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Research Article

Citizen science program detects range expansion of the globally invasive European green crab in Washington State (USA)

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Abstract

The European green crab, *Carcinus maenas,* has been established on the west coast of North America since at least 1989, yet populations were limited to coastal embayments for more than two decades. In 2012, the first population was identified within the Strait of Juan de Fuca, which provided the impetus to develop a citizen science program to monitor for invasive green crab within the inland marine waters of Washington State (USA). In 2016, 116 volunteers monitored 26 sites using baited traps and visual surveys. On August 30, 2016, a single live male crab (74 mm carapace width) was captured in Westcott Bay on San Juan Island, Washington, by volunteers – the first detected range expansion in these inland waters. In September 2016, an additional crab was collected in Padilla Bay, Washington. The citizen science program and subsequent rapid assessment efforts by multiple partners found one green crab molt carapace in Westcott Bay, and three additional live crabs in Padilla Bay. Based on our results, the current extent of the invasion might be spatially and numerically restricted, but the occurrence of green crab in the San Juan Islands and Padilla Bay could portend future establishment of the species in the inland waters of Washington State and elsewhere in the Salish Sea. The citizen science program and rapid assessment efforts serve the dual purpose of providing ongoing monitoring and limited control in habitats vulnerable to invasion.

Key words: early detection, rapid response, *Carcinus maenas*, Salish Sea, invasive species

Introduction

The European green crab *Carcinus maenas* (henceforth green crab) is among the most widespread and well-documented marine invaders (see review by Carlton and Cohen 2003). Established invasive populations occur in shallow coastal waters of Atlantic North America, southeastern Australia and Tasmania, South Africa, Pacific North America, and most recently Atlantic Patagonia (LeRoux et al. 1990; Griffiths et al. 1992; Cohen et al. 1995; Grosholz and Ruiz 1995; Hidalgo et al. 2005).

Native to coastal waters from Mauritania to Norway (Almaca 1962; Christiansen 1969; Manning and Holthius 1981), green crab are abundant within a variety of habitats (Crothers 1970; Berrill 1982). In these habitats, they compete with other decapods (Eriksson et al. 1975) and regulate community structure through predation (Reise 1977; Jensen and Jensen 1985; Sanchez-Salazar et al. 1987) and sediment disturbance during foraging (Schratzberger and Warwick 1999). At high densities, the species also limits the distribution of some benthic invertebrates (Dare and Edwards 1976; Jensen and Jensen 1985; Sanchez-Salazar et al. 1987; Richards et al. 1999).

Significant impacts have been attributed to green crab within portions of the introduced range, particularly the coasts of the western Atlantic. Green crab predation results in local depletion of a commercially important bivalve (i.e., the softshell clam, *Mya arenaria*) in New England, which has periodically contributed to collapse of that fishery (Glude 1955; Hanks 1961; Floyd and Williams 2004). In Maine (Neckles 2015) and Nova Scotia (Garbary et al. 2014), green crab digging and burrowing has been implicated in the loss of eelgrass beds, resulting in cascading ecosystem impacts including declines in fish abundance and biomass (Matheson et al. 2016). Phenotypic and behavioral changes, considered adaptive responses to intense crab predation, have also been observed among snails and mussels in conjunction with the northward range expansion of green crab in the western Atlantic (Vermeij 1982; Seeley 1986; Leonard et al. 1999; Smith and Jennings 2000).

Due in part to the variety and severity of impacts observed as populations grew and expanded in the western Atlantic, the spread of green crab into the northeastern Pacific was viewed with concern by scientists, resource managers, and citizen conservation groups (Cohen et al. 1995; Jamieson et al. 1998; Carr and Dumbauld 2000; Grosholz and Olin 2000; Grosholz and Ruiz 2000; Grosholz et al. 2000; McDonald et al. 2001; Palacios and Ferraro 2003). The first green crab on the US West Coast were observed in San Francisco Bay in 1989, but not detected in coastal waters of Washington State (USA) until 1998, after warm El Niño-Southern Oscillation (ENSO) currents spread larvae of California populations as far north as Vancouver Island, British Columbia. Because of perceived risks to coastal resources, the species was classified at the time as a deleterious species in Washington State (subsequently reclassified as a prohibited level 1 species; 2014 c 202 § 105), which among other actions, mandated monitoring and control in State waters.

During this expansion, monitoring by state agencies and volunteer groups detected green crab only in two coastal estuaries of Washington State: Willapa Bay and Grays Harbor (Behrens Yamada and Gillespie 2008; Eissinger 2010). Because these small coastal estuaries are oceanographically distinct from Washington's inland waters (i.e., the Salish Sea, which includes Puget Sound, the Strait of Juan de Fuca, and the San Juan Islands), and green crab recruiting to the coastal estuaries failed to establish large populations (Behrens Yamada and Gillespie 2008), monitoring and control efforts were curtailed in Washington State by 2010. However, in 2012, Canadian wildlife officials discovered a population of green crab in Sooke Basin near Victoria, British Columbia, within the Strait of Juan de Fuca (Curtis et al. 2015).

This discovery of green crab prompted the re-establishment of early detection monitoring along Washington's inland shorelines. To more effectively surveil the nearly 3,000 km of Washington's inland shoreline, citizen science monitoring was selected as the most efficient approach, because it provides a framework whereby volunteers can collect data over large spatial and temporal scales at relatively low cost (Bonney et al. 2009). There are potential challenges to working with volunteers; including limited experience identifying invertebrates, or reluctance to commit to a long-term monitoring project. Yet previous work by Delaney et al. (2008) has demonstrated that trained volunteers can identify green crab for monitoring purposes, and the ubiquity of cell phone cameras enables nearly instant expert verification of species identity.

We describe here the volunteer-based monitoring program in Washington State (i.e., *Crab Team*) and collaborative rapid assessments, and report patterns of green crab occurrence within the inland marine waters of Washington State.

Methods

Two approaches were used to monitor for the presence of green crab – a regular (i.e. monthly), geographically-distributed, volunteer-based monitoring program, and an intensive, targeted, rapid assessment survey in areas where green crab have been detected.

Volunteer monitoring

The volunteer early detection and monitoring program (Crab Team) was initiated by Washington Sea Grant (WSG) in coordination with the Washington Department of Fish & Wildlife (WDFW). Early detection monitoring was designed to provide ongoing surveillance on a regional scale at a coarse geographic resolution (see below). WSG Crab Team piloted volunteer-based monitoring in August and September of 2015 at seven sites in Washington's inland marine waters. In 2016, 116 Crab Team volunteers monitored 26 sites (including six of the sites monitored in 2015) throughout inland waters of Washington State using baited traps and visual surveys (Figure 1).

Site selection

Given limited volunteer and equipment resources, and a large area for surveillance (ca. 3,000 km of shoreline), a habitat suitability assessment was conducted to prioritize localities for early detection efforts. Unlike in the native range, or other invaded regions, on the US West Coast, green crab has historically

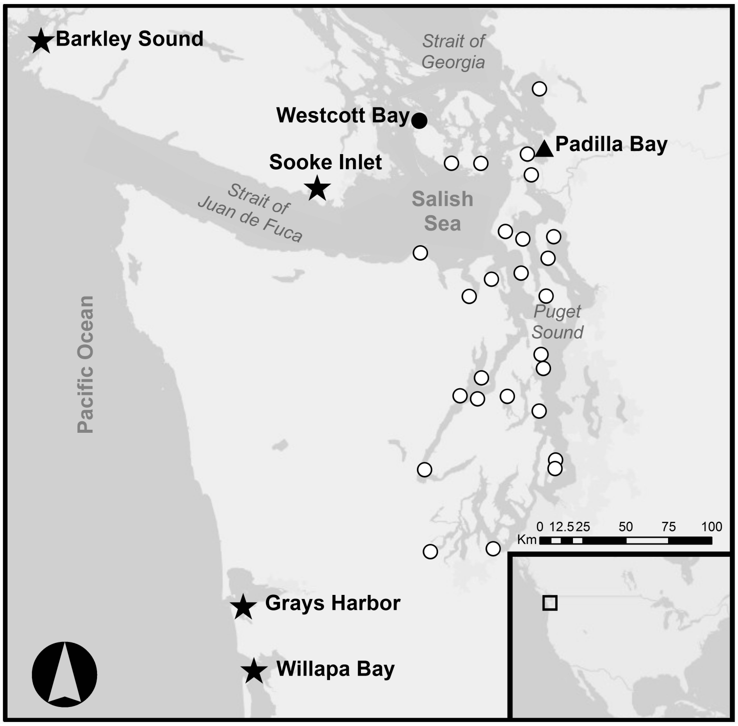

Figure 1. Map of known populations and sampling locations for European green crab (*Carcinus maenas*) in Washington State (USA) and southern Vancouver Island (Canada). Stars indicate sites with known populations of green crab as of 2012. WSG Crab Team monitoring sites from 2015 and 2016 are marked by circles; open/white circles indicate volunteer monitoring has not yielded any evidence of green crab to date, and the filled/black circle marks the site of the first confirmed capture of the crab in Washington's inland shorelines by WSG Crab Team volunteers. The site of the second detection of green crab, marked by a black triangle, occurred in Padilla Bay.

been restricted to soft-sediment habitats (Grosholz and Ruiz 1996), where it reaches its greatest abundance in intertidal areas with restricted flow and in marsh habitats lacking large native crabs (e.g., red rock crab, *Cancer productus*, Hunt and Behrens Yamada 2003; Jensen et al. 2007). Prior experience with Willapa Bay and central California populations suggests best habitats for this species include features such as impounded lagoons and tidal sloughs with attributes like emergent saltmarsh vegetation and epibenthic structure (McDonald 2006; McDonald et al. 2006). These habitats integrate environmental factors (e.g., topography, biotic conditions, hydrography, exposure, and substrate) known to influence distribution of green crab globally (see review by Cosham et al. 2016). Thus we assessed locations within inland waters of Washington State with a simple additive model by scoring characteristics visible in publicly available aerial photography and satellite imagery (Washington Sea Grant 2017). The primary inclusion variable was coarse-scale habitat feature (i.e., lagoons, tidal sloughs and channels, intertidal mudflats > 100 m wide) and more than 400 locations were evaluated. For a given location, points were added when positive attributes were present (e.g., marsh vegetation, rock rip-rap) and points were subtracted for negative attributes (e.g., high wave energy or extensive freshwater input) (Washington Sea Grant 2017). Locations were categorized as high, medium, and low suitability based on the total number of points accumulated. Monitoring sites were selected from this group based on feasibility and logistical constraints (e.g., access, safety, volunteer availability), which are important considerations in citizen science monitoring programs (e.g., Cox et al. 2012).

Monitoring protocols

At each site, volunteers conducted three standardized survey protocols: a baited trap survey, molt hunt, and shoreline habitat transect. The protocols were aimed at increasing the detection probability for green crab via multi-modal search techniques, as well as collecting community and habitat data (i.e., other species present, vegetation cover, sediment type) to enable robust assessment of ecological effects via a multiple before-after control-impact (BACI) design should green crab become locally abundant. Evaluating diversity and abundance of native organisms and habitat attributes also provides region-wide, baseline observations on relatively understudied estuarine marsh habitats and pocket estuaries (Grason et al. 2016) and was designed to help maintain ongoing citizen science volunteer engagement even where green crab were not observed (e.g., Dickinson et al. 2012).

In baited trapping surveys, six traps – three galvanized steel cylindrical minnow traps (5 cm opening, 0.5 cm mesh) and three rectangular Fukui model FT-100 fish traps (1 cm mesh) – were deployed from shore to capture an overnight high tide event once per month during the period of peak green crab activity (April–September; McDonald 2006; McDonald et al. 2006). Adult green crab are somewhat cryptic, exhibit fairly localized daily movements and maintain home ranges on the order of tens of meters in coastal Washington estuaries (McDonald 2006; McDonald et al. 2006). Baited traps, while currently the most practical, scalable option for live capture, target relatively small areas and only attract crabs that are actively searching for food. Therefore, traps were positioned to capture green crab emerging from burrows to forage on the returning tide. The traps were arrayed in a horizontal transect parallel and adjacent to the lower edge of the terrestrial habitat boundary at the same tide level. This orientation ensured consistency across all sites and meant traps were in close proximity to structure that provides green crab shelter during low tide (mud banks, marsh vegetation, or rock rip-rap). Within the transect, traps were placed 10 m apart, alternating trap type, and anchored with a thin metal rod.

The number of traps placed at each site (n = 6) is a compromise to satisfy the primary objectives of the program: 1) to detect presence of green crab and 2) to engage volunteers in citizen science. While some sites could accommodate additional traps, we limited the time commitment and physical demands of the work in consideration of volunteer satisfaction (J. Adams, unpublished data). Total area covered by an individual trap array was typically 10–25% of a site. Traps were baited with 200 g of frozen mackerel (e.g., Jensen et al. 2007; McDonald et al. 2006) and set on the returning lower-low tide, placed so they were more than half submerged at the time of setting to ensure trap submergence for the entire deployment and reduce bycatch mortality. On the ebbing lower-low tide the following day, volunteers returned to identify, count, and record all species in the traps and release all native organisms on site. Volunteers submitted photographs of trap catches, which were reviewed by Crab Team staff for quality assurance and to ensure green crab were not inadvertently released (i.e., reduce risk of false negatives). Additional targeted photographs were used to verify the identity of any cryptic or unknown organisms.

Range expansions of green crab are occasionally detected first by molts (i.e., exuviae) rather than live individuals. In 2015, we piloted a standardized molt survey along a 50 m transect in the terrestrial habitat boundary adjacent to the trapping array. However, molt deposition typically occurs broadly at these sampling sites (personal observation), and timed searches are expected to be more effective for detecting rare species (Metcalfe-Smith et al. 2000). Accordingly, in 2016 a molt survey was conducted at each site April–September, which consisted of a timed search (20 person minutes) originating at a fixed site marker. Volunteers searched areas of wrack deposition, collected all molts detected in the time allowed, and identified them to the lowest taxonomic group possible (typically species).

Table 1. Scope, effort, and results of rapid assessment trapping surveys in response to the two captures of European green crab (*Carcinus maenas*) on inland Washington State (USA) shorelines during 2016.

	Westcott Bay, San Juan County	Padilla Bay, Skagit County
Dates	Sept. 12–14	Sept. 26–28
Trapping sites	7	31
Trap sets	193	368
Radius from initial green crab	3 km	6.5 km
Additional live green crab captured	0	3
Green crab molts found	1	0

To assess habitat characteristics at each site and quantify changes over time, potentially due to green crab, volunteers collected data on shoreline features (i.e., percent cover of wrack type, rooted vegetation, and live epifauna, and predominant substrate type) along a 50 m transect in the terrestrial habitat boundary adjacent to the trapping array. Data were collected monthly (April–September) in ten 0.1 m^2 quadrats at randomly-assigned distances along the transect. Detailed protocols for these surveys can be found online (Washington Sea Grant 2017).

Rapid assessment surveys

As soon as feasible following detection of green crab, rapid assessment surveys were undertaken to assess the scope of any potential established population at a local scale. Traps were set broadly (ca. 20 m trap distance) across as much suitable habitat as possible within a 3–5 km radius, given the constraints of staff time, tides, and equipment (Table 1). Nearly all sites were trapped for two consecutive overnight high tides using a combination of baited minnow and Fukui traps. In addition to live trapping, the survey participants also opportunistically inspected molts within wrack deposited at each site. Rapid assessment actions were led by WDFW in coordination with WSG Crab Team and with key assistance from local

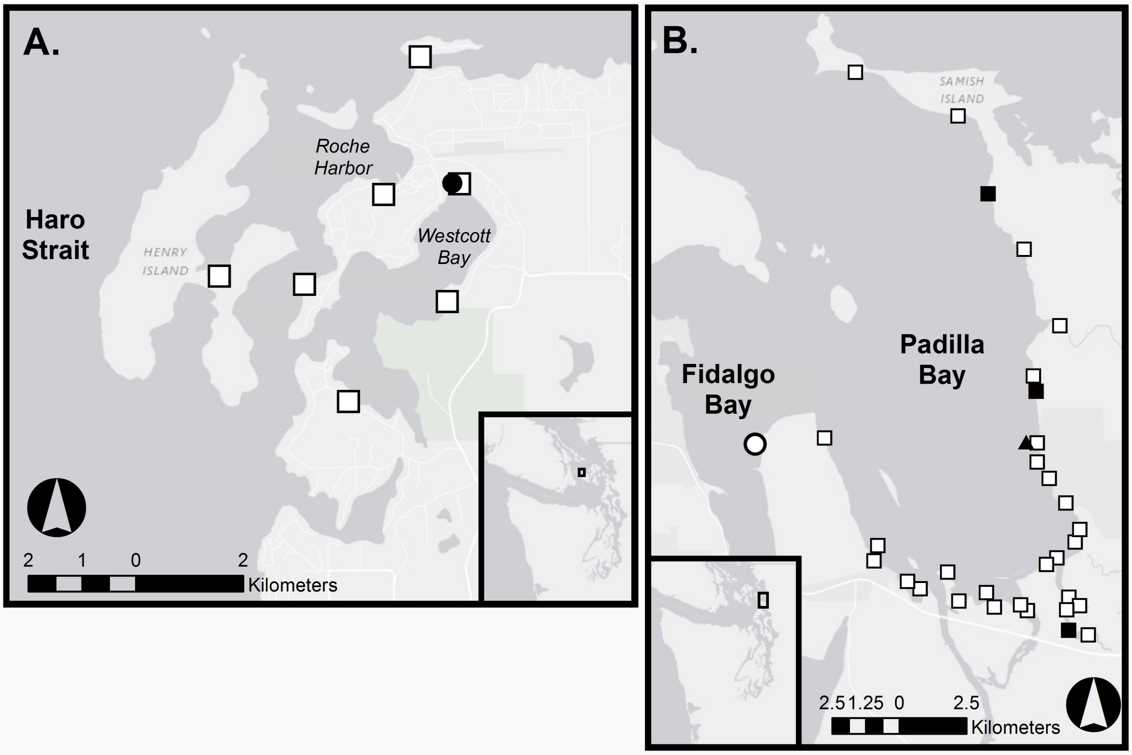

Figure 2. Maps of sampling activities and captures for European green crab (*Carcinus maenas*) near Westcott Bay (A) and Padilla Bay (B) in Washington State (USA). Marker shape denotes type of observation: Circles indicate Crab Team monitoring sites, and squares mark sites at which multiple traps were set for rapid assessment surveys. The triangle in panel B indicates the site of hand capture site by staff at Padilla Bay. Filled/black symbols indicate green crab capture, open/white symbols indicate no green crab were detected as a part of the respective sampling effort. For both panels, the site of the original capture was also targeted for rapid assessment trapping, but the markers have been jittered slightly for visibility.

stakeholders. All participants in the rapid response assessment surveys were qualified research or monitoring staff (i.e., field biologists) representing the different collaborating institutions. Presence or absence of green crab was recorded for each trap.

Results

In the 2015 pilot season, monitoring occurred at seven sites across two months, resulting in 84 trap sets. The program expanded in 2016, but monitoring was not initiated at all sites at the beginning of the season in April. In total for that year, 139 trapping surveys (and 140 molt surveys) occurred across 26 sites (including six of the sites monitored in 2015), resulting in a total effort of 834 trap sets (Supplementary material Table S1).

The first observation of green crab in Washington inland marine waters was made by a team of WSG Crab Team volunteers during their regular monthly monitoring. The crab was a single adult male (74 mm carapace width, CW) captured in a Fukui trap at Westcott Bay, San Juan Island (Figure 2A) on August 30, 2016, during the fifth month of surveying at that site. Identification was confirmed on site (Sylvia Behrens Yamada, personal communication), and the crab was retained and frozen per WDFW guidelines and later transferred to Crab Team staff. The size of the crab indicated it was likely age 2+ or 3+ (Behrens Yamada et al. 2005). Rapid assessment trapping by WDFW and Crab Team staff subsequent to that detection did not yield any additional live crabs (Table 1; Figure 2A), although a single molted carapace from an adult green crab (sex unknown) was found in the channel very close to the original capture site. Based on the size of the carapace (69 mm CW) and information about growth increment (Behrens Yamada et al. 2005), the molt could not have come from the crab captured in the trap. This suggests that at least one more green crab occurred at the site but was not captured by follow-up efforts, including the regular monthly trapping by volunteers in September 2016 that occurred two weeks after the rapid assessment trapping.

On September 19, 2016 a single female green crab (38 mm CW), was collected opportunistically by education staff overturning rocks at the Padilla Bay National Estuarine Research Reserve (PBNERR). No Crab Team monitoring sites were located in Padilla Bay in 2015 or 2016, but PBNERR maintained an independent annual monitoring regime that had not detected evidence of green crab to date (Riggs 2016). The closest Crab Team site to the Padilla Bay collection location was in Fidalgo Bay (~ 7 km away), where monitoring was conducted in July and September of 2016, but showed no evidence of green crab. Rapid assessment trapping by WDFW, WSG, and PBNERR staff resulted in the capture of three additional juvenile crabs (two females: 39 mm CW and 40 mm CW, and a male: 58 mm CW), distributed across the bay (Table 1; Figure 2B). All crabs captured in Padilla Bay were presumed to be young of the year based on size and shell condition using the relationship estimated by Behrens Yamada et al. (2005). No green crab molts were found during this assessment.

No other evidence of green crab was observed at monitoring sites throughout the inland waters of Washington State in 2015 and 2016, including other sites in the Strait of Juan de Fuca, San Juan Islands, Hood Canal or Puget Sound (Figure 1). This includes expert review of photographs of all trap catches submitted by Crab Team volunteers. In addition, previous diverse monitoring efforts (e.g., baited trapping, habitat surveys) in the region, dating back to 2001, failed to detect green crab (Behrens Yamada et al. 2017). All crabs detected to date have come from the 2015 or 2016 year class, with no evidence of multiple year classes within a single site, which would indicate potential local reproduction. Together, these lines of evidence support the inference that these observations document the earliest arrivals of this species.

Discussion

The capture of a green crab in surveys on San Juan Island by trained volunteers demonstrates the potential for citizen science to support early detection monitoring and expands on previous efforts to use citizen science to detect this species across a large spatial scale (e.g., Delaney et al. 2008). This approach enabled a greatly expanded scope of monitoring, as government and academic resources can only support monitoring at a handful of sites (e.g., Dickinson et al. 2012). Coupled with follow-up rapid assessments by professional biologists, the citizen science program has allowed WDFW to satisfy the state legislative mandate for management of a prohibited level 1 species.

These observations mark the first confirmed detections of green crab in Washington's inland marine waters (i.e., Puget Sound and San Juan Islands; Figure 1) and indicate a potential range expansion of a globally invasive crab. No green crab had been documented in these waters previously despite trapping efforts (see summary in Behrens Yamada and Gillespie 2008) and public outreach that began in 1998, when the first crab were captured in Washington coastal estuaries (e.g., Carr and Dumbauld 2000). One putative report of a molt from Boundary Bay (Canada) was made in 2014, but lacked physical or photographic evidence to confirm identification, and follow up trapping failed to detect green crab in that area (T.W. Therriault, personal communication).

It is possible the lack of sightings prior to 2016 resulted from misidentification. During the 1990's, WDFW supplemented monitoring by conducting a broad public outreach campaign, asking beachgoers to report any suspected green crab. Green crab, however, have characteristics similar to native species and WDFW received hundreds of reports of green crab in the Salish Sea, none of which was a correct identification, i.e., all of which were native species. Presumably, misidentification could work in the opposite direction as well, and green crab observed by beachgoers could have been mistaken for native species. This challenge of correctly identifying a cryptic invader can be mitigated by incorporating robust volunteer training, clear, directed, public outreach materials, and engagement of diverse stakeholders with local ecological knowledge into early detection programs. For instance, green crab are less likely to have been mistaken for native species by shellfish growers because they have greater familiarity with local fauna than casual beachgoers. Commercial shellfish activities overlap with suitable green crab habitat, yet, to date, no reports of this species have been made by shellfish growers operating in the Salish Sea, strengthening the inference that green crab were absent from the region until recently.

Transport vectors and the source population(s) of the green crab described here remain unknown. Past human-mediated worldwide introductions of green crab have likely been facilitated by ballast exchange, hull and gear fouling, shellfish transfers, and seafood shipments, while regional spread often occurs via larval dispersal once a nascent population becomes established (Carlton and Cohen 2003). Human-mediated transport cannot be ruled out, particularly for the Westcott Bay crab, but there is better support for natural dispersal in Padilla Bay. First, WDFW maintains strict quarantine for transport of commercial shellfish and materials from waters known to be infested with green crab, and there are currently no commercial operations in Westcott Bay (P. Kohn, personal communication). Padilla Bay also lacks marinas or other infrastructure for recreational and commercial boats and the shallow depth and paucity of navigable channels makes it unsuitable for most watercraft, thereby limiting risks related to those vectors. Last, the four green crab captured in Padilla Bay, while likely all part of the same cohort (based on CW; Behrens Yamada et al. 2005), were spread across more than 10 km of shoreline, making it likely they arrived as larvae rather than juveniles or adults; yet no documented discharges of untreated ballast water have occurred in the area for many years (A. Pleus, unpublished data).

If larval dispersal is the most parsimonious explanation for the recent arrival, then the established population in Sooke Basin is the most likely source, although alternative explanations exist (Behrens Yamada et al. 2017). In the early stages of the West Coast invasion, the Strait of Juan de Fuca was believed to provide a semi-permeable hydrogeographic barrier to expansion into the Salish Sea, particularly along the northern shore because prevailing surface currents favor export (Jamieson et al. 2002). It appears this was partially overcome by human-mediated transport to Sooke Basin (T. Therriault, personal communication) and establishment of green crab populations there as of 2012 (Curtis et al. 2015), thereby increasing the probability of further expansion. Sooke Basin is the closest known established population to both Padilla and Westcott Bays, and might enable larvae to partially bypass the presumed hydrogeographic barrier presented by conditions of the Strait of Juan de Fuca. Moreover, preliminary passive-particle modeling simulations suggest larvae could be carried eastward from Sooke Basin into inland waters (P. MacCready, unpublished data).

The capture of green crab of separate year classes in different locations might indicate at least two distinct recruitment events have taken place. The size of the crabs suggests that larvae arrived in Westcott Bay in the winter of 2014/2015 and in Padilla Bay during the winter of 2015/2016. It has been suggested that warm years of strong positive ENSO conditions are favorable for larval survival (Behrens Yamada et al. 2015). The highest ENSO indices on record since the 1997/1998 dispersal event occurred during 2014/2015 and 2015/2016 (NOAA Climate Prediction Center), coincident with the assumed arrival dates of the two year classes, and therefore might have also contributed to the timing of this expansion (Behrens Yamada et al. 2017). Additional populations of green crab, as yet undetected, on Canadian shorelines within the Salish Sea, might also be a source of larvae, particularly for the San Juan Islands (Behrens Yamada et al. 2017).

The future of green crab in the Salish Sea remains unknown, but the potential for ecological damage could be substantial. Washington's inland marine shorelines are characterized by abundant suitable habitat for green crab and by geography that favors retention and regional distribution of larvae, conditions that could promote establishment and rapid expansion of the species throughout the Salish Sea. Much of this suitable habitat is also critical for culturally and economically important species and habitats, such as eelgrass (*Zostera marina*), juvenile salmonids, and Dungeness crabs (*Cancer* [*Metacarcinus*] *magister*). Green crab have a well-documented history of negative impacts on shellfish (e.g., Whitlow 2010; Walton et al. 2002), and recent evidence points to the potential for green crab to damage and impair the restoration of eelgrass (Neckles 2015; Matheson et al. 2016). Thus, if stated goals of shoreline habitat integrity and eelgrass expansion are a priority (Washington State Department of Natural Resources 2015), it is important to respond to this expansion swiftly. Previous efforts in central California (i.e., Bodega Bay Harbor and Seadrift Lagoon) demonstrated that, with intensive and sustained trapping, green crab populations can be reduced in isolated habitats (C. deRivera, personal communication). Citizen science programs leveraging support from multiple stakeholder groups can provide a model for effective early detection monitoring, which in turn can significantly improve the effectiveness of rapid response efforts by state and local field biologists. In light of the risks, and to support management goals, WSG Crab Team doubled the number of monitoring sites during 2017, and continues the model of early detection/rapid assessment for this globally damaging invasive species.

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References

Almaca C (1962) Sur la distribution geographique du genre *Carcinus* Leach (Crust. Dec. Brach.). *Revista da Faculdade de Ciencias, Universidade de Lisboa,* Series 2 10: 109–113

Behrens 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, https://doi.org/10.1007/s10530-004-0877-2

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

Behrens Yamada SB, Peterson WT, Kosro PM (2015) Biological and physical ocean indicators predict the success of an invasive crab, *Carcinus maenas*, in the northern California Current. *Marine Ecology Progress Series* 537: 175–189, https://doi.org/10.3354/meps11431

Behrens Yamada SB, Thomson RE, Gillespie GE, Norgard TC (2017) Lifting barriers to range expansion: The European green crab *Carcinus maenas* (Linnaeus, 1758) enters the Salish Sea. *Journal of Shellfish Research* 36: 201–208, https://doi.org/10.2983/035.036.0121

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, https://doi.org/10.2307/1548108

Bonney R, Cooper CB, Dickinson J, Kelling S, Phillips T, Rosenberg KV, Shirk J (2009) Citizen science: a developing tool for expanding science knowledge and scientific literacy. *BioScience* 59: 977–984, https://doi.org/10.1525/bio.2009.59.11.9

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, https://doi.org/10.1111/j.1365-2699.2003.00962.x

Carr E, Dumbauld B (2000) Status of the European green crab invasion in Washington coastal estuaries: can expansion be prevented? *Journal of Shellfish Research* 19: 629–630

Christiansen ME (1969) Crustacea Decapoda Brachyura. Marine invertebrates of Scandinavia. Unversitetsforlaget, Oslo, 143 pp

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

Cosham J, Beazley KF, McCarthy C (2016) Environmental factors influencing local distributions of European green crab (*Carcinus maenas*) for modeling and management applications. *Environmental Reviews* 24: 244–252, https://doi.org/10.1139/er-2015-0053

Cox TE, Philippoff J, Baumgartner E, Smith CM (2012) Expert variability provides perspective on the strengths and weaknesses of citizen-driven intertidal monitoring program. *Ecological Applications* 22: 1201–1212, https://doi.org/10.1890/11-1614.1

Crothers JH (1970) The distribution of crabs on rocky shores around the Dale Peninsula. *Field Studies* 3: 263–274

Curtis LJF, Curtis DL, Matkin H, Thompson M, Choi F, Callow P, Gillespie GE, Therriault 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 maenas*) and other non-indigenous invertebrate species. DFO Canadian Science Advisory Secretariat Research Document 2015/014, vi + 74 pp

Dare PJ, Edwards DB (1976) Experiments on the survival, growth and yield of relaid seed mussels (*Mytilus edulis* L.) in the Menai Straits, North Wales. *ICES Journal of Marine Science* 37: 16–28, https://doi.org/10.1093/icesjms/37.1.16

Delaney DG, Sperling CD, Adams CS, Leung B (2008) Marine invasive species: validation of citizen science and implications for national monitoring networks. *Biological Invasions* 10: 117–128, https://doi.org/10.1007/s10530-007-9114-0

Dickinson J, Shirk J, Bonter D, Bonney R, Crain R, Martin J, Phillips T, Purcell K (2012) The current state of citizen science as a tool for ecological research and public engagement. *Frontiers in Ecology and the Environment* 10: 291–297, https://doi.org/10.1890/110236

Eissinger A (2010) Puget Sound Marine Invasive Species Volunteer Monitoring Program. Final Summary Report. Prepared for Washington Department of Fish and Wildlife. Nahkeeta Northwest Wildlife Services. Bow, Washington, 56 pp

Eriksson S, Evans S, Tallmark B (1975) On the coexistence of scavengers on shallow, sandy bottoms in Gullmar Fjord (Sweden): activity patterns and feeding ability. *Zoon* 3: 121–124

Floyd T, Williams J (2004) Impact of green crab (*Carcinus maenas* L.) predation on a population of soft-shell clams (*Mya arenaria* L.) in the Southern Gulf of St. Lawrence. *Journal of Shellfish Research* 23: 457–462

Garbary DJ, Miller AG, Williams J, Seymour NR (2014) Drastic decline of an extensive eelgrass bed in Nova Scotia due to the activity of the invasive green crab (*Carcinus maenas*). *Marine Biology* 161: 3–15, https://doi.org/10.1007/s00227-013-2323-4

Glude JB (1955) The effects of temperature and predators on the abundance of the softshell clam *Mya arenaria* in New England. *Transactions of the American Fisheries Society* 84: 13–26, https://doi.org/10.1577/1548-8659(1954)84[13:TEOTAP]2.0.CO;2

Grason EW, Adams JW, Litle K, McDonald PS, Dalton PD (2016) European green crab early detection and monitoring. Washington Sea Grant, Final Report WSG-TR 16-07, 73 p

Griffiths CL, Hockey PAR, Schurink CVE (1992) Marine invasive aliens on South African shores: implications for community structure and trophic functioning. *South African Journal of Marine Science* 12: 713–722, https://doi.org/10.2989/02577619209504736

Grosholz ED, Olin P (2000) Predation by European green crabs on Manila clams in central California. *Journal of Shellfish Research* 19: 631

Grosholz ED, Ruiz GM (1995) Spread and potential impact of the recently introduced European green crab, *Carcinus maenas*, in central California. *Marine Biology* 122: 239–247

Grosholz ED, Ruiz GM (1996) Predicting the impact of introduced marine species: lessons from the multiple invasions of the European green crab *Carcinus maenas*. *Biological Conservation* 78: 59–66, https://doi.org/10.1016/0006-3207(94)00018-2

Grosholz ED, Ruiz GM (2000) The impact of European green crabs in central California. *Journal of Shellfish Research* 19: 631–632

Grosholz ED, Ruiz GM, Dean CA, Shirley KA, Maron JL, Connors PG (2000) The impacts of a nonindigenous marine predator in a California bay. *Ecology* 81: 1206–1224, https://doi.org/10.1890/0012-9658(2000)081[1206:TIOANM]2.0.CO;2

Hanks RW (1961) Chemical control of the green crab *Carcinus maenas* (L.). *Proceedings of the National Shellfish Association* 52: 75–86

Hidalgo FJ, Baron PJ, Orensanz JM (2005) A prediction come true: the green crab invades the Patagonian coast. *Biological Invasions* 7: 547–552, https://doi.org/10.1007/s10530-004-5452-3

Hunt CE, Behrens Yamada SB (2003) Biotic resistance experienced by an invasive crustacean in a temperate estuary. *Biological Invasions* 5: 33–43, https://doi.org/10.1023/A:1024011226799

Jamieson GS, Grosholz ED, Armstrong DA, Elner RW (1998) Potential ecological implications from the introduction of the European green crab, *Carcinus maenas* (Linneaus), to British Columbia, Canada, and Washington, USA. *Journal of Natural History* 32: 10–11, https://doi.org/10.1080/00222939800771121

Jamieson GS, Foreman M, Cherniawsky J, Levings C (2002) European green crab (*Carcinus maenas*) dispersal: The Pacific experience. In: Paul AJ, Dawe EG, Elner R, Jamieson GS, Kruse GH, Otto RS, Sainte-Marie B, Shirley TC, Woodby D (eds), Crabs in cold water regions: Biology, management, and economics. University of Alaska Sea Grant, AK-SG-02-01, Fairbanks, 876 pp, https://doi.org/10.4027/ccwrbme.2002.41

Jensen GC, McDonald PS, Armstrong DA (2007) Biotic resistance to green crab, *Carcinus maenas*, in California bays. *Marine Biology* 151: 2231–2242, https://doi.org/10.1007/s00227-007-0658-4

Jensen KT, Jensen JN (1985) The importance of some epibenthic predators on the density of juvenile benthic macrofauna in the Danish Wadden sea. *Journal of Experimental Marine Biology and Ecology* 89: 157–174, https://doi.org/10.1016/0022-0981(85)90124-8

Leonard GH, Bertness MD, Yund PO (1999) Crab predation, waterborne cues and inducible defenses in the blue mussel, *Mytilus edulis*. *Ecology* 80: 1–14, https://doi.org/10.1890/0012-9658(1999)080[0001:CPWCAI]2.0.CO;2

LeRoux PJ, Branch GM, Joska MAP (1990) On the distribution, diet and possible impact of the invasive European shore crab *Carcinus maenas* (L.) along the South African coast. *South African Journal of Marine Science* 9: 85–93, https://doi.org/10.2989/025776190784378835

Manning RB, Holthius LB (1981) West African brachyuran crabs (Crustacea: Decapoda). *Smithsonian Contributions to Zoology* 89: 1–41, https://doi.org/10.5479/si.00810282.306

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, https://doi.org/10.3354/meps11674

McDonald PS (2006) Biotic resistance and other factors affecting the distribution, habitat use, and potential impacts of invasive European green crab, *Carcinus maenas*, in the northeastern Pacific. Doctoral Dissertation, University of Washington, Seattle, Washington, 169 pp

McDonald PS, Holsman KK, Beauchamp DA, Dumbauld BR, Armstrong DA (2006) Bioenergetics modeling to investigate habitat use by the nonindigenous crab, *Carcinus maenas*, in Willapa Bay, Washington. *Estuaries* 29: 1132–1149, https://doi.org/10.1007/BF02781815

McDonald PS, Jensen GC, Armstrong DA (2001) The competitive and predatory impacts of the nonindigenous crab *Carcinus maenas* (L.) on early benthic phase Dungeness crab *Cancer magister* Dana. *Journal of Experimental Marine Biology and Ecology* 258: 39–54, https://doi.org/10.1016/S0022-0981(00)00344-0

Metcalfe-Smith JL, Di Maio J, Staton SK, Mackie GL (2000) Effect of sampling effort on the efficiency of the timed search method for sampling freshwater mussel communities. *Journal of the North American Benthological Society* 19: 725–732, https://doi.org/10.2307/1468129

Neckles HA (2015) Loss of eelgrass in Casco Bay, Maine, linked to green crab disturbance. *Northeastern Naturalist* 22: 478–500, https://doi.org/10.1656/045.022.0305

Palacios KC, Ferraro SP (2003) Green crab (*Carcinus maenas* Linnaeus) consumption rates on and prey preferences among four bivalve prey species. *Journal of Shellfish Research* 22: 865–871

Reise K (1977) Predator exclusion experiments in an intertidal mud flat. *Helgoländer wissenschaftliche Meeresuntersuchungen* 30: 263–271, https://doi.org/10.1007/BF02207840

Richards MG, Huxham M, Bryant A (1999) Predation: a causal mechanism for variability in intertidal bivalve populations. *Journal of Experimental Marine Biology and Ecology* 241: 159–177, https://doi.org/10.1016/S0022-0981(99)00075-1

Riggs SR (2016) Monitoring for invasive crab in Padilla Bay, Skagit County, Washington, in 2016. Padilla Bay National Estuarine Research Reserve, Mount Vernon, Washington, 16 pp

Sanchez-Salazar ME, Griffiths CL, Seed R (1987) The interactive roles of predation and tidal elevation in structuring populations of the edible cockle *Cerastoderma edule*. *Estuarine Coastal and Shelf Science* 25: 245–260, https://doi.org/10.1016/0272-7714(87)90125-9

Schratzberger M, Warwick RM (1999) Impact of predation and sediment disturbance by *Carcinus maenas* (L.) on free-living nematode community structure. *Journal of Experimental Marine Biology and Ecology* 235: 255–271, https://doi.org/10.1016/S0022-0981(98)00165-8

Seeley RH (1986) Intense natural selection caused a rapid morphological transition in a living marine snail *Littorina obtusata*. *Proceedings of the National Academy of Sciences USA* 83: 6897–6901, https://doi.org/10.1073/pnas.83.18.6897

Smith LD, Jennings JA (2000) Induced defensive responses by the bivalve *Mytilus edulis* to predators with different attack modes. *Marine Biology* 136: 461–469, https://doi.org/10.1007/s002270050705

Vermeij GJ (1982) Environmental change and the evolutionary history of the periwinkle (*Littorina littorea*) in North America. *Evolution* 36: 561–580

Walton WC, MacKinnon C, Rodriguez LF, Proctor C, Ruiz GM (2002) Effect of an invasive crab upon a marine fishery: green crab, *Carcinus maenas*, predation upon a venerid clam, *Katelysia scalarina*, in Tasmania (Australia). *Journal of Experimental Marine Biology and Ecology* 272: 171–189, https://doi.org/10.1016/S0022-0981(02)00127-2

Washington Sea Grant (2017) WSG Crab Team. https://wsg.washington.edu/crabteam (accessed 15 January 2017)

Washington State Department of Natural Resources (2015) Puget Sound eelgrass (*Zostera marina*) recovery strategy. Olympia, Washington, 46 pp

Whitlow WL (2010) Changes in survivorship, behavior, and morphology in native soft-shell clams induced by invasive green crab predators. *Marine Ecology* 31: 418–430

Supplementary material

The following supplementary material is available for this article:

Table S1. Georeferenced sampling locations for trapping efforts and captures of European green crabs (*Carcinus maenas*) related to the Washington Sea Grant Crab Team activities.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2018/Supplements/MBI_2018_Grason_etal_Table_S1.xls