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**Research Article**

# Evaluating trapping as a method to control the European green crab, *Carcinus maenas*, population at Pipestem Inlet, British Columbia

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**Editor's note:**

This study was first presented at the 9th International Conference on Marine Bioinvasions held in Sydney, Australia, January 19–21, 2016 (http://www.marinebioinvasions.info/previous-conferences). Since their inception in 1999, ICMB series have provided a venue for the exchange of information on various aspects of biological invasions in marine ecosystems, including ecological research, education, management and policies tackling marine bioinvasions.

## Abstract

The invasive European green crab, *Carcinus maenas*, has been present on the west coast of Vancouver Island since at least 1998. Annual trapping was conducted between 2010 and 2014 at Pipestem Inlet, British Columbia, Canada to determine if depletion is a potential mechanism to eradicate or control established populations. Catch per unit effort (CPUE) decreased over time within years suggesting depletion was reducing population abundance but this trend was not apparent between years suggesting control measures may be of limited utility over the longer term. For example, there was an increase in population size between 2010 and 2012 despite annual depletion efforts, likely due to good recruitment. Although the effects of depletion efforts on population size are less apparent, these events have significantly altered the demographics of the population at Pipestem Inlet, including decreased carapace width. Also, catch rates generally showed a bias towards female crabs among years. These demographic changes could have implications for the continuing green crab invasion on the west coast of North America, especially northward spread.

**Key words:** depletion trapping, invasive species, AIS control, catch per unit effort, population demographics, carapace width (CW), West Coast Vancouver Island

## Introduction

The European green crab, *Carcinus maenas*, is native to the Atlantic coast of Europe but this species has invaded both the Atlantic and Pacific coasts of North America, Australia, South Africa, Japan and most recently South America (Crothers 1967; Carlton and Cohen 2003; Hidalgo et al. 2005). On the west coast of North America, its primary introduction was to San Francisco Bay, California in 1989 (Cohen et al. 1995, Grosholz and Ruiz 1995). It subsequently spread north to Bodega Harbour in 1993 and then to estuaries of northern California, Oregon, Washington, and the west coast of Vancouver Island, British Columbia, in part due to the strong 1997–98 El Niño event that promoted northward larval dispersal (Behrens Yamada et al. 2005; Gillespie et al. 2007; Behrens Yamada and Kosro 2010). By 2011 green crab had been observed in the Central Coast of British Columbia but had not been detected in Haida Gwaii or the Prince Rupert area (Gillespie et al. 2015). There are several traits associated with European green crab that make it such a prolific global invader including high fecundity, high dispersal capability, robust feeding behaviour, broad preferred habitat and environmental tolerances, and behavioural and phenotypic plasticity (Roman and Palumbi 2004; Klassen and Locke 2007; Lockwood et al. 2007;

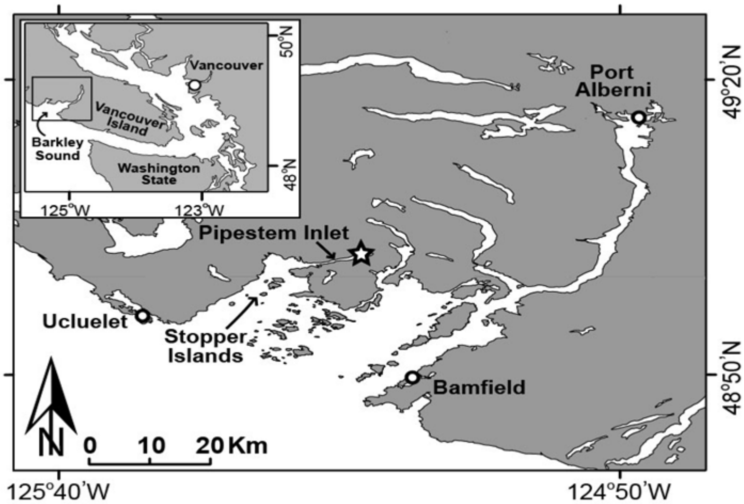


**Figure 1.** Pipestem Inlet, a 10 km long fjord-type estuary in northwestern Barkley Sound on the southwest coast of Vancouver Island, British Columbia, Canada.

Tepolt et al. 2009; Hänfling et al. 2011). Adult green crab can survive in salinities ranging from 4–54‰ (Crothers 1967; Beukema 1991) while larvae do not survive below 20‰ (Anger et al. 1998). Similarly, the thermal tolerance of adults is also wide ranging from 0–30 °C but narrower for larvae ranging from 6–25 °C (Dawirs et al. 1986; Harms et al. 1994). This led Behrens Yamada et al. (2015) to suggest an optimal bound between 10–18 °C. Further, as a predator or competitor green crab invasions often result in negative ecosystem consequences. For example, green crabs are well known predators of molluscs, both bivalves and gastropods, and they have been shown to have caused significant population declines in these species (Grosholz et al. 2000; Grosholz and Ruiz 1995, 1996). Further, this species has been implicated in the loss/destruction of eelgrass beds (Davis et al. 1998) and the foraging behaviour of this species has been implicated in changes to invertebrate community structure (Lutz-Collins et al. 2016). In British Columbia this could translate to negative impacts on commercially important species including Littleneck clams (*Leukoma staminea*), Manila clams (*Venerupis philippinarum*), Varnish clams (*Nuttallia obscurata*) and Pacific oyster (*Crassostrea gigas*), especially smaller sized individuals that would be seeded by industry (Jamieson et al. 1998; Curtis et al. 2012). Thus, control options that limit these negative impacts are desirable for managers and stakeholders and industries that could be affected.

With the establishment of green crab in British Columbia, including higher density populations such as those in Pipestem Inlet (Gillespie et al. 2007), it has become important to understand what control options are available to reduce localized impacts and prevent further spread. Many control options have been considered, including, sound pulses, air exposure, chemical control, biological control by guarding bivalve seeds with toadfish, genetic manipulations, local physical barriers such as nets, fences and rafts, commercial harvesting, and parasitic castrators (Klassen and Locke 2007), but to our knowledge none have been employed successfully and many could have detrimental effects on native species. Trapping is desirable as the traps can be set in potential green crab habitat, especially the intertidal zone, thereby limiting bycatch of native crab species (which could be released live even if caught) and it has little impact on the native ecosystem in contrast to the potential environmental impacts that could arise with chemical or biological control options. However, trapping success will be influenced by catchability, which can be influenced by a number of factors (Crothers 1968; Miller 1990). Thus, the aim of this study was to evaluate trapping as a method to control a population of green crab at Pipestem Inlet. If successful, depletion efforts for green crab could have localized benefits for impacted species, including cultivated shellfish species, but also serve to prevent the Pipestem Inlet population from acting as a source population either maintaining already invaded locations or supplying new locations.

## Materials and methods

### *Study site and sampling*

This study was conducted at the head of Pipestem Inlet in Barkley Sound, on the west coast of Vancouver Island, British Columbia, Canada between 2010 and

2014 (Figure 1). Although it averages about 300 meters in width, it ranges from >2 km at the mouth to about 100 meters near the head where trapping was conducted. Pipestem Inlet had the highest green crab abundance on the west coast of Vancouver Island at the start of the study (Gillespie et al. 2007; DFO unpublished data) making it an ideal location for an experimental depletion effort. Further, other trapping surveys (DFO unpublished data) suggested the adult crabs found at the head of the inlet were geographically isolated from nearby populations thereby negating immigration or emigration over short time periods such that depletion efforts should reflect actual changes within the population (hence viability of trapping as a potential control measure).

Primary depletion trapping surveys were conducted from September 8–19, 2010 (12 trapping days); September 8–15, 2011 (8 trapping days); August 17–23, 2012 (8 trapping days); August 15–27, 2013 (11 trapping days); and September 27–October 9, 2014 (13 trapping days). Previous trapping surveys in Pipestem Inlet had confirmed both sexes of green crab were equally available to the sampling gear during this time (see DiBacco and Therriault 2015). Also, shallow subtidal bottom water temperatures during this time are relatively constant (average 14.34 °C during 2010 survey and average 13.57 °C during 2011 survey) suggesting catchability should be similar among years during this period. Secondary follow-up trapping surveys were conducted from November 12–15, 2013 (3 trapping days) and April 8–10, 2014 (3 trapping days) to determine if there was immigration of new individuals to the area or recruitment to the adult (catchable) population after the primary depletion survey in 2013. However, due to lower water temperatures (approximately 5 °C based on logger data from 2010–11) and behavioural differences among sexes (females less vulnerable to gear during the winter), the April trapping data might not be as comparable to other survey dates but is included here for reference. Traps were deployed daily following established protocols in the intertidal zone where green crab in British Columbia are expected following Gillespie et al. (2007). Briefly, each string consisted of six Fukui folding traps (Fukui FT-100; dimensions, 60 cm × 45 cm × 20 cm with 12 mm mesh, with two entrances [two inward facing 45° mesh panels] extending the width of the traps at opposite ends) set at 10-meter spacing on 60-meter lead-weighted ground lines anchored on one end to minimize drifting. Twelve strings with six traps each were set daily and remained in the water for a total soak time of 18–24 hours. All traps were set with new frozen herring bait enclosed in standard commercial plastic bait jars (so bait never consumed) drilled with small holes to allow an odour plume to escape, which were then suspended inside from the upper surface of the trap. GPS coordinates and water depth for each string were recorded along with soak time.

Biological sample processing for the first 100 crabs caught per string, to the nearest full trap, included: crab species, sex, and carapace width (CW) (measured point-to-point for green crab and notch-to-notch for all other crab species). For the remainder of the crabs caught (predominately green crab), only sex and species were recorded. All native species caught (only a few individuals of *Cancer gracilis*) were released after sampling and green crabs were removed from the study site.

### *Data analysis*

Catch per unit effort (CPUE) was determined by dividing the total catch each day by the number of traps set. Any traps that malfunctioned or were damaged were excluded from the CPUE calculation. Using R statistical software (R Development Core Team 2012), an analysis of covariance (ANCOVA) was used to determine if CPUE changed over time, both within a sampling event or over the entire duration of the depletion program. The 2011 data were excluded from the analysis as it violated statistical assumptions (see below). In addition, regression was used to determine how CPUE changed within annual depletion surveys.

A two-sample t-test was used to determine if CPUE differed significantly from the last trapping day in an annual survey to the first trapping day in the subsequent secondary survey as a proxy for potential immigration of crabs into the study site during the months immediately following an intensive trapping event. Specifically August to November 2013 and November 2013 to April 2014 recognizing cooler water temperatures and green crab reproductive cycles could affect catchability in April differently from the summer/fall period.

Separate ANCOVAs for male and female green crab were used to determine if average CW changed either during a sampling event or among years. In addition, regression was used to determine how CW changed within annual depletion surveys for both males and females separately owing to known size differences between sexes. Also, the ratio of males to females was determined as an indicator of potential demographic change within the population both within a trapping year and over the entire duration of the sampling program.

To evaluate if trapping is an effective control method we estimated green crab population size over

**Table 1.** Analysis of Covariance of the Effects of Trapping Day and Survey (Trapping Year) on European Green Crab Catch Per Unit Effort (CPUE – crabs per trap per day).

| Variable | df | MS | F | p-value |
|---|---|---|---|---|
| Trapping Day | 1 | 3485.6 | 39.26 | <0.0001 |
| Year | 3 | 1131.7 | 12.75 | <0.0001 |
| Trapping Day * Year | 3 | 311.0 | 3.50 | <0.05 |

time using the trapping data from Pipestem Inlet. To estimate total population size for each year we standardized for the highest number of traps set (72) and applied Zippin's (1958) multinomial removal method of estimating populations. Zippin (1958) makes three assumptions that must be met in order to estimate a population: 1) the population remains stationary throughout the trapping period; 2) the probability of capture is equal for all individuals; and 3) the probability of capture remains constant from one trapping day to the next. This method was applied to all years except 2011 when the assumption that trapping conditions remain the same from day to day was violated. This was due to changes in bait freshness (hence effectiveness) part way through the survey, and the variable availability of other (competing) food in the survey area, as a result of dead pilchards in the water. Also, the estimated proportion of the population removed during each trapping event was resolved based on the methods in Zippin (1958). Once determined, the estimated total population at the start of each sampling event was calculated by dividing the total catch (standardized for effort) by the estimated proportion of the population that was captured. After the estimated population size at the start of each sampling event was calculated, the estimated population at the end of each sampling event was calculated by subtracting the total number of crabs captured in the sampling event from the initial estimated population. This was calculated in order to determine how much the population was recovering from depletion efforts.

## Results

CPUE was significantly different both among survey years and over the duration of depletion surveys (Table 1; Supplementary material Table S1). On the first survey day in 2010 CPUE was approximately 5 green crab per trap per day compared to 2013 and 2014 when it was approximately 60 green crab per trap per day (Table S1). Also, CPUE on the first day of trapping in 2010, 2013 and 2014 was highest and declined within each sampling event (Figure 2; regression, 2010: $F_{(1, 10)} = 0.09$, $p < 0.05$; 2013: $F_{(1,9)} = 19.60$, $p < 0.005$; 2014: $F_{(1,11)} = 11.37$, $p < 0.05$). However, in 2011, CPUE initially decreased, but then increased unexpectedly during the final three days of trapping and in 2012 the decrease in CPUE over the duration of the survey was not significant ($F_{(1, 6)} = 3.48$, $p = 0.111$), potentially due to the highest CPUE recorded on Day 3 of the survey (Figure 2; Table S1). Although the primary surveys were conducted annually from 2010 to 2014 during late summer, secondary surveys during the fall of 2013 and spring of 2014 provided an opportunity to compare CPUE over shorter time periods. Although temperature data was not available for all surveys, generally water temperatures in Pipestem Inlet are approximately 2 °C cooler in early November compared to September and approximately 5 °C cooler in April compared to September (DFO unpublished data from 2010–11). CPUE increased significantly from the final day of trapping in August 2013 to the first day of trapping in November 2013 (two sample, $t_{(71)} = 7.34$, $p < 0.001$) but was significantly lower than on the first day of trapping in August 2013 (two sample, $t_{(71)} = 5.05$, $p < 0.001$). CPUE decreased significantly from the final day of trapping in November 2013 to the first day of trapping in April 2014 (two sample, $t_{(75)} = 4.99$, $p < 0.001$) but this could be confounded by reduced water temperature and changes in catchability in April. CPUE from the final day of trapping in April 2014 to the first day of trapping in September 2014 rose significantly (two sample, $t_{(73)} = -16.66$, $p < 0.001$). CPUE data per day for both Pipestem Inlet and an adjacent sampling site in Barkley Sound, Hillier Island, are provided in Supplementary material Table S1 which includes green crab data from surveys in addition to the depletion ones.

CW was significantly different both among survey years and over the duration of depletion surveys for both males and females (Table 2). The difference in average CW between males and females decreased over time (Figure 3). In 2010, males were approximately 10 mm larger than females but in 2011 and 2012 males were only 1–3 mm larger than females. In 2013 and 2014, the size difference increased, but males were no more than 8 mm larger than females on average. Further, the number of large crabs caught

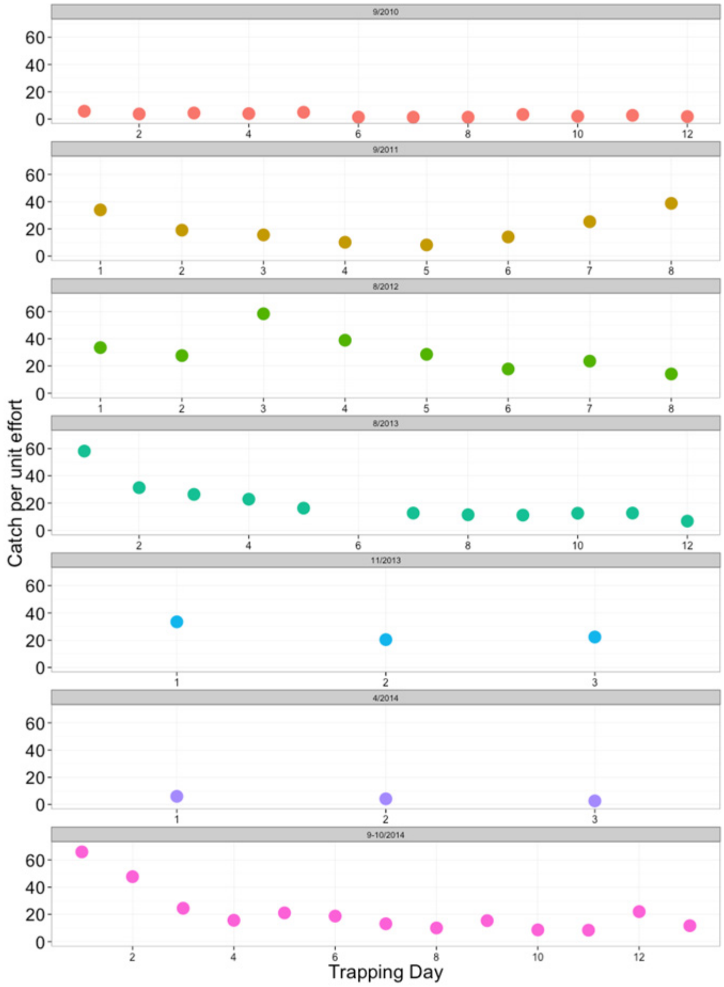


**Figure 2.** Changes in catch per unit effort (CPUE – crabs per trap per day) of European green crab over time for each depletion survey.

for both males and females has been declining since 2010 while the number of smaller crabs caught has been increasing (Figures 4 and 5). In addition, CW tended to decrease significantly within a single sampling event for both males and females (Table 3) except 2010 when female CW remained similar over the duration of the survey and 2011 when no difference was detected for males or females (Table 3). Although not directly comparable as a control site, trapping surveys at Hillier Island also showed crabs tended to be smaller after 2011 although larger individuals are encountered in each survey at both sites (males > 90 mm and females > 80 mm; Table S2). The male to female catch ratio was female biased on 40 of 55 trapping days between 2010 and 2014 (Figure 6).

Total population size at the beginning of the sampling event was calculated for 2010, 2012, 2013 and 2014. The total green crab population at Pipestem Inlet increased from fewer than four thousand individuals in 2010 to more than twenty thousand individuals in 2012, and had been decreasing annually since 2012, before increasing again in 2014 to its highest level (Table 4). Total population size for the end of each sampling event showed that while a large proportion of the population was removed each year (approximately 87 to 88% for primary surveys except 2010 which was about 69%), the population generally rebounded by the start of the next sampling event (Table 4).

## Discussion

Removal trapping in Pipestem Inlet was able to reduce the green crab population by nearly 90% over the course of a survey but the population almost fully recovered within a year. Given the larval dispersal stages of green crab and the persistent existence of populations in Pipestem Inlet, elsewhere on the west coast of Vancouver Island and further south

**Table 2.** Analysis of Covariance of the Effects of Trapping Day and Survey (Trapping Year) on Average Carapace Width (CW) of European Green Crab by Sex.

| Variable | Males | | | | Females | | | |
|---|---|---|---|---|---|---|---|---|
| | df | MS | F | p-value | df | MS | F | p-value |
| Trapping Day | 1 | 12.2 | 5.96 | <0.05 | 1 | 11.9 | 6.64 | <0.05 |
| Year | 4 | 1648.3 | 803.34 | <0.0001 | 4 | 861.5 | 482.86 | <0.0001 |
| Trapping Day * Year | 4 | 24.8 | 12.07 | <0.005 | 4 | 11.1 | 6.21 | <0.001 |

**Table 3.** Regression of Average Carapace Width (CW) of European Green Crab on Trapping Day by Survey (Year) and Sex.

| Year | Males | | | | Females | | | |
|---|---|---|---|---|---|---|---|---|
| | df | Adj $R^2$ | F | p-value | df | Adj $R^2$ | F | p-value |
| 2010 | 1,10 | 0.38 | 6.11 | <0.05 | 1,10 | 0.03 | 0.33 | 0.579 |
| 2011 | 1,6 | 0.13 | 0.92 | 0.375 | 1,6 | 0.02 | 0.10 | 0.763 |
| 2012 | 1,6 | 0.50 | 5.93 | 0.05 | 1,6 | 0.51 | 6.36 | <0.05 |
| 2013 | 1,9 | 0.83 | 54.87 | <0.0001 | 1,9 | 0.85 | 55.78 | <0.0001 |
| 2014 | 1,11 | 0.51 | 11.29 | <0.005 | 1,11 | 0.45 | 8.83 | <0.05 |

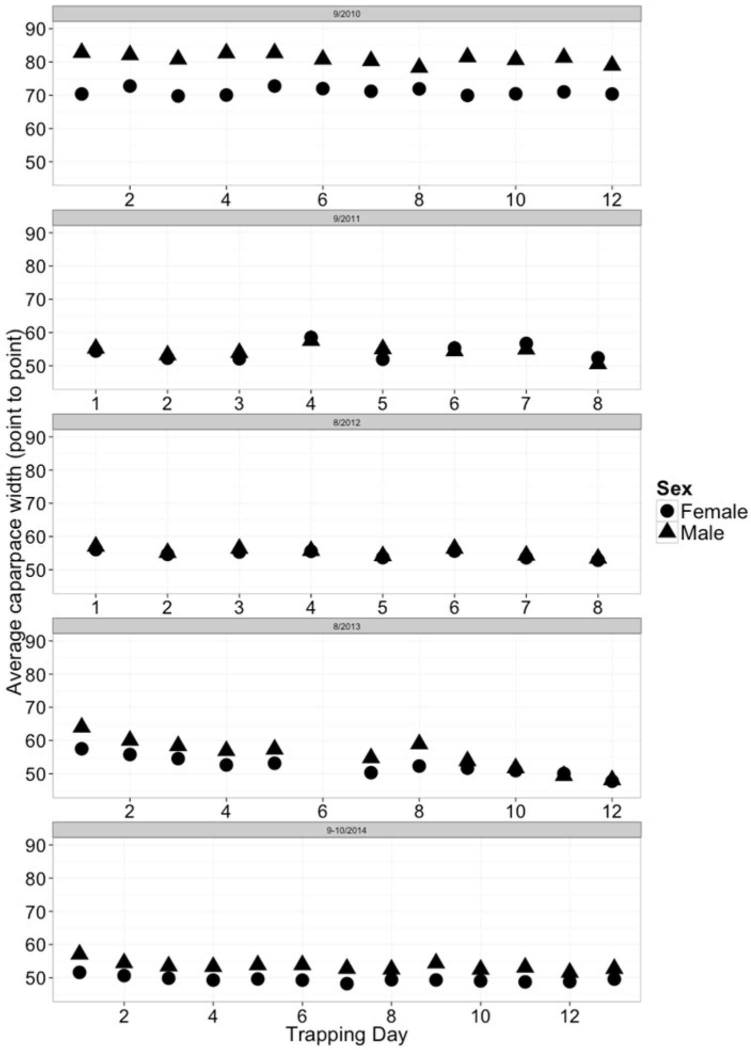


**Figure 3.** Change in average carapace width (CW) for male and female European green crabs by trapping day and survey.

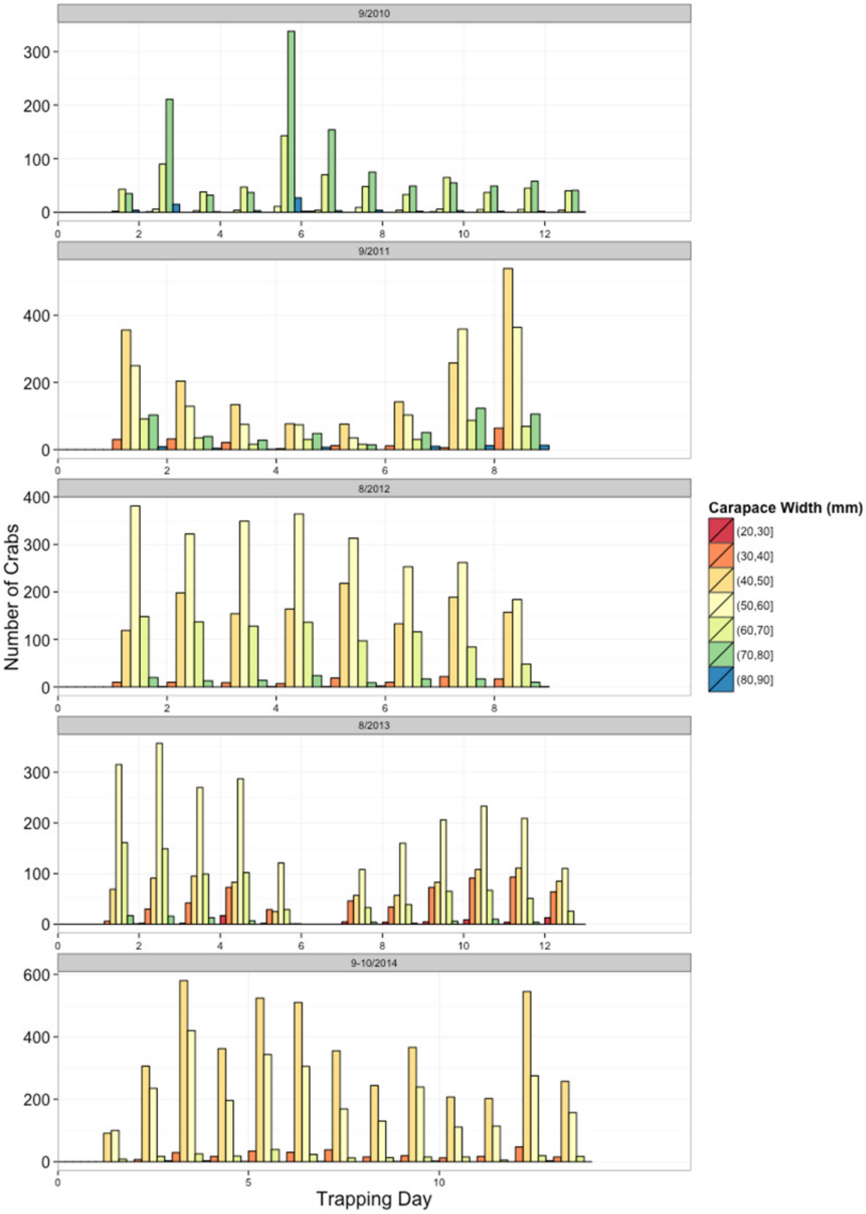


**Figure 4.** Female European green crab carapace width (CW) by trapping day and survey.

(Gillespie et al. 2007; Behrens Yamada and Kosro 2010; Gillespie et al. 2015) the annual trapping effort was too low to reduce or eradicate the current population. Trapping can be quite effective at reducing green crab abundances during a sampling event and short-term benefits might result at local scales, but annual trapping may have less utility in the longer term and may lead to green crab population increases via overcompensation as suggested, but not identified, by Turner et al. (2016).

Catchability can be influenced by a number of factors (e.g. molt and reproductive stages, sex, tidal, lunar and diurnal cycles, temperature, etc.) while catch itself is further affected by additional factors (e.g., gear, bait, saturation, etc.) (Miller 1990). We standardized this to the extent possible by using the same gear, bait and survey methodology for the primary surveys but recognize the secondary follow-up surveys were conducted during a different time period that could have affected both catch and catchability (see Table S1). Perhaps not surprisingly CPUE was lower for the April 2014 survey. This is likely attributable to cooler water temperatures during this spring period (less than 10°C in 2010 and 2011; DFO unpublished data) that corresponds to decreased green crab activity (hence also less vulnerable

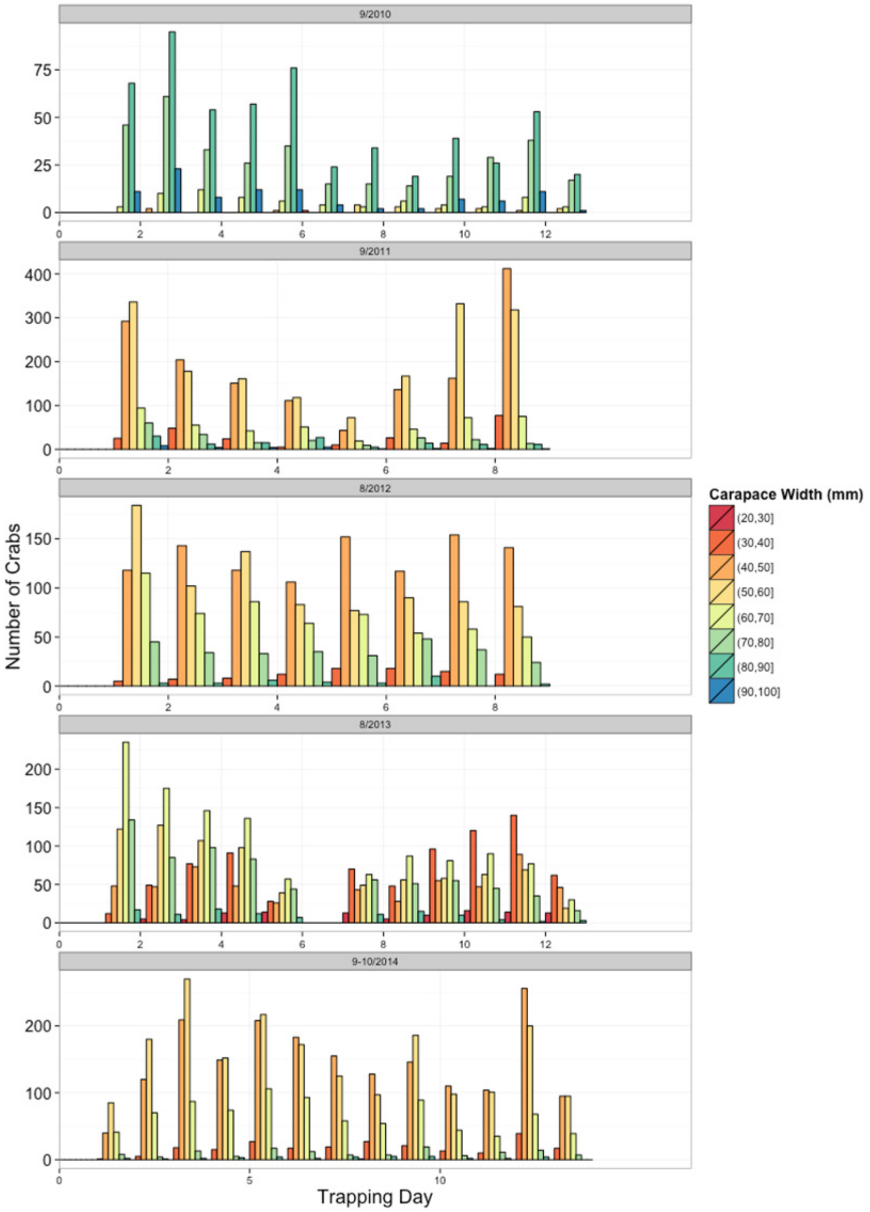


**Figure 5.** Male European green crab carapace width (CW) by trapping day and survey.

to trapping). In addition, DiBacco and Therriault (2015) showed that in 2007 in Pipestem Inlet males dominated the adult green crab catch in March–April suggesting differential catchability between sexes which could at least partially contribute to reduced overall CPUE. Similarly, Crothers (1968) showed that the entire population is not vulnerable to trapping at any given time (in fact only about 80%) which also can affect CPUE. However, CPUE was also lower during the first primary depletion survey in 2010 when water temperatures were warmer and during a time when DiBacco and Therriault (2015) showed approximately equal catches of male and female green crab in Pipestem Inlet in 2007. Although CPUE declined over the duration of this survey as expected (and observed in other years) it is possible that CPUE was lower overall due to fewer traps in the water per day compared to surveys conducted between 2012 and 2014 which could have reduced trapping efficiency and the percentage of the population vulnerable to the gear. Further, recruitment failure prior to 2010 may have contributed to a skewed population structure (see below) and the low population size observed which also may have contributed to the lower CPUE.

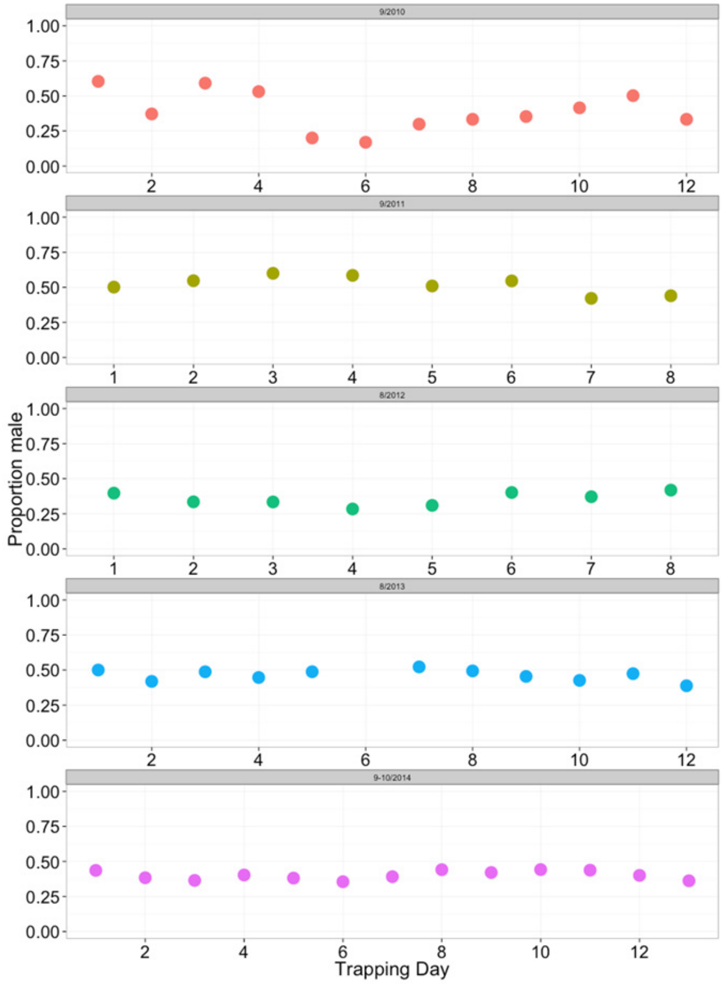


**Figure 6.** Changes in the ratio of male to female European green crab caught each trapping day by survey.

While it was unexpected to see the population increase, especially during a period of removal trapping, it is important to consider how the population demographics changed over that time period. On the first day of trapping in 2010, the average CW was > 80 mm for males and > 70 mm for females. Based on green crab population structure in Oregon and Washington (Behrens Yamada et al. 2005), the large green crabs removed from the Pipestem Inlet population in 2010 were at least three years old. While average CW decreased slightly over the next 11 days of trapping in 2010 it remained relatively stable (Figure 3). However, the average CW was significantly smaller on Day 1 in 2011 (~55 mm) for both males ($t = 27.04$, $df = 133.83$, $p < 0.0001$) and females ($t = 22.66$, $df = 46.72$, $p < 0.0001$) and has remained below 64 mm since 2011. Thus, the green crab population at Pipestem Inlet has less crabs older than three years, with the majority of the population being only one or two years old in subsequent years (Figures 4 and 5). In addition, in August 2013, crabs <30 mm were caught routinely for the first time at Pipestem Inlet since large scale trapping began in 2010 and in 2014 there were 279 crabs <40 mm caught, further confirming a shift to a younger population structure. However, since the Fukui traps do not sample juvenile crabs (<25 to 30 mm) well, the number of juvenile green crab in the system will remain unknown. In addition, it is unknown if juvenile abundance changed from year to year or if it was affected by trapping efforts. It is possible that this depletion effort was initiated when the green crab population in Pipestem Inlet was biased towards larger, older individuals, possibly owing to years of poor recruitment (hence few smaller crabs available/vulnerable to trapping during the 2010 survey) and we cannot exclude potential senescence contributing to a reduction in larger, older crabs in addition

**Table 4.** Estimation of Total Population Standardized for Number of Traps at the Beginning and End of Each Sampling Event from 2010 to 2014. $k$ = number of trapping days, T = total catch standardized for 72 traps, R = Zippin ratio, $1\text{-}q^k$ = estimated proportion of the population captured, N = estimated total population, SE = standard error of N, $N_i$ = estimated population size at the end of the sampling event.

| Date | $k$ | T | R | $1\text{-}q^k$ | N | SE(N) | $N_i$ |
|---|---|---|---|---|---|---|---|
| Sept 2010 | 12 | 2631 | 4.357 | 0.69 | 3802 | 125 | 1171 |
| Aug 2012 | 8 | 17449 | 2.90 | 0.87 | 20113 | 105 | 2664 |
| Aug 2013 | 11 | 15993 | 3.19 | 0.88 | 18123 | 89 | 2130 |
| Nov 2013 | 3 | 5484 | 0.85 | 0.50 | 11034 | 571 | 5550 |
| Apr 2014 | 3 | 923 | 0.74 | 0.63 | 1451 | 107 | 528 |
| Sept/Oct 2014 | 13 | 20362 | 4.02 | 0.87 | 23508 | 114 | 3146 |

to removal. At smaller temporal scales CW generally declined within a sampling event confirming the older, larger crabs were the first to be removed from the population. Further, males did not dominate the catch as might have been expected after the 2010 sampling event, possibly owing to the smaller sizes of crabs that reduced the size difference between males and females (Figure 6). If both males and females are smaller, and therefore closer in size, the effect of males entering the traps first and subsequently acting as a deterrent for females to enter could be less prominent (Crothers 1968). The demographic shift seen here could have been favourable for newly settled larvae in Pipestem Inlet in being less exposed to competition and predation resulting in higher survival rates. This would be consistent with Turner et al. (2016) who found only weak evidence for intraspecific impacts of adult green crab on juvenile conspecifics in California. Further, although Turner et al. (2016) did not find evidence for overcompensation with green crab removal efforts in California, they did suggest it remains plausible for higher density populations such as Pipestem Inlet. Thus, additional research may be required to inform green crab management decisions in British Columbia.

The shift in population structure in Pipestem Inlet may have other implications for the green crab invasion along the west coast of North America. Although green crabs in the Pacific Northwest can reach sexual maturity by the end of their first summer (Behrens Yamada et al. 2005) by reducing the size and age of the population it is probable the reproductive capacity of the population may have been reduced also. Larger females have a greater reproductive capacity than smaller ones given that once females reach a CW of approximately 28 mm, the growth rate of their abdomen increases abruptly in relation to their body size indicating that the larger the female is, the more eggs she can bear (Audet et al. 2008). However, total reproductive output from the population could be compensated for by a dramatic increase in smaller, younger and reproductively active crabs assuming survival rates remain high and are not density dependant. In addition to potential changes in reproductive output there could be changes in fitness and growth rates.

Larval supply to or within the inlet is critical for recruitment to maintain the population and without the ability to restrict larval supply it could allow for the inter-annual population recovery noted here. Green crab is well established on the west coast of North America (e.g., Grosholz and Ruiz 1995; Behrens Yamada et al. 2005; Gillespie et al. 2015) and natural larval dispersal from populations further south are likely contributing to the maintenance of the population in Pipestem Inlet. Further, the conditions within Pipestem Inlet are different to the surrounding area (e.g., Barkley Sound) due to its unique geology as being a narrow inlet that changes the local hydrodynamics. These conditions allow for, and in some years may enhance, localized larval supply (recruitment) within Pipestem Inlet itself (DiBacco and Therriault 2015). Also, like other crustaceans, green crab larval development times are temperature dependant (Klassen and Locke 2007) and under favourable temperature regimes it is possible that green crab could have more than one breeding event each year. Thus, to effectively reduce the green crab population size longer-term, larval supply both to and within the inlet would need to be reduced. Otherwise, depletion efforts might not reach their full potential as a more permanent control option. In Bodega Bay, California, Turner et al. (2016) found no evidence that juvenile recruitment was affected by removal trapping efforts providing further evidence that potential green crab management efforts need to consider the metapopulation structure on the west coast of North America.

Although some studies have found that removal efforts can change the demographics of a population most are not from aquatic systems. For example, Brown and Tuan (2005) detected a significant shift in demographics of rat populations after conducting removal sampling. This shift was towards a younger population with reduced body mass and reduced reproductive potential which is consistent with our study. The lack of reduction in population size found by Brown and Tuan (2005) suggests that removal sampling may not be effective at significantly reducing population size for an unwanted species but these efforts may be effective at reducing the spread of a species. Similarly, studying the management of Mountain Pine Beetle Trzcinski and Reid (2008) suggested that removing portions of the population had some success in reducing the spread of the species, particularly over large distances. This supports the suggestion that depletion efforts at Pipestem Inlet have the potential to reduce propagules that have the potential to either maintain or establish other populations.

## Conclusions and Recommendations

Annual trapping efforts of European green crab at Pipestem Inlet can remove a very large proportion of the population but due to either significant recruitment from larval supply or immigration to the population do not appear effective at reducing population abundance in the longer term. The addition of more depletion efforts (e.g., seasonally) may suppress the population below a desired threshold, but studies need to assess concurrently larval supply maintaining this (and potentially other) populations. If depletion efforts are able to supress the population size and coincide with years of recruitment failure, some impacts may be mitigated.

The population of green crab in Pipestem Inlet may be a source population for green crabs settling further north on the west coast of Vancouver Island or British Columbia's Central Coast (Gillespie et al. 2015). Pipestem Inlet is in Barkley Sound which is a destination for recreational boating, fishing and kayaking, so the potential for human mediated translocation, in addition to natural larval dispersal, is likely.

The population demographics of green crab in Pipestem Inlet are shifting as a result of trapping efforts. The larger and older crabs removed in 2010 have not been consistently captured since (although large individuals are captured each year). The average CW decreased both over a sampling event and every year since 2010. Thus, the population at Pipestem Inlet has shifted to a younger population that is replenished after 10–12 months. Despite the relative stability in population size the reduction in crab size may have lowered reproductive capacity without compensation, which could help prevent population increases in and around Pipestem Inlet, while also reducing larval supply to other areas.

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## Supplementary material

The following supplementary material is available for this article:

**Table S1.** Summary of European green crab Catch Per Unit Effort (CPUE – crabs per trap per day) data based on various trapping surveys in Pipestem Inlet and Hillier Island.

**Table S2.** Summary of European green crab size (Carapace Width – CW [point-to-point]) based on various trapping surveys in Pipestem Inlet and Hillier Island.

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