence of established green crab populations in all sites sampled in 2015, a mean green crab catch per deployment above our elimination threshold of 10 was limited to Fair Haven, NL and Little Port Harmon, NL. We hypothesize that the low catch rates at the other locations could be attributed to environmental factors. Newfoundland experienced a prolonged winter in 2014 – 2015 with above normal ice extent, followed by a late spring warming (DFO, 2016). It has been shown that unusually low winter temperatures can result in mass mortality of adult green crab, and poor recruitment (Crisp, 1964; Welch, 1968; Berrill, 1982; Beukema, 1991). These low temperatures could have had an impact on green crab populations, producing less catch in certain areas than was seen in previous years (Welch, 1968; Yamada & Kosro, 2010).

When deploying the camera apparatus we had to ensure that the camera would not breach the water's surface with the changing tides, so the cameras were deployed approximately 1 m deep at low tide levels. Green crabs are most commonly found in depths ranging from high tide levels to 5 – 6 m, and have been reported at depths of up to 60 m (Crothers J. H., 1967; Klassen & Locke, 2007). Therefore, we are confident that the placement of our traps was sufficient to catch green crab if they were present at each trapping location, despite the minimum depth limitation dictated by the height of the frame above the Fukui trap. With these factors in mind, when we examined catch data for the purpose of comparing catch between camera and non-camera traps we assumed that the instances of zero catch were a result of environmental factors.

As seen in Table 2, bycatch at each location was generally low, suggesting that the Fukui trap has a minimal impact on native species and is an appropriate trap for targeting green crabs in areas where other species are present. Predation by green crabs (suspected) causing bycatch mortality was rare and limited to soft-bodied species such as winter flounder (*Pseudopleuronectes americanus*), cunner (*Tautogolabrus adspersus*), and sculpin (Genus *Myoxocephalus*) in Fukui traps containing large quantities of green crabs. We saw no mortality of rock crab (*Cancer irroratus*) or American eel (*Anguilla rostrata*), and all bycatch species were released alive after retrieval of the Fukui trap.

*Step 2 – Green crab must detect the trap*

Foraging in green crabs is directed primarily by chemoreception and the detection of chemical cues to locate a food source (Shelton & Mackie, 1971). We observed that green crabs located and approached baited Fukui traps within seconds of the trap touching down on the ocean floor after deployment. The first green crab to approach the Fukui trap ranged from 53 seconds to 663 seconds (mean ± S.E. = 207.9 ± 71.0 seconds). Therefore, we can conclude that if green crabs were present in the area where the trap was deployed then the olfactory cues from the herring (*Clupea harengus)* functioned as effective bait.

*Step 3 – Green crab must approach the trap*

We observed a range of different behaviours associated with green crab approaching the Fukui trap. Some green crabs would make an entry attempt right away, entering the camera's

FOV and proceeding directly to the entrance tunnel in order to make an attempt. In other instances, green crabs would survey the trap for long periods of time before discovering the entrance tunnel or deciding to make an entry attempt. We frequently observed agonistic behaviour on and around the Fukui trap, especially once green crabs began to accumulate in the area. Green crab would often cluster on top of the trap, situating themselves above the bait container (hanging inside the center of the trap) as if they were guarding a food source, a behaviour that has been noted with Dungeness crab (*Metacarcinus magister*) (Barber & Cobb, 2009). This behaviour would result in confrontations between green crabs as they fought to either defend their position or to displace the green crab guarding the bait. It was common to witness one green crab pursuing another around the trap or to observe one crab grasping and immobilizing another. Size did not appear to have an impact on which green crab was the aggressor. Green crab did not only exhibit intraspecific agonistic behaviours, they would often engage with other species in the vicinity of the trap. It was not uncommon for green crab to display aggressive behaviour towards a larger fish species such as winter flounder.

It should be noted that we could not individually identify crabs as they entered and re-entered the FOV, therefore the number of approaches by green crab to the Fukui trap does not represent the absolute number of individual crabs that approached the trap. This is a common challenge associated *in situ* camera studies (Favaro, Duff & Côté, 2014). However, despite this caveat every entry attempt we observed was absolute, regardless of whether a green crab approached multiple times. If a target species repeatedly attempts to enter a piece of fishing gear, yet fails to become captured, this suggests a fundamental problem with the fishing gear itself that must be addressed.

*Step 4 – Green crab must make an entry attempt*

We observed a total of 1,226 green crabs make entry attempts, however the majority of the entry attempts we observed (84.0 ± 4.0%, n = 1045) were unsuccessful. We were able to classify the outcome of these failed attempts according to four common scenarios as outlined in the methods.

An entry attempt was classified as a partial entry (PE) when the crab entered the entrance tunnel, but turned around and exited before contacting the trap entry slit. There was often no obvious reason driving this behaviour, however, occasionally a green crab's leg would hook the mesh on the top or side panel of the entrance tunnel, causing the crab to be turned around or upside down instead of directed further inside the trap. An entry attempt was classified as a full entry (FE) when the crab fully entered the entrance tunnel and contacted the trap entry slit, but subsequently turned around and exited the entrance tunnel.

The most common failure scenario occurred when a green crab had difficulty completing the entry attempt (DCE). This was characterized by the green crab experiencing varying degrees of difficulty passing through the entry slit of the trap and subsequently aborting the attempt. The amount of time spent by a green crab attempting to pass through the trap entry slit ranged widely from 19 to 2,789 seconds, and often even the most determined green crab was unable to enter the Fukui trap. A combination of mesh size and the restrictive opening of the trap entry slit made successful entries difficult. It was not uncommon for the sharp pereopods or anterio-lateral spines on the crab's carapace to become entangled or caught in the mesh (1 cm x 1 cm) of the Fukui trap, inhibiting successful entry. Similarly, the five anterio-lateral spines on either side of the green crab's eyes would often catch on the mesh of the entry slit as a green crab attempted to enter. Furthermore, even without getting caught in the mesh of the trap, the entry slit was often too tight for the crabs to easily slip through, causing them to become stuck or entangled, and ultimately fail the entry attempt. If a crab was able to reach one of its pereopods or chelipeds through the trap entry slit, there was often nothing for the trap to grab hold of in order to pull itself through the tight-fitting entry slit, resulting in a failed entry attempt.

Finally, the least common reason for failure was intraspecific and interspecific agonistic behaviour (AGON) which deterred or prevented green crab from entering the Fukui trap. Often, if two green crabs were making a simultaneous entry attempt, agonistic behaviour between the two crabs would cause one or both of the crabs to abort the entry attempt. Alternatively, it was not uncommon for a crab already inside the entry tunnel to deter other crabs from entering the entrance tunnel in order to make an attempt. This agonistic behaviour was not limited to crabs outside of the trap, as green crab that were already successfully inside the trap would occasionally attempt to deter other crabs from entering the trap. Similar behaviour has been documented in Dungeness crab (*Metacarcinus magister*) and American lobster (*Homarus americanus*) where they have been observed guarding the entrances to traps or using their bodies to prevent other individuals from entering the trap (Jury et al., 2001; Barber & Cobb, 2009).

*Step 5 – Green crab must successfully enter the trap*

~~As seen in Table~~ 3, the number of entry attempts is far greater than the number of successful entries, suggesting that the capture efficiency of the Fukui trap is low. The time for a green crab to enter the trap ranged greatly from 8 – 837 seconds (mean = 140.3 ± 11.0 seconds), demonstrating varying levels of difficultly completing an entry attempt. We observed several scenarios that often assisted green crab in entering the Fukui trap. If a crab approached the entrance tunnel at a fast pace it was often able to use this momentum to push through the trap entry slit with minimal effort. Similarly, if a green crab approached the entry slit backwards, so that the anterio-lateral spines of the carapace did not become caught in the mesh, they were often able to enter the trap relatively quickly. In other situations, crab would struggle for long periods of time to get through the trap entry slit, some eventually achieving success. We also observed crabs using the bait container hanging in the center of the trap to assist in pulling themselves through the entry slit.

Figure 7 demonstrates drastically varied levels of success from one video to the next, ranging from only 0.9% to 31.0% (mean = 16.0 ± 4.0%). As seen in Figure 7A, there were 2373 approaches across all videos, but of these approaches few green crab were actually captured, demonstrating a disconnect between abundance and final catch. The lines for each video in Figure 7A were similar in shape to those in Figure 7B, showing that if there were many approaches to the trap, there were generally many entry attempts. The large number of attempts seen in Figure 7B indicates that green crab were actively trying to enter the Fukui trap, however Figure 7C shows that this does not necessarily reflect how many green crab were captured. This point is further demonstrated in Figure 8, showing that the number of green crab entry attempts is not linked to the success rate in any meaningful or positive relationship.

Figure 7C demonstrates that catch is not an accurate representation of entry attempt effort, as the success rate varied widely. Certain videos (e.g. PH5) had many green crab entry attempts, resulting in comparatively high catch. However, some videos (e.g. FH3, PH1) had a large number of approaches and attempts, yet caught very few crab. The low success rate in certain videos suggests that the variability in success rate could be due to the condition of the specific Fukui trap used. For example, if the metal frame of the trap is distorted in such a way that the tension of the entry slit has been altered, this could affect how well a green crab is able to enter the trap. Alternatively, if the mesh of the trap is worn or sagging, this could have a variable influence on catch. These hypotheses emphasize the importance of regularly inspecting the condition of the Fukui trap in order to promote successful entry attempts.

The variable success rates as seen in Figure 8 not only suggest there may be a fundamental problem with the design of the Fukui trap, but also that final catch does not necessarily reflect the abundance of green crab in an ecosystem. From an invasive species management perspective, this shows that there may be more green crab in an area than is suggested by catch data alone, emphasising the importance of not relying exclusively on catch data to estimate green crab populations in invaded areas.

*Step 6 – Green crab must not exit the trap*

Over the 73 hours of video we analyzed, we did not observe a single escape from the Fukui trap, demonstrating that although it is difficult to enter the trap, once inside there is very little chance of a green crab escaping. However it should be noted that we were not always able to retrieve the trap before the end of the video recording, therefore our final catch numbers do not necessarily correspond to what was observed in the video. Given the low rate of successful entry, the benefits of a highly secure trap that prevents escapes are lost when compared to the potential number of green crab that could be captured if the entrance to the trap was less restrictive to begin with. To be more efficient, the Fukui trap needs to have a balance between effective catch and the risk of potential escapes.

*4.3 – Regional performance of the Fukui trap*

The green crab is considered a global invader and has established populations on almost every continent around the globe (Yamada, 2001; Carlton & Cohen, 2003). In North America, current distributions of green crab on the west coast range from California, USA (Cohen, Carlton & Fountain, 1995; Yamada et al., 2008) up to British Columbia, Canada (Gillespie et al., 2007). On the east coast green crab can be found from Virginia, USA (Williams, 1984) to Newfoundland, Canada (Blakeslee et al., 2010; McKenzie et al., 2011). The Newfoundland green crab invasion is relatively recent when compared to the rest of North America, where its presence was confirmed in 2007 in North Harbour, Placentia Bay. Since this discovery, the green crab has spread to the west (St. George's Bay, the Bay of Islands, Bonne Bay) and south (Fortune Bay) coasts of Newfoundland (DFO, 2011a).

Evidence suggests that green crab populations in the northwest Atlantic are made up of both northern and southern genotypes that originated from two separate introduction events. First, the historical invasion of the northeastern United States in the early 1800's by green crab originating from the southern UK (Say, 1817; Roman, 2006; Blakeslee et al., 2010). Second, an introduction into the Maritimes in the late 1980's by a more cold-tolerant population from the northern limit of the green crab's range in Europe (Roman, 2006; Blakeslee et al., 2010; DFO, 2011a). In Newfoundland, genetic analysis of green crab populations indicate a mixed ancestry of both the southern and northern genotypes, with a close relationship to the more cold-tolerant, northern population (Blakeslee et al., 2010; DFO, 2011a). Recent findings show that green crab populations on the west coast of Newfoundland (i.e. St. George's Bay) are genetically different from those on the southeast coasts (i.e. Placentia Bay), which could manifest itself in different behaviours and invasion characteristics (Jeffery et al., 2017). For this reason, we chose study sites across Newfoundland in order to evaluate the effectiveness of the Fukui trap as a mitigation tool across multiple regions with genetically diverse green crab populations.

The expansive distribution of invasive green crab populations across North America, coupled with variations in genetic origin, suggests that there may not be a one-size-fits-all approach when responding to green crab invasions. That being said, the Fukui trap is being used on both the east (Matheson & Gagnon, 2012; Rossong et al., 2012; McNive, Quijon & Mitchell, 2013; Best, McKenzie & Couturier, 2014) and west (Yamada et al., 2005, 2008; Jensen, McDonald & Armstrong, 2007; Duncombe & Therriault, 2017) coasts of North America, and remains the trap of choice for green crab mitigation due to its relative effectiveness, durability, and ease-of-use compared with other traps (CHM).

For this study, we analyzed video footage from the west (i.e. Little Port Harmon, NL) and southeast (i.e. Fair Haven, NL and Fox Harbour, NL) coasts of Newfoundland, which enabled us to examine regional differences in the performance of the Fukui trap. Overall, we saw little variation in the performance of the Fukui trap from one study site to the next and there did not appear to be any regional differences in trap efficiency (Fig. 10). The proportion of successful entry attempts by green crab into the Fukui trap was consistently low at each study site regardless of region (i.e. southeastern Newfoundland and western Newfoundland). Similarly, the average time taken for each type of entry attempt followed a similar trend at each study site. This suggests that the factors that contribute to high entry attempt failure, and therefore limit catch efficiency, are underlying problems with the Fukui trap itself and are not influenced by behavioural variations in local green crab populations. If these underlying factors that limit catch efficiency can be addressed and corrected, then we expect that catch efficiency can be improved wherever Fukui traps are being utilized as a mitigation tool, regardless of genetic differences and regional green crab characteristics.

Furthermore, we did not observe any clear site-specific variations between the study sites in the proportion of successful and failed entry attempts as the density of green crab within the Fukui trap increased (Fig. 11). Regardless of variable in-trap density, local green crab behavioural characteristics, or green crab population size, the low catch-rates of the Fukui trap remain consistent across all sites. Finally, the fact that we did not observe saturation of the Fukui trap at any point is likely due to the fact that ambient green crab densities were low and could not meet saturation densities within the scope of our video recordings.

### *4.4 – Efficiency and modification*

Only 16.0 ± 4.0% of entry attempts into Fukui traps were successful, demonstrating that there is much room for improvement in the performance and efficiency of the trap. Still, the Fukui trap is a common choice for green crab mitigation across Canada and intensive trapping has proven to be an effective technique for reducing green crab populations (Gillespie et al., 2007; DFO, 2011a,b). It has been shown that continuous trapping can decrease the average carapace width of green crab caught in an invaded area, making them more susceptible to predation by native shorebirds and crustaceans (DFO, 2011a). Furthermore, it has been shown that in areas where intensive trapping has occurred that the abundance of native species increases (DFO, 2011a). Although population size in an area will influence the number of green crab that are captured (Maceina, Rider & Lowery, 1993; Wright, Caputi & Penn, 2006; Walter, Hoenig & Gedamke, 2007), catch data alone will not yield accurate estimates of abundance. Therefore, the effectiveness of trapping as a control measure for green crab should be approached with caution when assessing abundance and evaluating the success of mitigation efforts based on catch. In the case of the Fukui trap, low success rates suggest that ambient green crab abundance is often much greater than what is indicated by the catch data alone. This suggests that catch-per-unit-effort (CPUE) alone is not a suitable proxy for green crab abundance in an invaded area.

Furthermore, the effectiveness of a baited trap as a tool to estimate relative abundance is dependent on the influence of factors such as activity levels, temperature, feeding rates, and reproductive condition. These factors can vary both spatially and temporally to ultimately affect the catchability of a C. maenas ~~target species~~ (Crothers J. H., 1967; Murray & Seed, 2010). Therefore, abundance estimates based on CPUE should be supplemented with additional sampling techniques such as SCUBA transects, shoreline surveys, acoustic tagging equipment, and discussions with fish harvesters, harbour authorities, and the local community (DFO, 2011a). By combining catch data with these additional techniques, a more accurate understanding of green crab populations within an invaded ecosystem can be provided for management decisions.

Despite these limitations, removal efforts using the Fukui trap remain an important technique for reducing green crab populations in invaded ecosystems. However, our study has revealed that there is room for improvement in the performance of the Fukui trap. Through our underwater videos we have discovered that a substantial proportion (84.0 ± 4.0%) of green crab that attempt to enter the Fukui trap do not successfully complete these entries. The proportion of successful entry attempts into the Fukui trap is low when compared to similar studies of baited traps. For example, traps used to capture Atlantic cod (*Gadus morhua*) and spot prawns (*Pandalus platyceros*) have successful entry attempt proportions of 22% and 46%, respectively (Favaro, Duff & Côté, 2014; Meintzer, Walsh & Favaro, 2017).

We believe there is scope to develop an improved trap that will facilitate entry of green crab into the fishing gear. The knowledge gained from our study has provided us with sufficient insight into how the Fukui trap could be improved to increase overall catch efficiency for green crab. ~~Furthermore,~~ the problems associated with the design of the Fukui trap are predominately mechanical issues that can likely be addressed through various modifications. Even simple modifications, such as adjusting the mesh size in the entrance tunnel or widening the restrictive entry slit, could have dramatic impacts on the catch efficiency of the Fukui trap.

The efficiency of the Fukui trap can be addressed through simple modifications that can be easily applied to standard Fukui traps. If these design modifications are found to be effective, then this will greatly increase the number of green crab that are removed from invaded ecosystems during mitigation efforts. Additionally, a more efficient Fukui trap will mean higher CPUE, maximizing trap usage for mitigation and control. Ultimately, a more efficient Fukui trap will help to control green crab populations in order to preserve the function and integrity of ecosystems invaded by the green crab.

## 5. Conclusions

Our study represents the first formal investigation into the performance of the Fukui trap as a mitigation tool for the invasive green crab in Newfoundland. Our use of underwater video was a novel approach that allowed us to accurately determine the capture efficiency of these traps in a way that would be unachievable from catch data alone. Through the use of underwater video we were able to gain insight into the efficiency of the Fukui trap, as well as the interactions that occur around and inside these traps as they are actively fished for green crab *in-situ*. Although our results revealed the rate of successful entries into the Fukui trap was low, we are confident that the mechanical inefficiencies of the trap can be addressed through simple modifications that will increase their CPUE. Furthermore, we were able to conclude that the underlying mechanisms contributing to low capture efficiency remained consistent regardless of the region or the local green crab population. The versatility of the Fukui trap as a control method for green crab has contributed to its widespread use on both the east and west coast of Canada, therefore if the performance and efficiency of the Fukui trap can be improved then this will benefit green crab mitigation efforts wherever these traps are being used.

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## References

Bacheler NM., Schobernd CM., Schobernd ZH., Mitchell WA., Berrane DJ., Kellison GT., Reichert MJM. 2013. Comparison of trap and underwater video gears for indexing reef fish presence and abundance in the southeast United States. *Fisheries Research* 143:81–88. DOI: 10.1016/j.fishres.2013.01.013.

Barber JS., Cobb JS. 2009. Qualitative observations of Dungeness crabs, *Cancer magister*, in and around traps: evidence of resource guarding and clustering. *Marine and Freshwater Behaviour and Physiology* 42:135–146. DOI: 10.1080/10236240902860011.

Bax N., Williamson A., Aguero M., Gonzalez E., Geeves W. 2003. Marine invasive alien species: a threat to global biodiversity. *Marine Policy* 27:313–323. DOI: 10.1016/S0308-597X(03)00041-1.

Bergshoeff JA., Zargarpour N., Legge G., Favaro B., Bay L., Ak NL. 2017. How to build a low-cost underwater camera housing for aquatic research. *Facets* 2:150–159. DOI: 10.1139/facets-2016-0048.

Berrill M. 1982. The life cycle of the green crab *Carcinus maenas* at the northern end of its range. *Journal of Crustacean Biology* 2:31–39.

Best K., McKenzie CH., Couturier C. 2014. Investigating mitigation of juvenile European green crab Carcinus maenas from seed mussels to prevent transfer during Newfoundland mussel aquaculture operations. *Management of Biological Invasions* 5:255–262.

Beukema JJ. 1991. The abundance of shore crabs *Carcinus maenas* (L.) on a tidal flat in the Wadden Sea after cold and mild winters. *Journal of Experimental Marine Biology and*

*Ecology* 153:97–113. DOI: 10.1016/S0022-0981(05)80009-7.

Blakeslee AMH., McKenzie CH., Darling JA., Byers JE., Pringle JM., Roman J. 2010. A hitchhiker's guide to the Maritimes: anthropogenic transport facilitates long-distance dispersal of an invasive marine crab to Newfoundland. *Diversity and Distributions* 16:879–891. DOI: 10.1111/j.1472-4642.2010.00703.x.

Carlton JT., Cohen AN. 2003. Episodic global dispersal in shallow water marine organisms: the case history of the European shore crabs *Carcinus maenas* and *C. aestuarii*. *Journal of Biogeography* 30:1809–1820. DOI: 10.1111/j.1365-2699.2003.00962.x.

Cohen AN., Carlton JT., Fountain MC. 1995. Introduction, dispersal and potential impacts of the green crab *Carcinus maenas* in San Francisco Bay, California. *Marine Biology* 122:225–237.

Crisp DJ. 1964. The effects of the severe winter of 1962-63 on marine life in Britain. *British Ecological Society* 33:165–210.

Crothers J. H. 1967. The biology of the shore crab *Carcinus maenas* (L.). *Field Studies* 2:579–614.

Curtis LJF., Curtis DL., Matkin H., Thompson M., Choi F., Callow P., Gillespie GE., Terriault TW., Pearce CM. 2015. Evaluating transfers of harvested shellfish products, from the west to the east coast of Vancouver Island, as a potential vector for European green crab (*Carcinus Maenus*) and other non-indigenous invertebrate species. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2015/014:vi + 74 p.

DFO. 2011a. Ecological assessment of the invasive European green crab (*Carcinus maenas*) in

Newfoundland 2007-2009. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.*:2011/033.

DFO. 2011b. Proceedings of the Regional Advisory Process on green crab, *Carcinus maenas*, populations and mitigations in the Newfoundland and Labrador region. *DFO Can. Sci. Advis. Sec. Proceed. Ser.* 2011/020.

DFO. 2016. Oceanographic conditions in the Atlantic zone in 2015. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.*:2016/041.

Duncombe LG., Therriault TW. 2017. Evaluating trapping as a method to control the European green crab, *Carcinus maenas*, population at Pipestem Inlet, British Columbia. *Management of Biological Invasions* 8:235–246.

Favaro B., Duff SD., Côté IM. 2013. A trap with a twist: evaluating a bycatch reduction device to prevent rockfish capture in crustacean traps. *ICES Journal of Marine Science* 70:114–122.

Favaro B., Duff SD., Côté IM. 2014. Density-dependent catchability of spot prawns (*Pandalus platyceros*) observed using underwater video. *The Journal of Ocean Technology* 9:84–98.

Favaro B., Lichota C., Côté IM., Duff SD. 2012. TrapCam: an inexpensive camera system for studying deep-water animals. *Methods in Ecology and Evolution* 3:39–46. DOI: 10.1111/j.2041-210X.2011.00128.x.

Gillespie GE., Phillips AC., Paltzat DL., Therriault TW. 2007. Status of the European green crab , *Carcinus maenas*, in British Columbia - 2006. *Canadian Technical Report of Fisheries and Aquatic Sciences* 2700:39 p.

Goldsmith TH., Fernandez HR. 1968. Comparative studies of crustacean spectral sensitivity.

*Vergleichende Physiologie* 60:156–175. DOI: 10.1007/BF00878449.

He P. 2003. Swimming behaviour of winter flounder (*Pleuronectes americanus*) on natural fishing grounds as observed by an underwater video camera. *Fisheries Research* 60:507–514. DOI: 10.1016/S0165-7836(02)00086-3.

Jeffery NW., DiBacco C., Van Wyngaarden M., Hamilton LC., Stanley RRE., Bernier R., FitzGerald J., Matheson K., McKenzie CH., Nadukkalam Ravindran P., Beiko R., Bradbury IR. 2017. RAD sequencing reveals genomewide divergence between independent invasions of the European green crab (*Carcinus maenas*) in the Northwest Atlantic. *Ecology and Evolution*:1–12. DOI: 10.1002/ece3.2872.

Jensen GC., McDonald PS., Armstrong DA. 2007. Biotic resistance to green crab, Carcinus maenas, in California bays. *Marine Biology* 151:2231–2243. DOI: 10.1007/s00227-007-0658-4.

Joseph V., Schmidt AL., Gregory RS. 2013. Use of eelgrass habitats by fish in eastern Canada. *Canadian Scientific Advisory Secretariat Science Research Document* 2012/138:ii + 12p.

Jury SH., Howell H., O’Grady DF., Watson WH., Jury, S.H., Howell, H., O’Grady, D.F.O. & Watson III WH. 2001. Lobster trap video: *in situ* video surveillance of the behaviour of *Homarus americanus* in and around traps. *Marine and Freshwater Research* 52:1125–1132.

Kahle D., Wickham H. 2013. ggmap: Spatial Visualization with ggplot2. *The R Journal* 5:144–161.

Klassen G., Locke A. 2007. A biological synopsis of the European green crab, *Carcinus maenas*. *Canadian Manuscript Report of Fisheries and Aquatic Sciences* 2818:1–82.

Lodge DM., Williams S., MacIsaac HJ., Hayes KR., Leung B., Reichard S., Mack RN., Moyle PB., Smith M., Andow DA., Carlton JT., McMichael A. 2006. Biological invaions: recommendations for U.S. policy and management. *Ecological Applications* 16:2035–2054. DOI: 10.1890/04-0922.

Lowe S., Browne M., Boudjelas S., De Poorter M. 2000. *100 of the world's worst invasive alien species: a selection from the global invasice species database*. Invasive Species Specialist group (ISSG), specialist group of the Species Survival Commission (SSC) of the World, Conservation Union (IUCN).

Maceina MJ., Rider SJ., Lowery DR. 1993. Use of a catch-depletion method to estimate population density of age-0 largemouth bass in submersed vegetation. *North American Journal of Fisheries Management* 13:847–851. DOI: 10.1577/1548-8675(1993)013<0847:UOACDM>2.3.CO;2.

Matheson K., Gagnon P. 2012. Temperature mediates non-competitive foraging in indigenous rock (*Cancer irroratus* Say) and recently introduced green (*Carcinus maenas* L.) crabs from Newfoundland and Labrador. *Journal of Experimental Marine Biology and Ecology* 414–415:6–18. DOI: 10.1016/j.jembe.2012.01.006.

Matheson K., McKenzie CH. 2014. Predation of sea scallops and other indigenous bivalves by invasive green crab, Carcinus maenas, from Newfoundland, Canada. *Journal of Shellfish Research* 33:495–501. DOI: 10.2983/035.033.0218.

Matheson K., McKenzie CH., Gregory RS., Robichaud DA., Bradbury IR., Snelgrove PVR., Rose GA. 2016. Linking eelgrass decline and impacts on associated fish communities to European green crab Carcinus maenas invasion. *Marine Ecology Progress Series* 548:31–

45. DOI: 10.3354/meps11674.

McKenzie CH., Han G., He M., Wells T., Maillet G. 2011. Alternate ballast water exchange zones for the Newfoundland and Labrador region – an aquatic invasive species risk assessment based on oceanographic modelling, ecologically and biologically significant areas and the sustainability of fisheries and aquacul. *DFO Can. Sci. Advis. Sec. Res. Doc.* 2010/087:viii + 39 p.

McNive MA., Quijon PA., Mitchell AW. 2013. Composition and distribution of the European green crab in Prince Edward Island, Canada. *Journal of Animal Science* 3:295–298.

Meintzer P., Walsh P., Favaro B. 2017. Will you swim into my parlour? *In situ* observations of Atlantic cod (*Gadus morhua*) interactions with baited pots, with implications for gear design. *PeerJ* 5:e2953. DOI: 10.7717/peerj.2953.

Murray LG., Seed R. 2010. Determining whether catch per unit effort is a suitable proxy for relative crab abundance. *Marine Ecology Progress Series* 401:173–182. DOI: 10.3354/meps08415.

Nguyen TX., Winger PD., Legge G., Dawe EG., Mullowney DR. 2014. Underwater observations of the behaviour of snow crab (*Chionoecetes opilio*) encountering a shrimp trawl off northeast Newfoundland. *Fisheries Research* 156:9–13. DOI: 10.1016/j.fishres.2014.04.013.

Orth RJ., Carruthers TJB., Dennison WC., Duarte CM., Fourqurean JW., Heck KL., Hughes AR., Kendrick GA., Kenworthy WJ., Olyarnik S., Short FT., Waycott M., Williams SL. 2006. A global crisis for seagrass ecosystems. *Bioscience* 56:987–996. DOI: 10.1641/0006-3568(2006)56[987:agcfse]2.0.co;2.

Pinhero J., Bates D., Debroy S., Sarkar D., R Core Team. 2017. nlme: linear and nonlinear mixed effects models. R package version 3.1-131, https://cran.r-project.org/package=nlme.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Robbins WD., Peddemors VM., Broadhurst MK., Gray CA. 2013. Hooked on fishing? Recreational angling interactions with the Critically Endangered grey nurse shark *Carcharias taurus* in eastern Australia. *Endangered Species Research* 21:161–170. DOI: 10.3354/esr00520.

Roman J. 2006. Diluting the founder effect: cryptic invasions expand a marine invader's range. *Proceedings of the Royal Society B: Biological Sciences* 273:2453–2459. DOI: 10.1098/rspb.2006.3597.

Ropes JW. 1968. The feeding habits of the green crab, *Carcinus maenas* (L.). *Fishery Bulletin* 67:183–203.

Rossong MA., Quijón PA., Snelgrove PVR., Barrett TJ., McKenzie CH., Locke A. 2012. Regional differences in foraging behaviour of invasive green crab (*Carcinus maenas*) populations in Atlantic Canada. *Biological Invasions* 14:659–669. DOI: 10.1007/s10530-011-0107-7.

Say T. 1817. An account of the crustacea of the United States. *Journal of the Academy of Natural Sciences of Philadelphia* 1:57–63.

Shelton RGJ., Mackie AM. 1971. Studies on the chemical preferences of the shore crab, *Carcinus maenas* (L.). *Journal of Experimental Marine Biology and Ecology* 7:41–49. DOI:

10.1016/0022-0981(71)90003-7.

Underwood MJ., Winger PD., Fernö A., Engås A. 2015. Behavior-dependent selectivity of yellowtail flounder (*Limanda ferruginea*) in the mouth of a commercial bottom trawl. *Fishery Bulletin* 113:430–441. DOI: 10.7755/FB.113.6.

Underwood M., Winger PD., Legge G. 2012. Development and evaluation of a new high definition self-contained underwater camera system to observe fish and fishing gears in situ. *The Journal of Ocean Technology* 7:59–70.

Walter JF., Hoenig JM., Gedamke T. 2007. Correcting for effective area fished in fishery-dependent depletion estimates of abundance and capture efficiency. *ICES Journal of Marine Science* 64:1760–1771. DOI: 10.1093/icesjms/fsm147.

Welch WR. 1968. Changes in abundance of green crab, *Carcinus maenas* (L.), in relation to recent temperature changes. *United States Fish and Wildlife Service Fishery Bulletin* 67:337–345.

Williams AB. 1984. *Shrimps, Lobsters, and Crabs of the Altantic Coast of the Eastern United States, Maine to Florida*. Washington, DC. DOI: 10.2307/1352125.

Wright I., Caputi N., Penn J. 2006. Depletion-based population estimates for western rock lobster (*Panulirus cygnus*) fishery in Western Australia. *New Zealand Journal of Marine and Freshwater Research* 40:107–122. DOI: 10.1080/00288330.2006.9517406.

Yamada S. 2001. *Global Invader: The European Green Crab*. Corvallis, Oregon: Oregon Sea Grant.

Yamada SB., Dumbauld BR., Kalin A., Hunt CE., Figlar-Barnes R., Randall A. 2005. Growth and persistence of a recent invader *Carcinus maenas* in estuaries of the northeastern Pacific. *Biological Invasions* 7:309–321. DOI: 10.1007/s10530-004-0877-2.

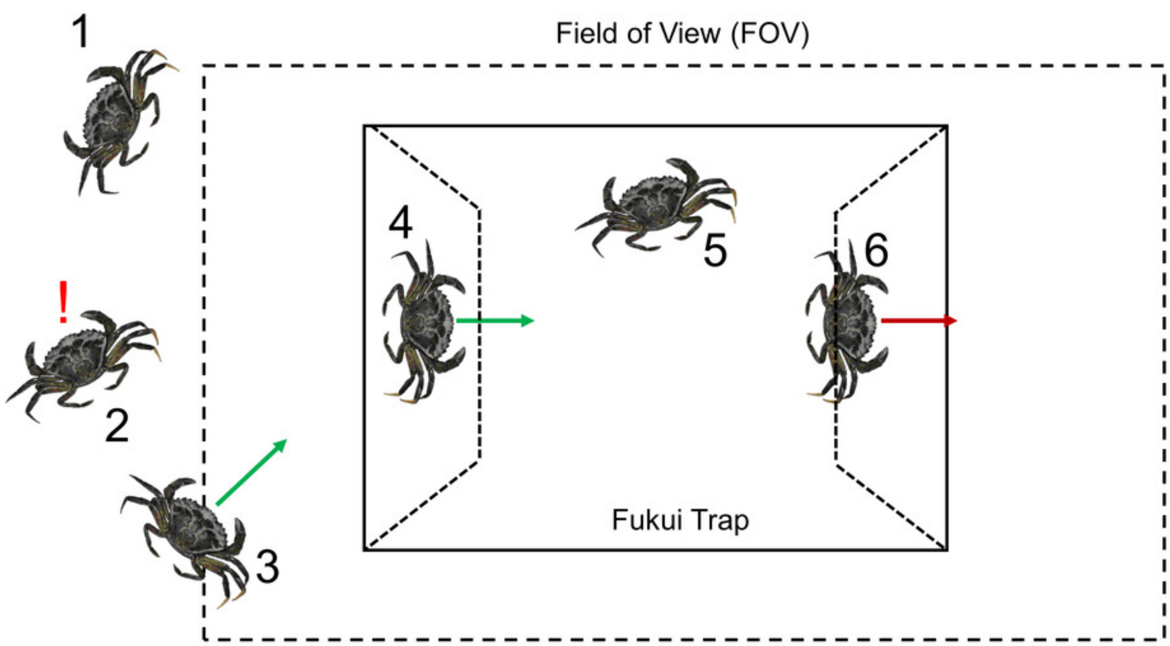
Yamada S., Gillespie GGE., Behrens Yamada S., Gillespie GGE. 2008. Will the European green crab (*Carcinus maenas*) persist in the Pacific Northwest? *ICES Journal of Marine Science* 65:725–729. DOI: 10.1093/icesjms/fsm191.

Yamada SB., Kosro PM. 2010. Linking ocean conditions to year class strength of the invasive European green crab, *Carcinus maenas*. *Biological Invasions* 12:1791–1804. DOI: 10.1007/s10530-009-9589-y.

# Figure 1

A visual representation of the six steps required for a green crab to become captured in a Fukui trap.

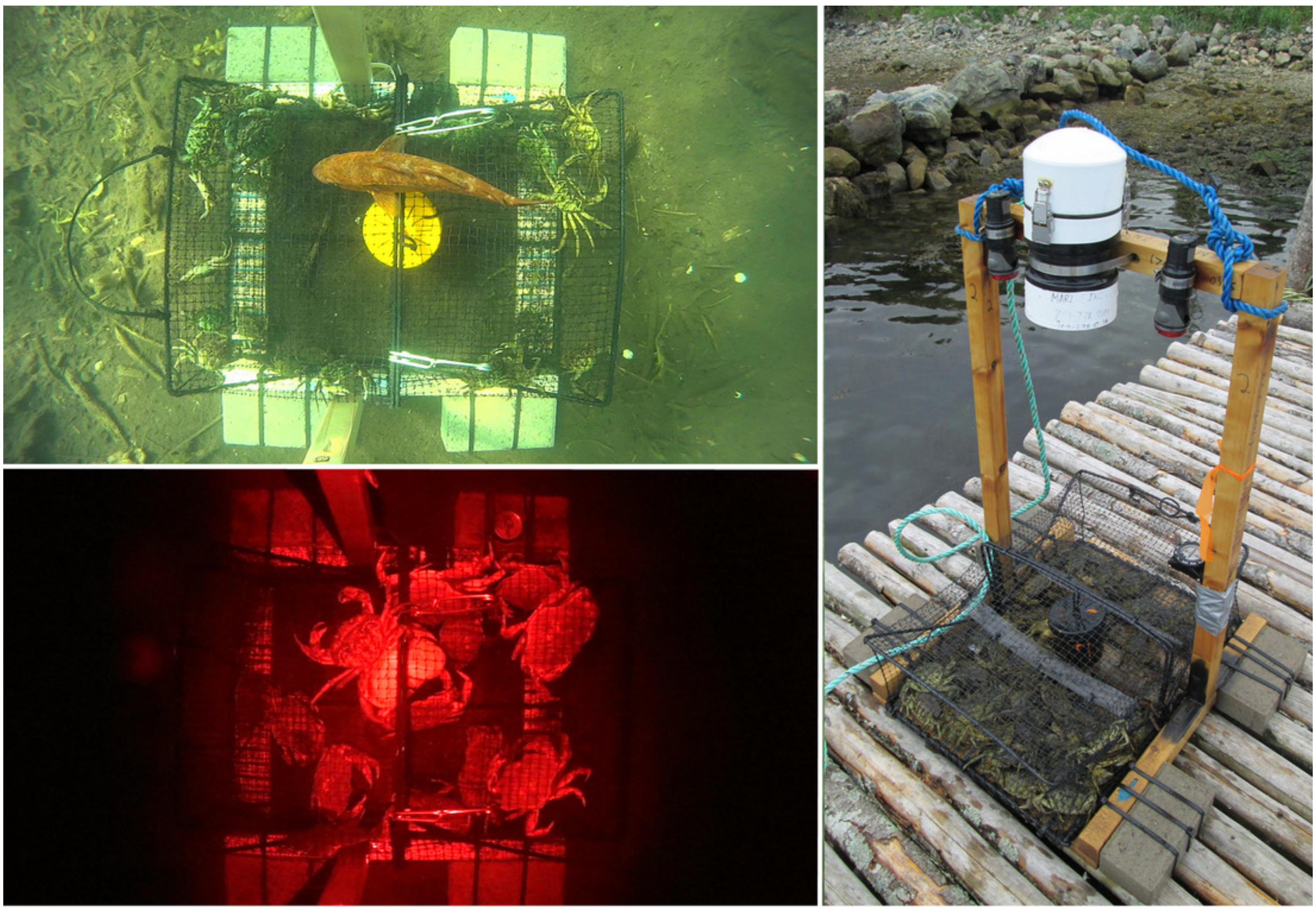
The numbers indicate the step in the capture process: 1) Presence, 2) Detection, 3) Approach, 4) Attempt, 5) Capture, 6) Exit



# Figure 2

The camera frame constructed around a Fukui trap and its field of view.

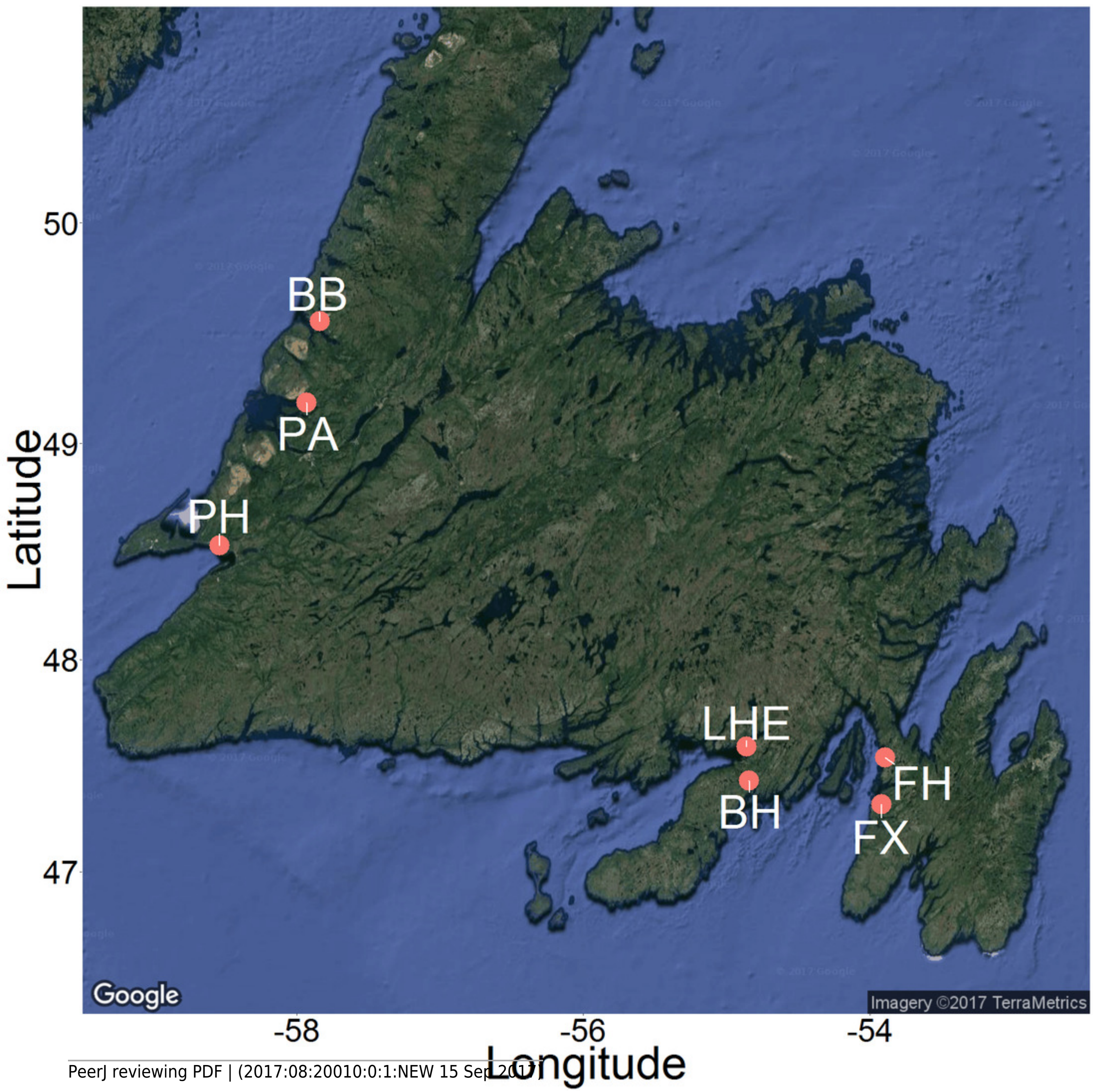
A top-down view of the Fukui trap recorded during a daytime deployment (top left) and night time deployment (bottom left). The entire camera apparatus mounted to a Fukui trap (right).



# Figure 3

Map of our 2015 and 2016 study sites across Newfoundland.

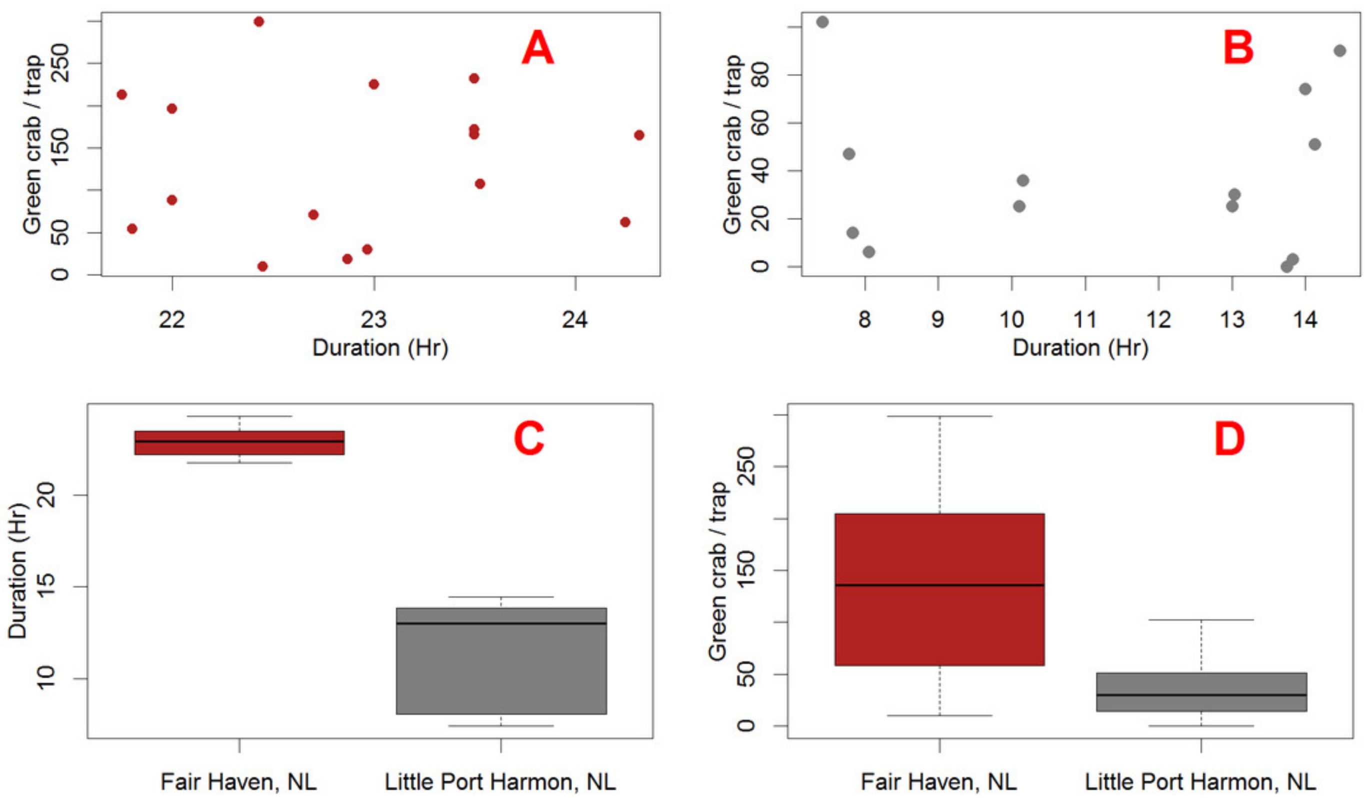
Sites included Bonne Bay (BB), Boat Harbour (BH), Fair Haven (FH), Little Harbour East (LHE), Penguin Arm (PA), Little Port Harmon (PH), and Fox Harbour (FX). Map imagery © 2017 TerraMetrics.



# Figure 4

Various plots comparing green crab catch and fishing duration between Fair Haven, NL and Little Port Harmon, NL.

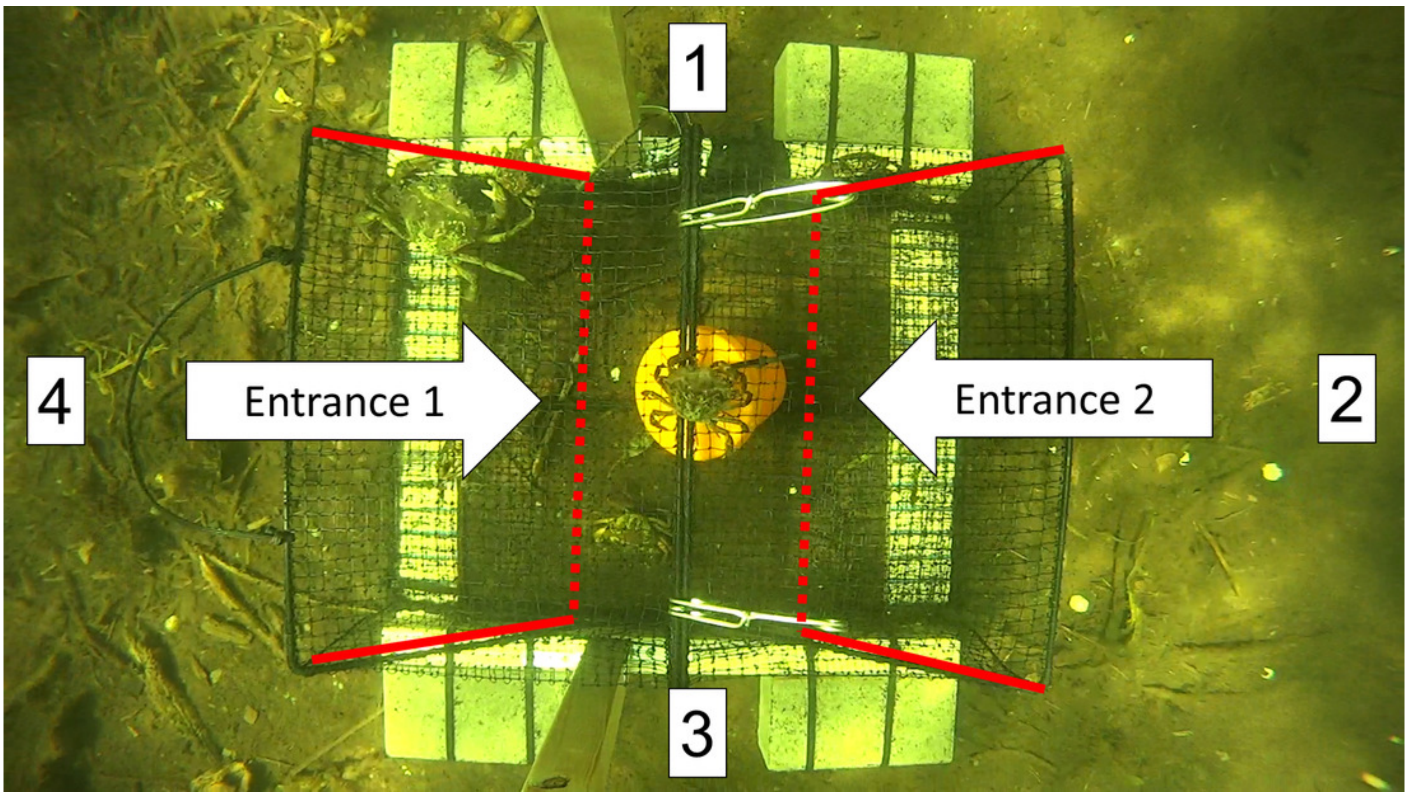
Scatterplot A and B show the duration and number of green crab captured for each deployment at Fair Haven (A) (n = 16) and Little Port Harmon (B) (n = 13), respectively. Boxplot C shows the mean deployment duration at Fair Haven and Little Port Harmon. Boxplot D shows the mean green crab catch per Fukui trap Fair Haven and Little Port Harmon.



# Figure 5

A screen shot from a video recording showing the top-down view of a Fukui trap as it actively fishes *in situ*.

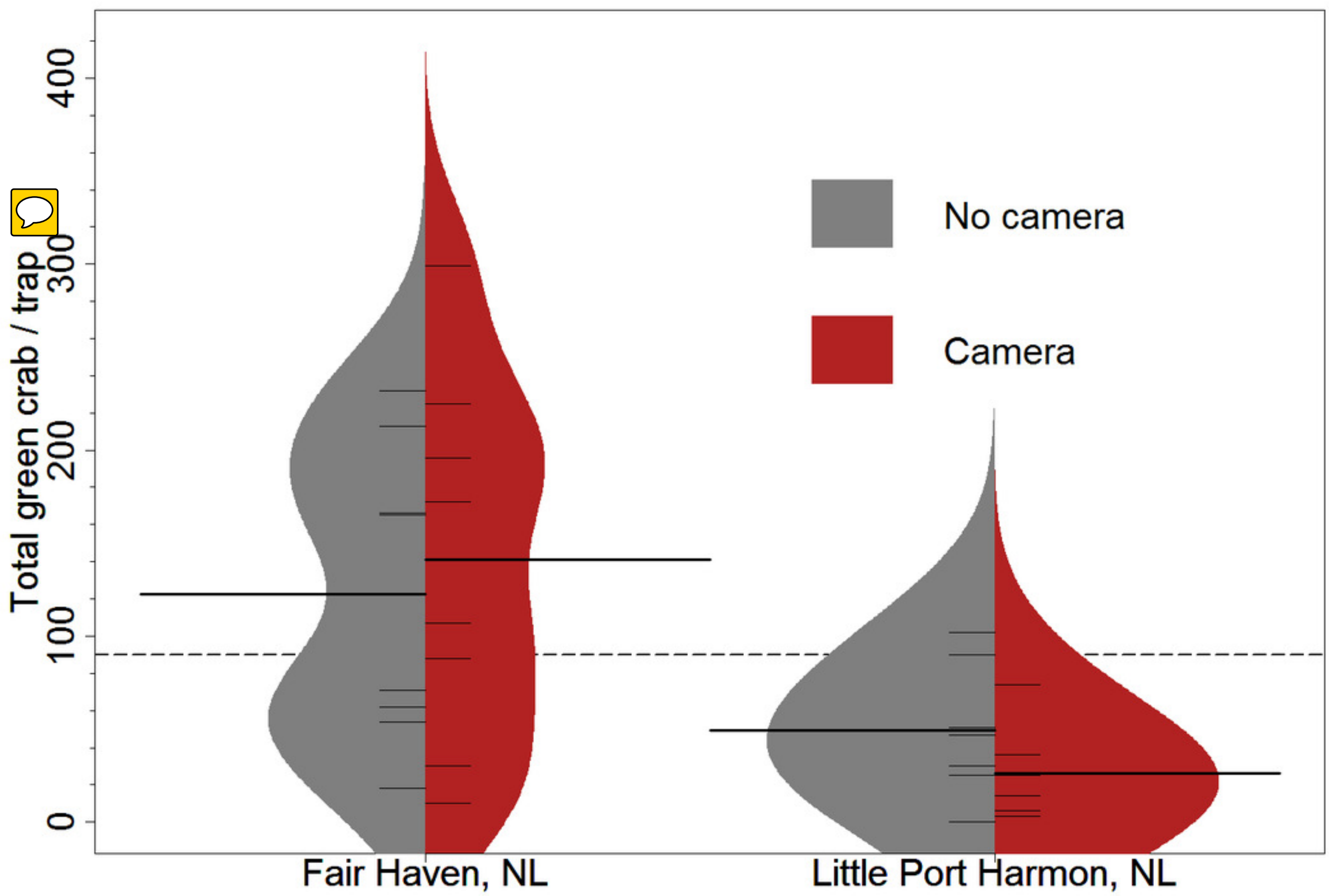
Approaches were recorded every time an animal entered the FOV from direction 1, 2, 3, or 4. The entrance tunnels are outlined with red lines. The dotted red line indicates the entry slit into the trap.



# Figure 6

Beanplot comparing total catch per trap between camera and non-camera traps at both the Fair Haven and Little Port Harmon study sites.

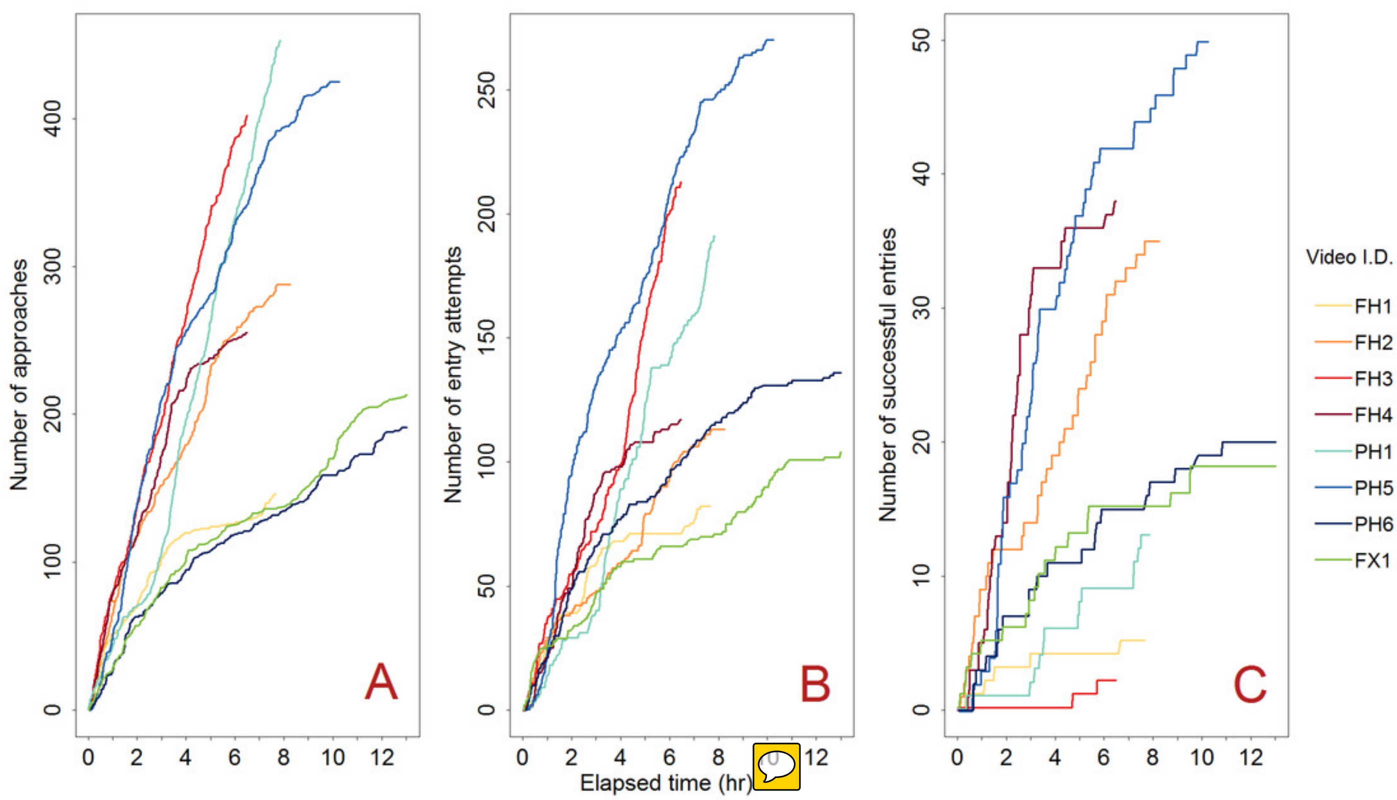
The dotted line indicates the mean catch across all pots (mean ± S.E. = 90.03 ± 15.37), while the long, solid black lines indicate mean catch in each trap type for both Fair Haven and Little Port Harmon. The short, thin black lines each represent a single pot deployment.



# Figure 7

Green crab accumulation over the course of each trap deployment (N = 8).

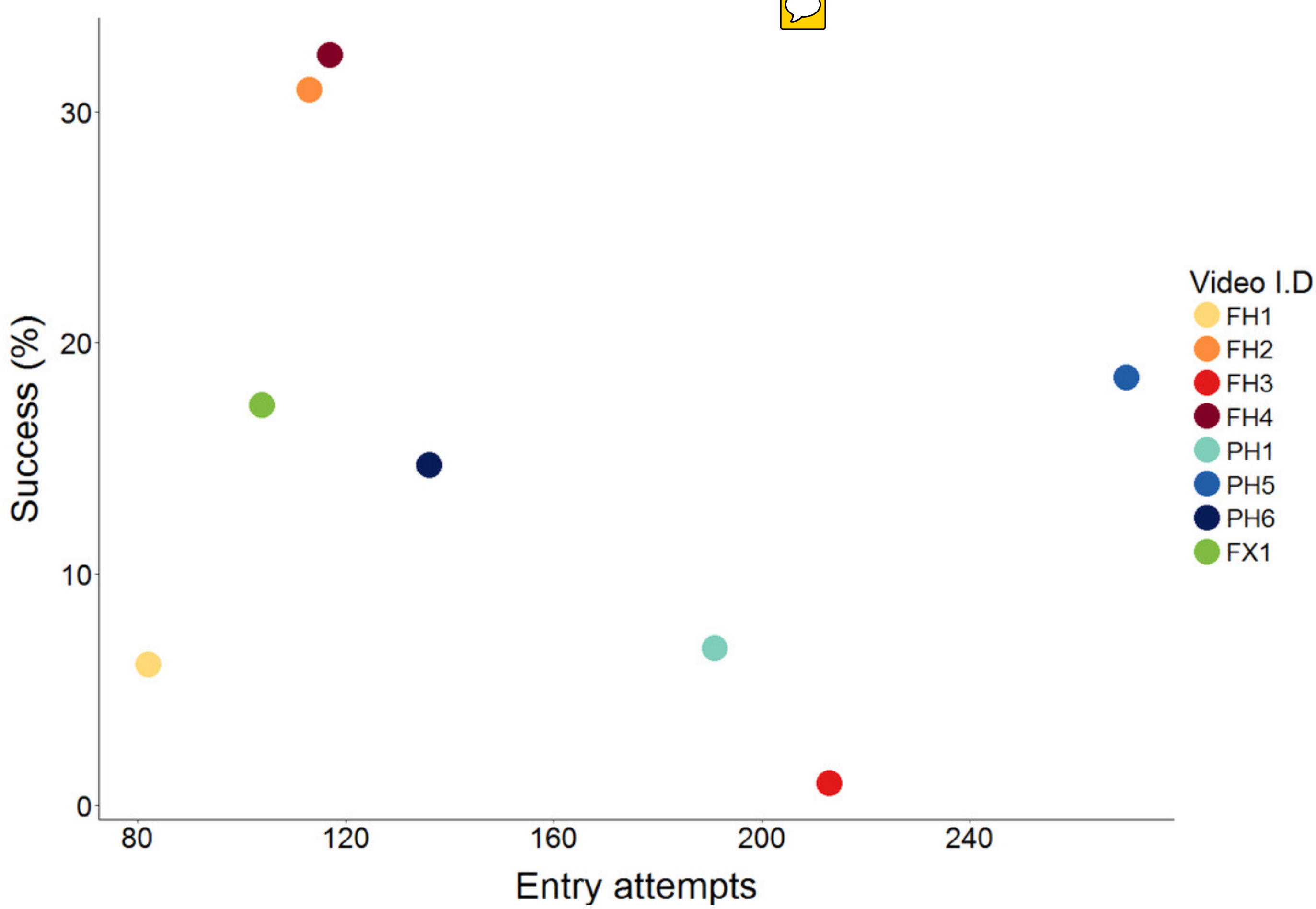
Green crab approaches ~~are shown in panel A~~ (A), green crab attempts ~~in panel B~~ (B), and accumulation of green crab in the Fukui trap ~~is shown in panel C~~ (C). We did not observe any exits, therefore panel C represents both the number of successful entries and the number of green crab in the trap. Each coloured line (Video I.D.) represents the individual deployment of a camera-equipped Fukui trap at either Fair Haven (FH), Little Port Harmon (PH), or Fox Harbour (FX). The red-orange colour scheme corresponds to deployments in Fair Haven, the blue colour scheme corresponds to deployments in Little Port Harmon, and the green colour scheme corresponds to a single deployment in Fox Harbour.



# Figure 8

The number of green crab entry attempts vs. the percentage of those attempts which resulted in a successful entry.

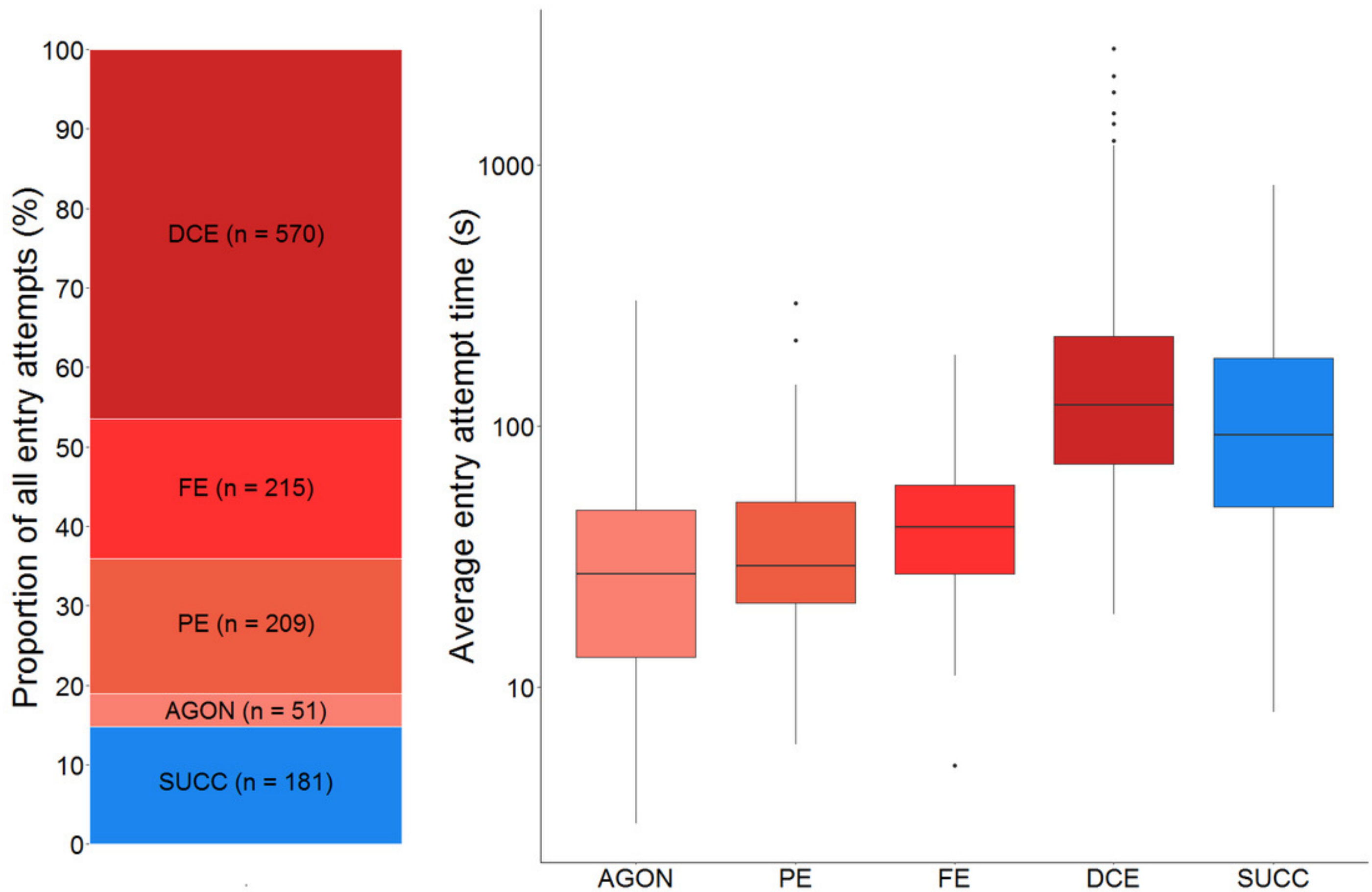
Each coloured dot (Video I.D.) represents the individual deployment of a camera-equipped Fukui trap at either Fair Haven (FH), Little Port Harmon (PH), or Fox Harbour (FX). The red-orange colour scheme corresponds to deployments in Fair Haven, the blue colour scheme corresponds to deployments in Little Port Harmon, and the green colour scheme corresponds to a single deployment in Fox Harbour.



# Figure 9

The proportional outcome and average time taken for all green crab entry attempts into the Fukui trap.

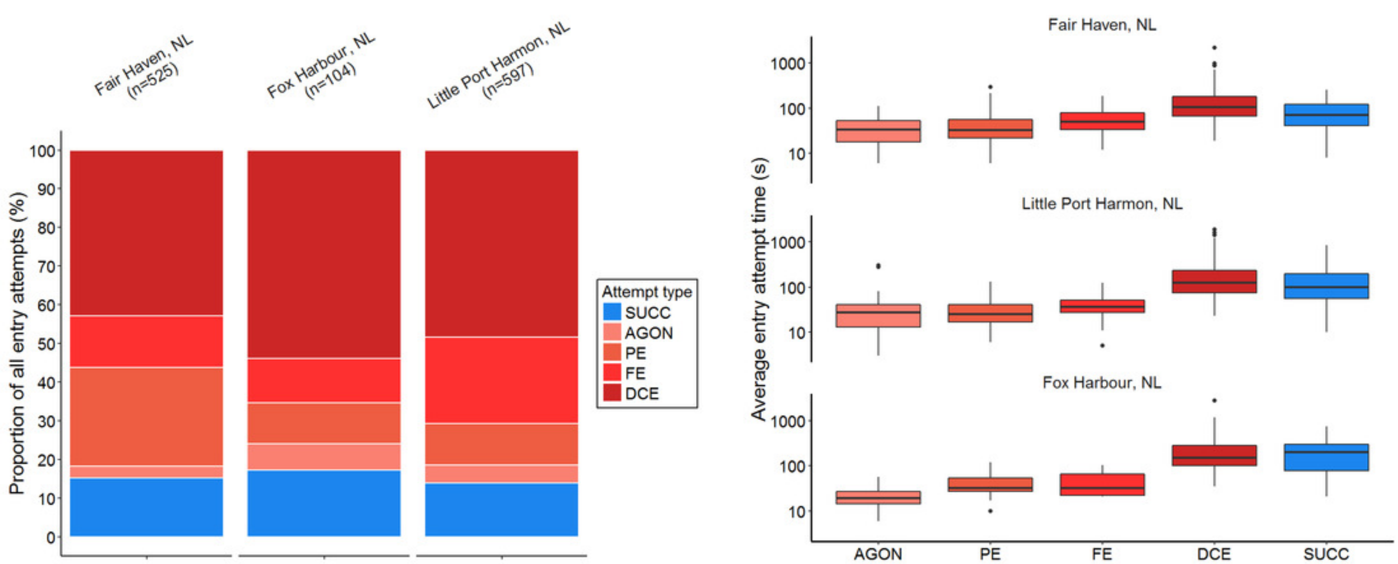
Left – The proportion of all green crab entry attempts that were successful (blue) and the proportion of all entry attempts that were failures (red colour scheme). The failed proportion is further broken down according to the four most common reasons for failure: agonistic behaviour (AGON), partial entry (PE), full entry (FE), and difficulty completing entry (DCE). The total number of entry attempts for each is given (n =). Right – A boxplot illustrating the average time (seconds, log scale used) for each type of entry attempt.



# Figure 10

A comparison of the outcome and average time of entry attempts at different study sites across NL.

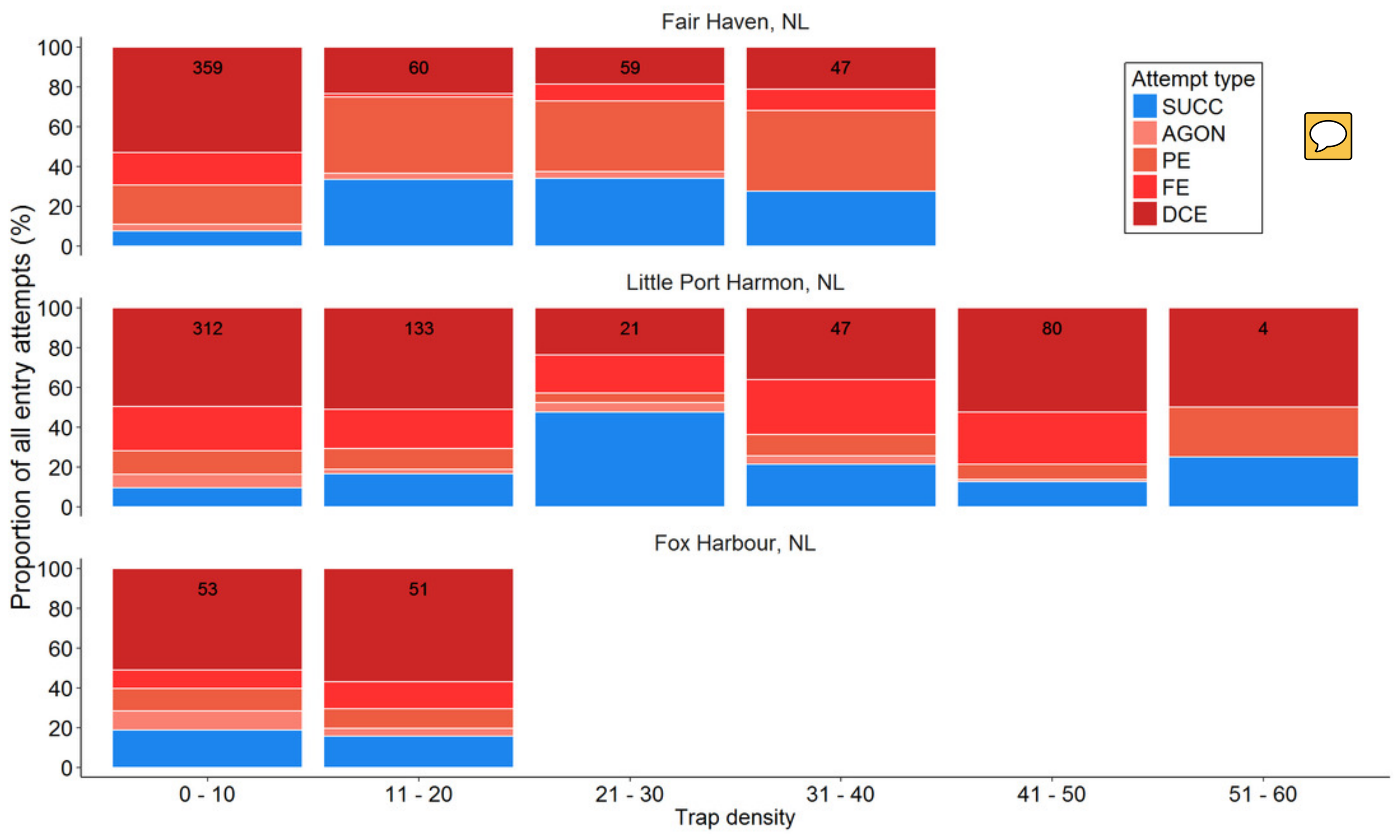
Left – The proportion of all green crab entry attempts that were successful (blue) and the proportion of all entry attempts that were failures (red colour scheme) at Fair Haven (n = 525), Little Port Harmon (n = 597) and Fox Harbour (n = 104). The proportion of failed entry attempts is broken down according to the four most common reasons for failure: agonistic behaviour (AGON), partial entry (PE), full entry (FE), and difficulty completing entry (DCE). Right – A boxplot illustrating the average time (seconds, log scale used) for each type of entry attempt at Fair Haven, Little Port Harmon, and Fox Harbour.



# Figure 11

The proportional outcome of all green crab entry attempts binned according to the density of green crab inside the Fukui trap.

The proportion of all green crab entry attempts that were successful (blue) and the proportion of all entry attempts that were failures (red colour scheme), binned according to the density of green crab inside the Fukui trap. The proportion of failed entry attempts is broken down according to the four most common reasons for failure: agonistic behaviour (AGON), partial entry (PE), full entry (FE), and difficulty completing entry (DCE). The number on each bar represents the total number of entry attempts observed across all videos for each density bin.



## Table 1(on next page)

Summary of green crab caught at each study site in 2015.

| Location | Deployments (n) | Mean catch | Standard error | Minimum catch | Maximum catch | Total catch |
|---|---|---|---|---|---|---|
| Fair Haven | 16 | 131.8 | 22.0 | 10 | 299 | 2108 |
| Little Port Harmon | 13 | 38.7 | 9.1 | 0 | 102 | 503 |
| Little Harbour East | 4 | 0.5 | 0.5 | 0 | 2 | 2 |
| Penguin Arm | 4 | 0 | 0 | 0 | 0 | 0 |
| Bonne Bay | 20 | 0.3 | 0.1 | 0 | 2 | 5 |
| Boat Harbour | 22 | 8.6 | 7.4 | 0 | 164 | 188 |
| All Sites | 79 | 35.5 | 7.6 | 0 | 299 | 2806 |

## Table 2(on next page)

Summary of all bycatch species caught at each study site in 2015.

| | Fair Haven | Little Port Harmon | Boat Harbour | Little Harbour East | Bonne Bay | Penguin Arm | All Sites |
|---|---|---|---|---|---|---|---|
| Rock crab (*Cancer irroratus*) | 0 | 2 | 116 | 0 | 84 | 4 | 206 |
| Cunner (*Tautogolabrus adspersus*) | 0 | 0 | 8 | 0 | 39 | 7 | 54 |
| Winter flounder (*Pseudopleuronectes americanus*) | 1 | 2 | 3 | 0 | 1 | 2 | 9 |
| Sculpin spp. (*Myoxocephalus spp.*) | 0 | 0 | 0 | 0 | 2 | 2 | 4 |
| American eel (*Anguilla rostrata*) | 0 | 1 | 0 | 0 | 0 | 1 | 2 |

## Table 3(on next page)

Summary of data from each video that was analyzed.

Video code represents the individual deployment of a camera-equipped Fukui trap at either Fair Haven (FH), Little Port Harmon (PH), or Fox Harbour (FX).

| Video code | Date (MM-DD-YY) | Video duration (hr) | # green crab approaches | # green crab attempts | # successful entries by green crab | # exits by green crab | Green crab success rate (%) | # approaches by other species | # entry attempts by other species | # successful entries by other species |
|---|---|---|---|---|---|---|---|---|---|---|
| FH1 | 06/09/15 | 7.7 | 146 | 82 | 5 | 0 | 6.1 | 46 | 15 | 1 |
| FH2 | 06/09/15 | 8.3 | 288 | 113 | 35 | 0 | 31.0 | 57 | 0 | 0 |
| FH3 | 06/10/15 | 6.5 | 402 | 213 | 2 | 0 | 0.9 | 83 | 6 | 0 |
| FH4 | 06/10/15 | 6.5 | 255 | 117 | 38 | 0 | 32.5 | 48 | 5 | 1 |
| PH1 | 07/07/15 | 7.9 | 453 | 191 | 13 | 0 | 6.8 | 16 | 0 | 0 |
| PH5 | 07/09/15 | 10.3 | 425 | 270 | 50 | 0 | 18.5 | 16 | 1 | 1 |
| PH6 | 07/09/15 | 13.0 | 191 | 136 | 20 | 0 | 14.7 | 81 | 2 | 0 |
| FX1 | 06/30/16 | 13.0 | 213 | 104 | 18 | 0 | 17.3 | 4 | 1 | 0 |