EUROPEAN GREEN CRAB

Early Detection and Monitoring, Phase 2

WSG.WASHINGTON.EDU/CRABTEAM

Sea Grant Washington

Crab Team: European Green Crab Early Detection and Monitoring, Phase 2

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ACRONYMS

CPUE - Catch Per Unit Effort

DFO - Fisheries and Oceans Canada

EPA - U.S. Environmental Protection Agency

NWR - National Wildlife Refuge

PSMFC - Pacific States Marine Fisheries Commission

QAPP - Quality Assurance Project Plan

QA - Quality Assurance

TEGC - Transboundary European Green Crab work group

USFWS - U.S. Fish and Wildlife Service

UW - University of Washington

WDFW - Washington Department of Fish and Wildlife

WSG - Washington Sea Grant

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BACKGROUND

After the 2012 discovery of European green crab (*Carcinus maenas*, referred to hereafter as green crab) in Vancouver Island's Sooke Basin, the Washington Department of Fish and Wildlife (WDFW) and the Pacific States Marine Fisheries Commission (PSMFC) sought support to reestablish a sustainable, volunteer-based monitoring network with the primary goal being early detection of green crab. In 2014 through the Puget Sound Marine and Nearshore Protection & Restoration Grant Program, U.S. Environmental Protection Agency (EPA) funds were awarded to Washington Sea Grant (WSG), a unit of the University of Washington College of the Environment, to develop and implement a program combining a rigorous green crab monitoring strategy with a broad outreach effort. The resulting program, WSG's Crab Team, was designed to increase the likelihood of finding and controlling green crab before populations establish and threaten Puget Sound shellfish, fish species and habitats.

When Crab Team was created, the program focused on regular volunteer monitoring at fixed sites, on the rapid assessment of green crab populations where detections occur, and on outreach to increase public awareness and reporting. In response to the 2016 discoveries of green crabs in Washington's portion of the Salish Sea, the number of sites monitored nearly doubled in 2017, as did the need for trained volunteers. The need for technical capacity to support response efforts also became apparent, as did the increasingly clear need for additional research to better understand potential source populations. Even more broadly, partners identified and began to address the need for a regional strategy to address the potential presence of green crabs throughout the Salish Sea. With the support of the the Puget Sound Marine and Nearshore Protection & Restoration Grant Program and EPA, WSG's Crab Team was able to work with WDFW and other partners to address these greatly expanded needs, while maintaining the critical core volunteer monitoring program.

The following report provides background on the European green crab and documents Crab Team activities from November 2017 to December 2018.

EUROPEAN GREEN CRAB

Invasion history

A successful global invader, the European green crab has well-documented negative effects on native marine ecosystems worldwide. The green crab's native range includes most of Europe's western and northern shorelines, as well as the northwest coast of Africa (Figure 1). Its native range reflects that the green crab can survive a broad range of water temperatures, from near freezing to 35 degrees Celsius (95 degrees Fahrenheit). The range of salinity in which green crab can survive is similarly broad, from largely fresh estuarine water, 4 parts per thousand (ppt), to full ocean water at 35 ppt and higher (Cohen and Carlton 1995). Such habitat tolerance, in combination with a generalist diet, enables the species to become established in other parts of the world if afforded the opportunity.

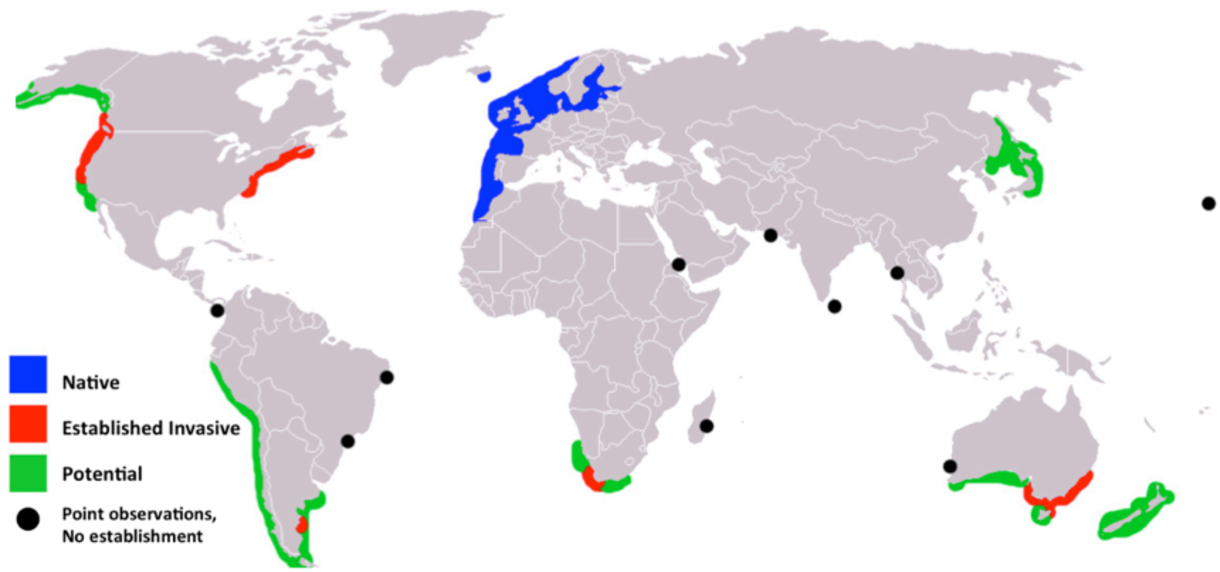

Figure 1. Realized and potential global distribution map of European green crab (*Carcinus maenas*). As of 2018, green crabs are found north to Newfoundland on the Atlantic Coast of North America. Map prepared by Stemonitis (2006), English-language Wikipedia, based on a blank world map and data from Commonwealth Scientific and Industrial Research Organization (CSIRO).

Opportunity came as European ships more frequently traversed the world's oceans, carrying with them goods and ballast that could hide stowaway crabs, whether as juvenile or mature individuals or as planktonic larvae (zoeae). Once it arrived in sufficient numbers to become established in a new habitat, green crabs could then spread locally on currents as zoeae. On the east coast of the United States, the species was introduced at least 200 years ago and has continued to spread regionally, even up to the present day. Green crab also continues to become more abundant in areas where it was previously rare.

Since its introduction to the United States, green crabs have been accidentally introduced across the globe, with great success in some locations and only point observations in others. The establishment and spread of populations on the west coast of North America has occurred as a series of discrete events, beginning with a population in San Francisco Bay — first observed in 1989 — followed by local expansion over the subsequent decade (Figure 2).

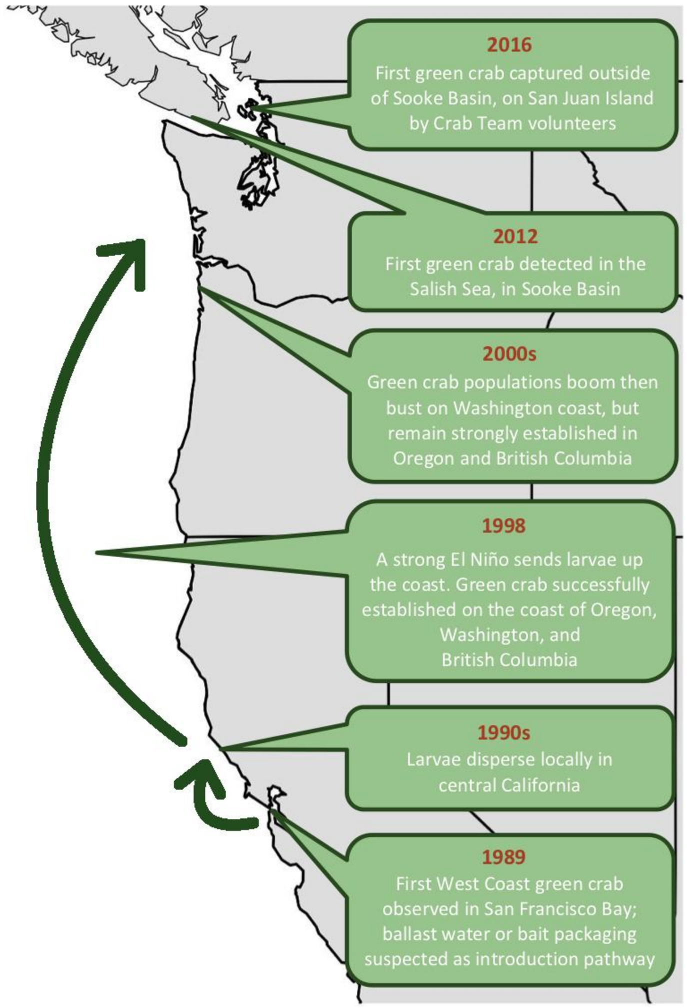

Figure 2. History of U.S. West Coast green crab invasion. Green crab numbers followed a boom and bust pattern on the Washington and Oregon coasts, but remain strongly established on the west coast of Vancouver Island. Oregon's green crabs just barely persisted until 2014. Since then, populations have increased in Oregon and coastal Washington estuaries.

Strong, positive, El Niño-Southern Oscillation (ENSO) conditions favor the survival and nearshore retention of green crab larvae from central California (Behrens Yamada et al. 2015). The ENSO of 1997–1998 provided ideal conditions for larvae to spread from abundant central California populations, north to the outer coasts of Oregon, Washington and British Columbia. While the populations in coastal estuaries of Oregon and Washington remained small, those in the bays and inlets of Vancouver Island have become well established (Gillespie et al. 2007, Behrens Yamada and Gillespie 2008). Between 1998 and 2012, agency, outreach and volunteer early detection efforts in Washington and British Columbia's inland marine waters (the Salish Sea) found no green crabs. The putative explanation for the absence of green crab centers on oceanographic conditions associated with water movement through the Strait of Juan de Fuca that reduce dispersal of larvae into the Salish Sea.

In 2012, however, DFO researchers confirmed an established European green crab population in Sooke Basin on the Strait of Juan de Fuca. These crabs also represented the first population documented in the Salish Sea. Evidence indicates the population in Sooke Basin became established through accidental introduction by human activities and not through natural dispersal (Curtis et al. 2015), suggesting water exchange through the Strait of Juan de Fuca could remain a substantial barrier to large numbers of green crab larvae entering the Salish Sea. However, with a population inside the Strait, the threat of dispersal within the Salish Sea appeared to be a stronger possibility.

With the discovery of the Sooke Basin green crab population in 2012, efforts to reestablish a volunteer-based early detection program focused on conducting targeted, intensive monitoring at prioritized sites, as well as broad outreach. WSG received support to establish Crab Team from the EPA through the Puget Sound Marine and Nearshore Protection & Restoration Grant program at WDFW in late 2014. Serendipitously, the project began just as an ENSO event was building steam, the strongest since the 1997-1998 ENSO that facilitated range expansion of green crab along the U.S. West Coast. Crab Team established a monitoring program focused on increasing the likelihood of detecting European green crab populations within Washington's inland marine waters at the earliest possible stage, to give control efforts the highest probability of reducing further spread. To do so, the approach taken was both targeted and broad, rigorous and opportunistic, and involved both monitoring and outreach.

Green crabs were indeed found in Washington's inland marine waters (Figure 3). In 2016, a green crab was collected by Crab Team volunteers in Westcott Bay and another in Padilla Bay by an informed educator during outreach activities on the beach (Grason et al. 2018). Subsequent, intense trapping found only a molt at Westcott Bay and three additional live green crabs at Padilla Bay. During the 2017 monitoring season, green crabs were found at Lagoon Point, Sequim Bay and Dungeness Spit with two additional green crabs caught at Padilla Bay. Rapid assessments at Lagoon Point and Sequim Bay resulted in few additional captures. However, at Dungeness Spit, numerous green crabs were captured (Figure 4), prompting the implementation of trapping control efforts throughout the summer. In 2018, green crabs were trapped in two new locations, Fidalgo Bay and Port Townsend.

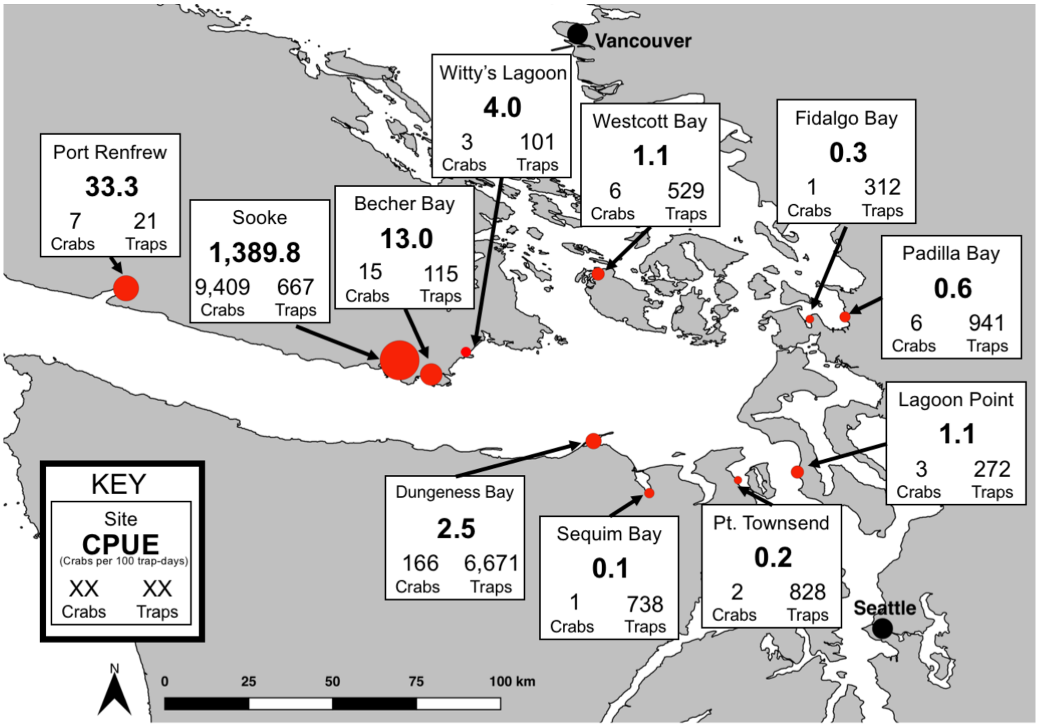

Figure 3. Summary of European green crab captures in the Salish Sea as of December 2018. Catch Per Unit Effort (CPUE) represents number of green crabs captured per 100 trap sets. Previous published work multiplied CPUE by 100 as convention because catches in Washington and Oregon were extremely low.

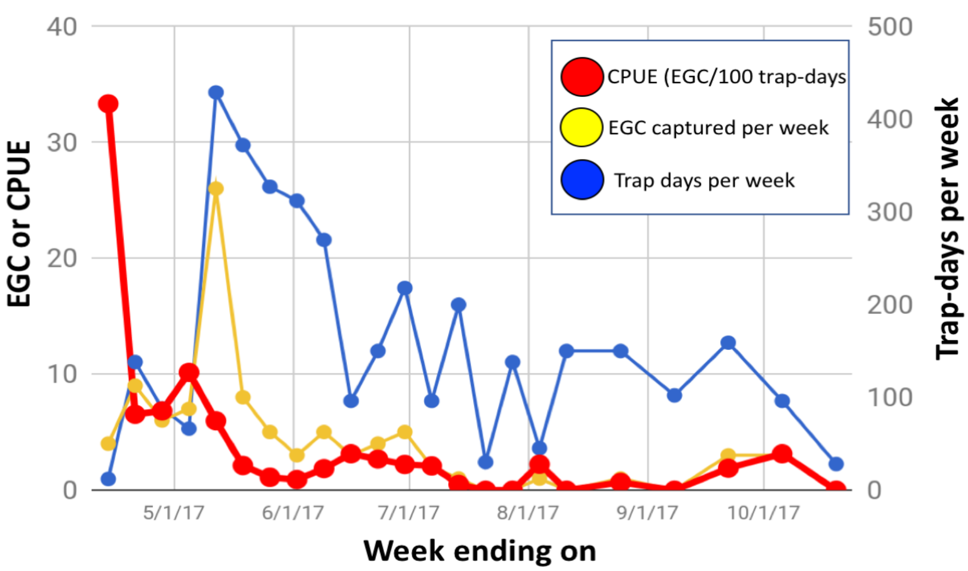

Figure 4. European green crab control trapping catch and effort on the Dungeness National Wildlife Refuge during 2017. Trap-days per week represents the number of traps multiplied by the days deployed that week.

Life history

The green crab's complex life history (Figure 5) has helped facilitate its spread though both human vectors and by natural processes. On the west coast of North America, female green crabs can become reproductively mature during their first year owing to suitable conditions for rapid growth, and can produce 200,000 eggs or more at a time (Cohen and Carlton 1995). When the eggs hatch, the free-swimming zoeae live 17–80 days, depending on water temperature (NIMPIS 2002), and can travel hundreds of miles on ocean currents during that time. During their time in the plankton, they go through four zoeal stages before metamorphosing into specialized megalopae that settle to the seafloor. After 5.5–26 days, the megalopae change into juvenile crabs (Dawirs and Dietrich 1986) that then mature into adults.

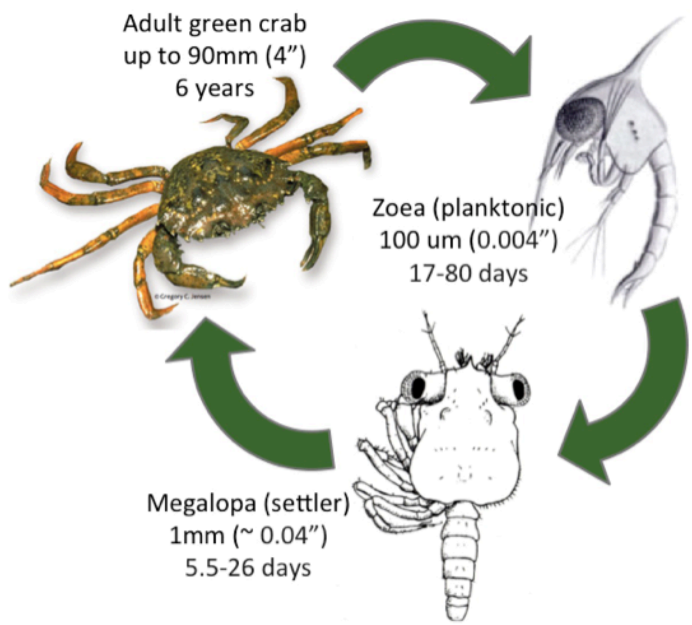

Figure 5. Life cycle of European green crab (*Carcinus maenas*). Adult photo: Greg Jensen; zoea illustration after E. Haeckel; megalopa illustration by Auguste Le Roux via Wikimedia Commons.

Identification

The European green crab is considered a shore crab, living in the intertidal and shallow subtidal. With a maximum carapace width of about 4 inches, green crabs can grow larger than native Puget Sound shore crabs (*Hemigrapsus* spp.) but are smaller than large native cancrid crabs (e.g., red rock, Dungeness and graceful). The carapace is slightly wider than it is long and is distinct from every other Puget Sound crab species in that it has five prominent marginal teeth (points) to the outside of each eye, along the front edge of the carapace (Figure 6). Green crabs also have three rounded lobes between the eyes, a characteristic not unique to them, but possibly helpful in confirming identification. The shape of the abdomen can be used to differentiate males and females (Figure 7). Although commonly referred to as “green” (Figure 8), this species often turns quite red as it ages (Figure 9), and can be found with many different colors and patterns, particularly as juveniles (Figure 10).

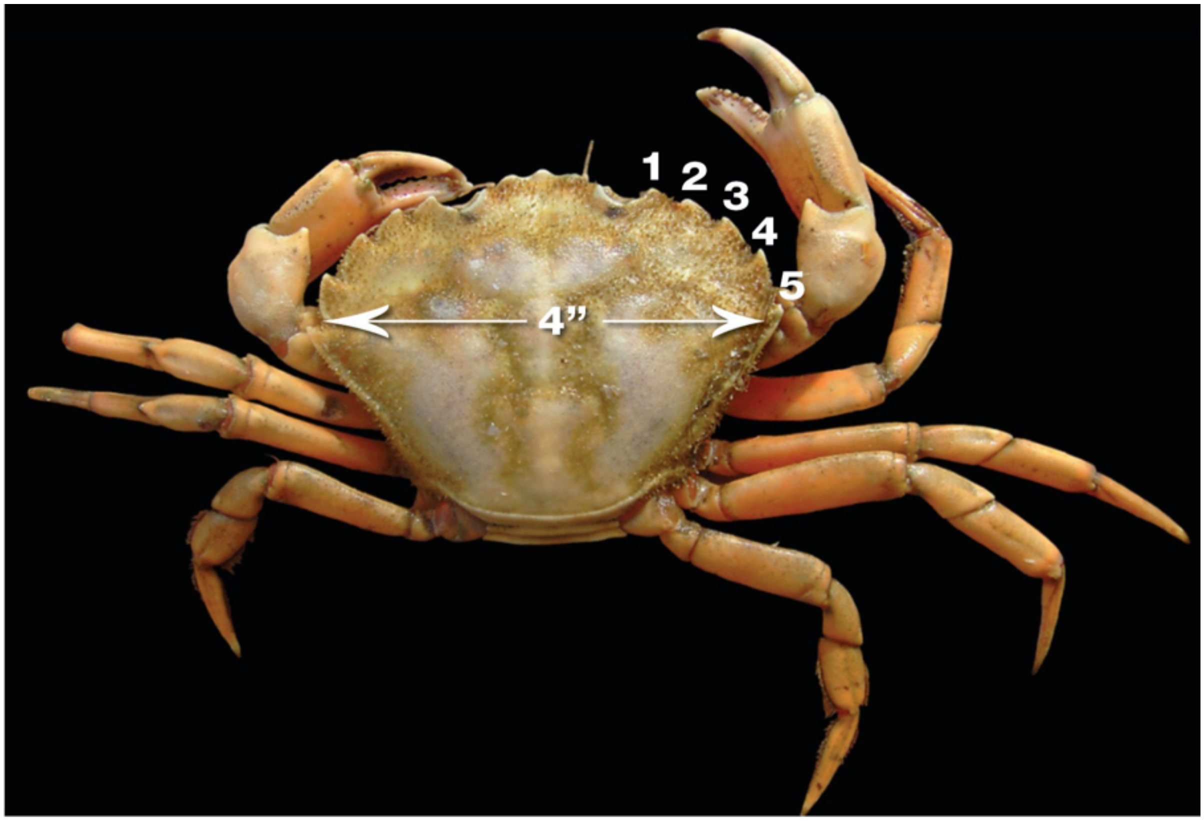

Figure 6. The key identifying feature for European green crab relative to native U.S. West Coast crabs is the five large marginal teeth (or lateral spines) from each eye to the widest edge of the carapace. This feature is apparent whether on a live individual or a molt, as shown here. The maximum size is 4 inches across the carapace. Image modified from Hans Hillewaert ©.

Figure 7. Examples of female (left) and male (right) green crabs. The differences in the sexes are more subtle than in many native Puget Sound crab species, but the male's abdomen is narrower with a slight constriction in the middle (strait or concave). The female abdomen is progressively wider toward the back of the crab and appears slightly convex. Crab Team volunteers receive substantial training on green crab biology and ecology as part of Crab Team educational activities. Photos by Jeff Adams.

Figure 8. Typical European green crab colors and patterns. A key message of Crab Team outreach is that color is highly variable in the species and thus not a reliable characteristic for identification. Photos by Jeff Adams.

Figure 9. European green crab from Willapa Bay, Washington. The predominantly reddish color is common in adults that have passed their terminal molt, reinforcing the need to focus on identifying characters other than color. Photo by P. Sean McDonald.

Figure 10. Color patterns vary widely in juvenile European green crabs to facilitate camouflage. Photos from Stevens et al. (2014).

Potential impacts

The effects of the European green crab on Puget Sound's ecological and economic resources are difficult to foresee and quantify because, like all invasions, impacts will ultimately depend on the abundance of green crabs, local biotic and abiotic factors and historical context. Broadly speaking, one of the best predictors of whether an invasion will have negative impacts on a habitat is whether that species has a history of negative impacts elsewhere. Therefore, evidence of green crab impacts from other regions can provide some indications of what might be expected in Washington's Salish Sea.

During a status, impacts and control session at the 2018 Salish Sea Ecosystem Conference, Brett Howard, a doctoral student at Simon Fraser University, presented a risk assessment of the diverse impacts green crabs could have on Washington's coastal ecosystems, based on the observed impacts of green crab invasions in other regions of the world. Howard defined nine categories of risk: population, biotic community, habitat, ecosystem, parasites, genetics, species at risk, industry, and global range and ranked each on two scales from low to high: "impact" being the potential severity of the changes caused by green crabs in that category, and "certainty" being how confident we are that these changes would take place in Salish Sea ecosystems (Figure 11).

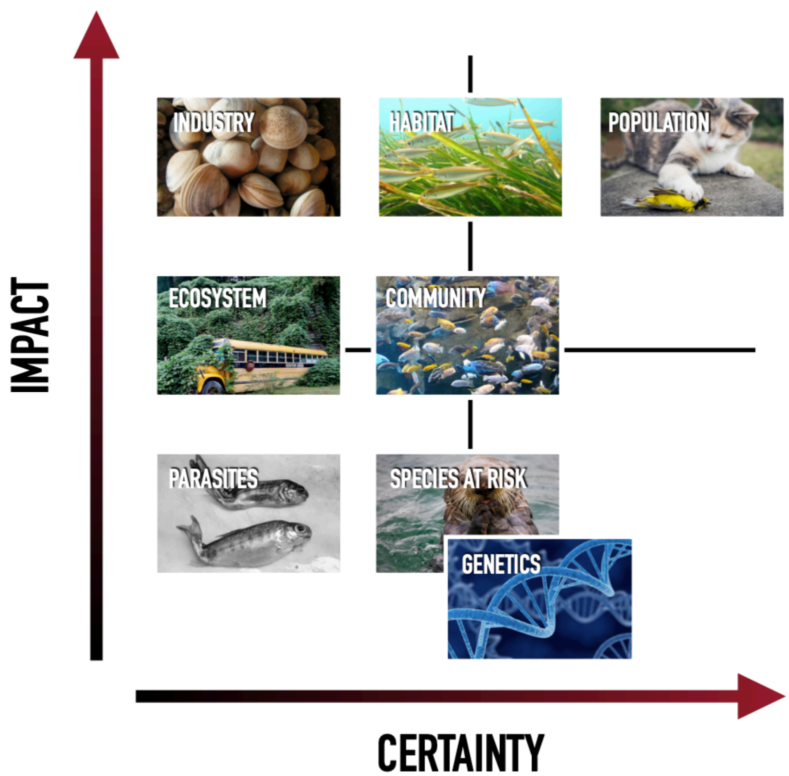

Figure 11. Impact-certainty schematic depicting the nine categories of potential impacts. Figure by Brett Howard, Simon Fraser University.

Evidence from other parts of the world where green crabs are invasive indicates we can be fairly confident green crab would have large impacts on habitat (i.e., physical and biological structure and processes), and populations (i.e., abundance and population structure of other species in our area). Nevertheless, for all categories, baseline data are critical to our potential future ability to detect and quantify impacts of green crab should they ultimately establish populations.

Habitat

By digging and burrowing, green crabs can impact banks in soft-sediment habitats, altering shoreline structure and function. In the eastern United States, green crab presence reduced the biomass of plant roots in high marsh sediments, resulting in lower bank stability (Figure 12, Aman et al. 2016). With reduced habitat value for native organisms, ripple effects could cascade to birds, fishes and even mammals.

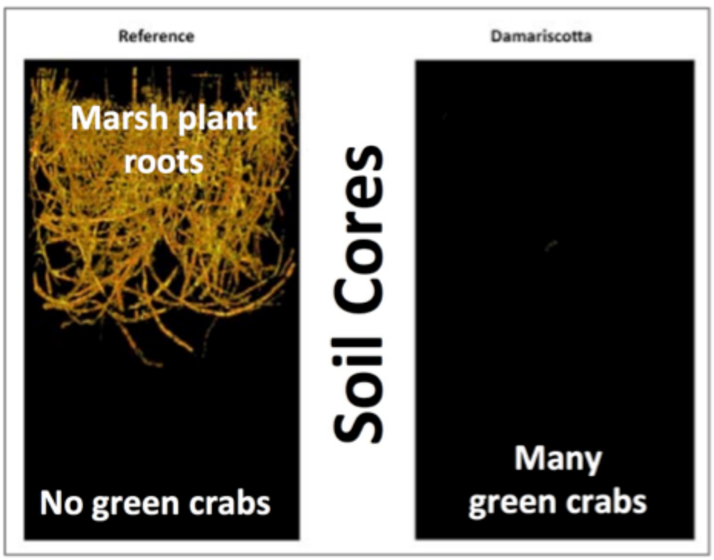

Figure 12. Computed tomography (CT) scans of soil cores, showing the amount of marsh plant root material below ground where green crabs are absent (left) and present (right). Digging and burrowing by green crabs reduces root biomass and decreases bank stability. Figure modified from Aman et al. 2016.

Green crabs can be destructive to eelgrass beds, an important habitat for a wide variety of wildlife and marine organisms. In Puget Sound, eelgrass provides valuable structure, stability and habitat where there would otherwise be relatively bare substrate. It is an important food source, nursery and refuge for birds, fishes, crabs, and many other marine invertebrates and seaweeds. Eelgrass meadows can play an important role in carbon cycling and might even reduce local effects of ocean acidification (Garrard et al. 2014, Hendriks et al. 2014). Eelgrass meadows also improve water quality by filtering sediment and nutrients from the water and help stabilize the sea floor with extensive networks of rhizomes and roots, which can help reduce shoreline erosion.

On eastern shorelines of North America, European green crabs have been implicated in damage to eelgrass (*Zostera marina*) beds and failed efforts to restore eelgrass habitats (Figure 13). Green crabs damage and uproot shoots as they forage for food and even graze directly on the basal meristem of the eelgrass, preventing shoots from growing new leaves (Disney et al. 2014, Malyshev et al. 2011). Green crabs can also destabilize the substrate and cause changes in the sediment, impacting eelgrass success.

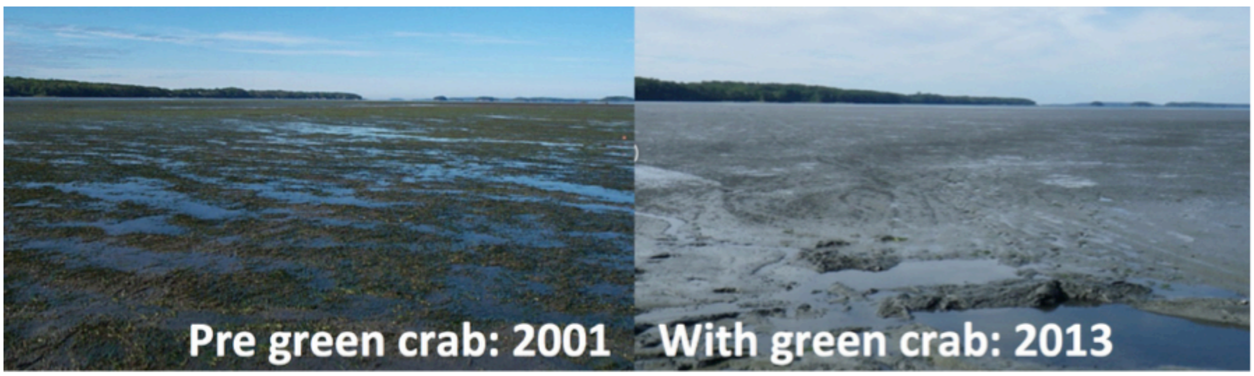

Figure 13. Photos of Maquoit Bay, Maine, before and after dense European green crab populations. Photos by Hillary Neckles USGS.

In Puget Sound, impacts to eelgrass and other habitats could result in such indirect impacts as:

- reduced habitat availability for juvenile salmonids, forage fishes, crabs and other species;
- impaired carbon-storage capacity of Washington tidelands;
- increased wave exposure and change tideland shape and
- reduced available foraging area for shorebirds.

Eelgrass is one of the Puget Sound Vital Sign indicators tracked by the Puget Sound Partnership to measure estuarine health (www.psp.wa.gov/vitalsigns/eelgrass.php). Establishment of dense populations of European green crabs could hinder efforts to achieve the Puget Sound recovery goal to increase eelgrass area by 20 percent by 2020.

Shellfish

European green crabs are considered generalists because of the wide range of food they consume, but bivalves are among their preferred prey. Across the globe, the most frequently cited effect of green crabs is predation on shellfish. On the east coast of the United States, green crab predation on shellfish has been estimated to cost $22.6 million per year (Lovell et al. 2007). In particular, green crabs have been cited as a contributing cause in the decline of the soft shell clam (*Mya arenaria*) industry. In the eastern United States, researchers demonstrated that more soft shell clams survived when green crabs were excluded (Whitlow 2010), while researchers in Australia found similar patterns for another commercially important species, *Katelysia scalarina* (Walton et al. 2002). In Washington, tribes and shellfish growers face potential economic and cultural losses if green crabs are able to establish at high densities. In 2013, Washington shellfish aquaculture production was valued at $92 million, approximately 80 percent of which was from Puget Sound (WSG 2015).

As an aggressive competitor for space, the green crab could displace the juvenile native Dungeness crab, increasing Dungeness crabs' vulnerability to predators. Research on the west coast of the United States indicated that young Dungeness crabs spent less time in protective shell habitat when green crabs were present (Figure 14, McDonald et al. 2001). Like shellfish aquaculture, the commercial Dungeness crab fishery contributes tens of millions of dollars to Washington State's economy every year, with a $61 million value in 2014 (Pacific States Marine Fisheries Commission 2015), approximately 20 percent of which was from Puget Sound (Childers and Cenci 2015). Puget Sound also hosts a very popular recreational crab fishery that harvested only slightly fewer crabs than the Puget Sound commercial fishery between 2011 and 2014. Potential impacts of green crab to Dungeness crab and other crab species have prompted much of the concern related to possible invasion of Puget Sound.

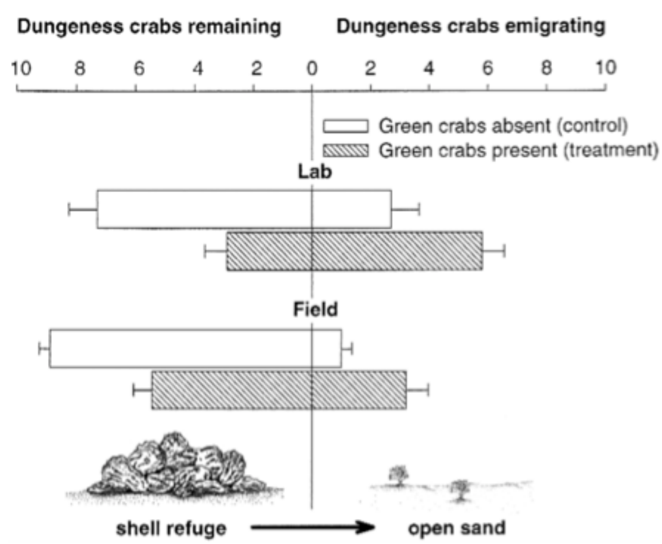

Figure 14. Green crabs outcompete juvenile Dungeness crabs for food and shelter. In the presence of green crabs, Dungeness crabs leave protective shell refuge, which may expose them to increased predation by fish and other predators. Figure from McDonald et al. 2001

Ecological communities and habitat

Green crabs have a broad diet that includes worms, barnacles, snails, bivalves and even vegetation, and the impacts on ecological functions could be equally as broad and difficult to predict. Direct impacts can also ripple through the ecosystem in complex indirect effects. For instance, in San Francisco Bay, selective predation by green crabs on native clams reduced competition for a previously-rare invasive clam, and allowed the invasive clam to become highly abundant (Grosholz 2005). Responses can also change with changes in green crab populations. After 14 years of surveys in central California, green crabs were associated with reduced abundance of native hairy shore crabs, but the hairy shore crab population recovered when the green crab population declined (de Rivera et al. 2011).

METHODS: CRAB TEAM APPROACH

The first step in the development of the Crab Team program was to use existing expertise to identify and prioritize the most suitable locations for green crab establishment. The expectation was that trapping sites where green crabs would have the highest survivorship should offer the most sensitive early detection feasible. Thus, using satellite imagery in Google Maps and Google Earth, Crab Team students and staff systematically assessed Washington's inland marine shorelines for habitat characteristics favorable to green crab success, including the presence of an isolated lagoon or pool, braided or meandering tidal sloughs or channels, impoundments, marsh vegetation, low wave energy and modest to low direct freshwater input. Sites were ranked on these characteristics to identify locations that past research (Grosholz and Ruiz 1996) and experience suggested would be most suitable for European green crab establishment.

The most suitable sites were then ground truthed as time allowed to confirm that the habitat reflected the inferences made from satellite imagery. In some cases, the water was too fresh or the habitat drained completely, making it less suitable for European green crabs than originally thought. A Google map of the highest suitability sites is available at *tinyurl.com/wagreencrab*, and is regularly updated with monitoring site locations and European green crab findings (Figure 15).

Site Selection and Establishment

In addition to habitat suitability, sites were selected based on a number of logistical factors: safe and legal access, volunteer proximity and convenience, geographic spread, and retention of water at low tide to reduce bycatch mortality. As a result of the latter constraint, all sites monitored had elevated sills that retained water at low tide, and were characterized as dominated by salt marsh channel, restricted lagoon or tideflat habitat.

Each site was established by recording detailed location information and general habitat information. A rebar stake tagged with program contact information (Figure 16) was then set into the substrate to ensure consistency in monitoring. This site marker was intended to remain on site as long as the location will be monitored and provided orientation for monitoring activities at the site. GPS coordinates of the site marker were recorded as the official site location.

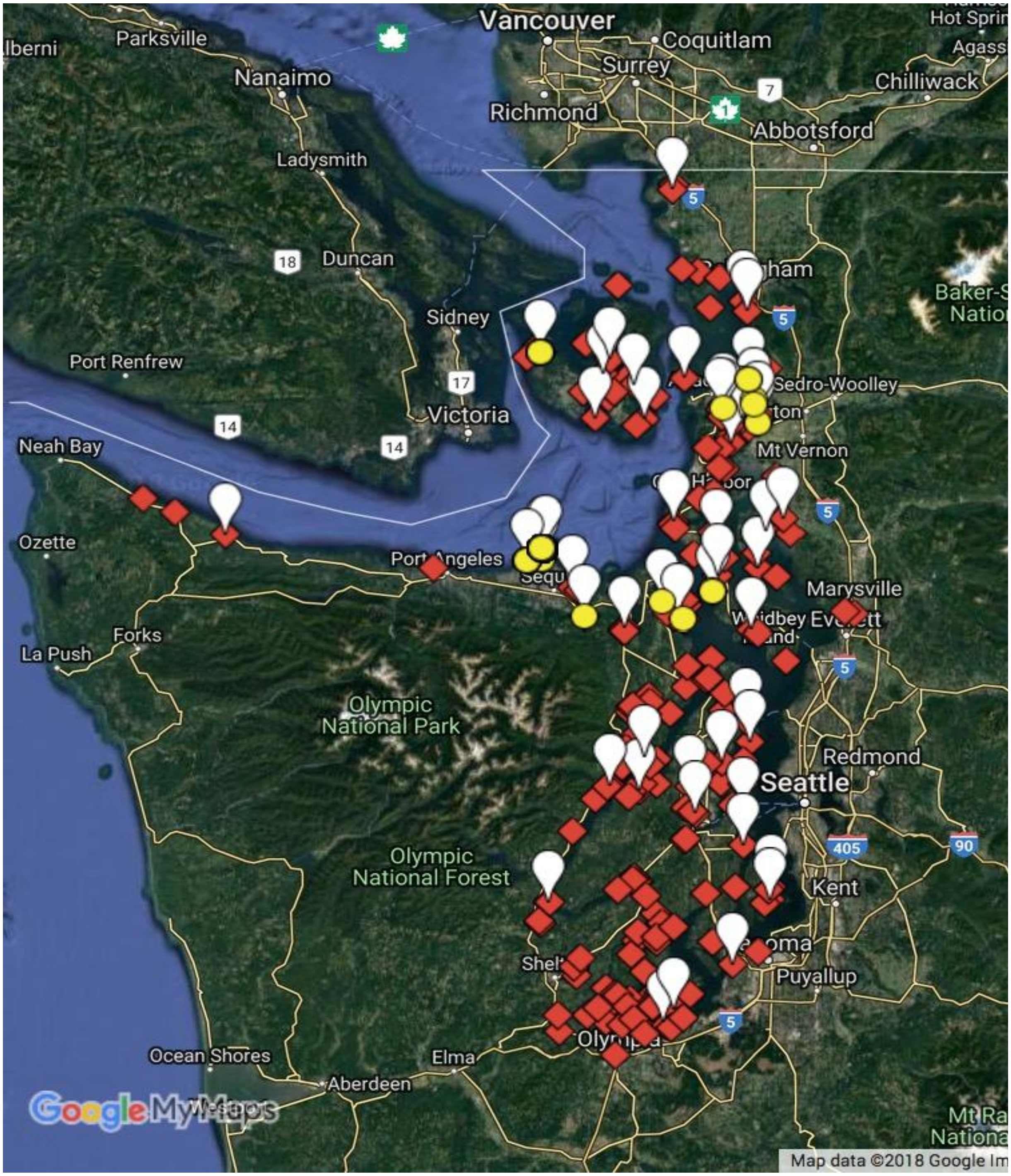

Figure 15. December 1, 2018 screenshot of the Crab Team map with most suitable habitat locations flagged as red diamonds; Crab Team monitoring sites as white bubbles and locations where green crabs have been found as yellow dots. The map also includes a layer of sites previously monitored for green crabs by other entities (e.g. USFWS). Data current as of December 2018.

Figure 16. Example of Crab Team site marker that establishes a start point for the application of Crab Team protocols at a site.

Crab Team Protocol

The Crab Team protocol has three core components: trapping, molt surveys and habitat surveys. Combined, the elements are intended to maximize the likelihood that Crab Team volunteers will find evidence of green crabs if they are present, to improve the understanding of the habitat being monitored and to maintain volunteer engagement. A team of three to five volunteers is assigned to each site with a volunteer captain as the primary point of contact. The team commits to monitor the site once a month (sampling on two consecutive days) from April through September. The Crab Team protocol elements are described in brief below, and the full volunteer manual is available under the Volunteer Toolbox tab of the Crab Team website *wsg.washington.edu/crabteam*.

Trapping

Two types of traps are used in Crab Team monitoring: galvanized steel cylindrical minnow traps and square Fukui fish traps (Figure 17). With a smaller mesh size and smaller openings, the cylindrical minnow traps are used to target young-of-the-year crab. Fukui traps have a larger mesh size and much larger openings to allow adult crabs to be captured. To reduce the risk of larger, or terrestrial organisms getting into the traps, the Fukui openings are narrowed by half by fastening the entrance panels together at the center with a zip tie. During each sampling event, three of each trap type are set on the rising tide, alternating trap type and spacing each trap approximately 10 meters apart at the same tide height (Figure 18). Each trap is baited with approximately 175 grams of frozen mackerel, enclosed in a bait jar, and then staked into the substrate using a 36-inch metal rod, bent at the top, to help hold the trap in place.

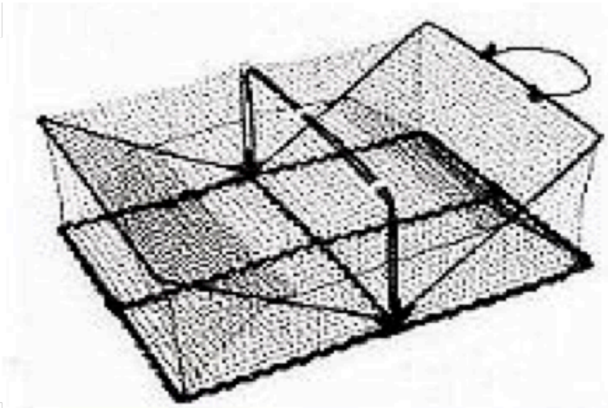

Figure 17. Galvanized steel cylindrical minnow traps (left) and square Fukui fish traps (right) are baited with mackerel and set at Crab Team monitoring sites to target different sizes of European green crabs.

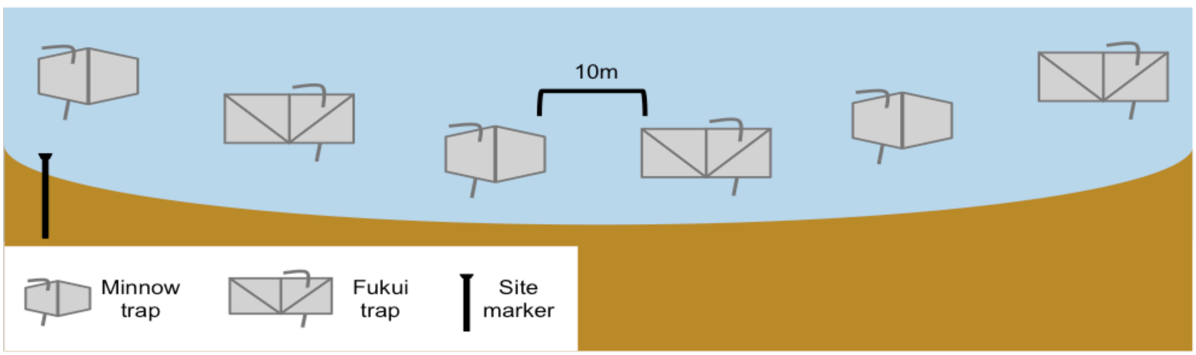

Figure 18. Schematic diagram of arrangement of baited traps in monthly sampling.

After a soak time of typically 20-22 hours, less in some cases, the traps are retrieved and the following actions taken:

- Trap contents are photographed
- Fish are identified, counted and released.
- Crabs (except hermit crabs) are sexed, sized, counted and released.
- Other invertebrates are identified, counted and released.

If a green crab is found, it is immediately reported to Crab Team staff by phone and retained under the project permit in a secure, cool, moist environment until it can be retrieved and by Crab Team staff.

Habitat survey

To better understand the type of habitat available to green crabs and other species at a monitoring site, the composition of the wrack (debris deposited by high tides), shoreline plants and substrate type are recorded along a 50-meter transect, parallel to the shoreline. A 50-meter rope, marked in one-meter intervals, is laid along the shoreline, starting at the site marker and tracing the lower edge of the terrestrial habitat, which is typically riprap or marsh vegetation such as pickleweed (Figure 19). Volunteers place a 0.1-square-meter quadrat at each of 10 randomly assigned distances along the transect and record estimates of percent cover of vegetation, animals and four categories of wrack, as well as substrate type.

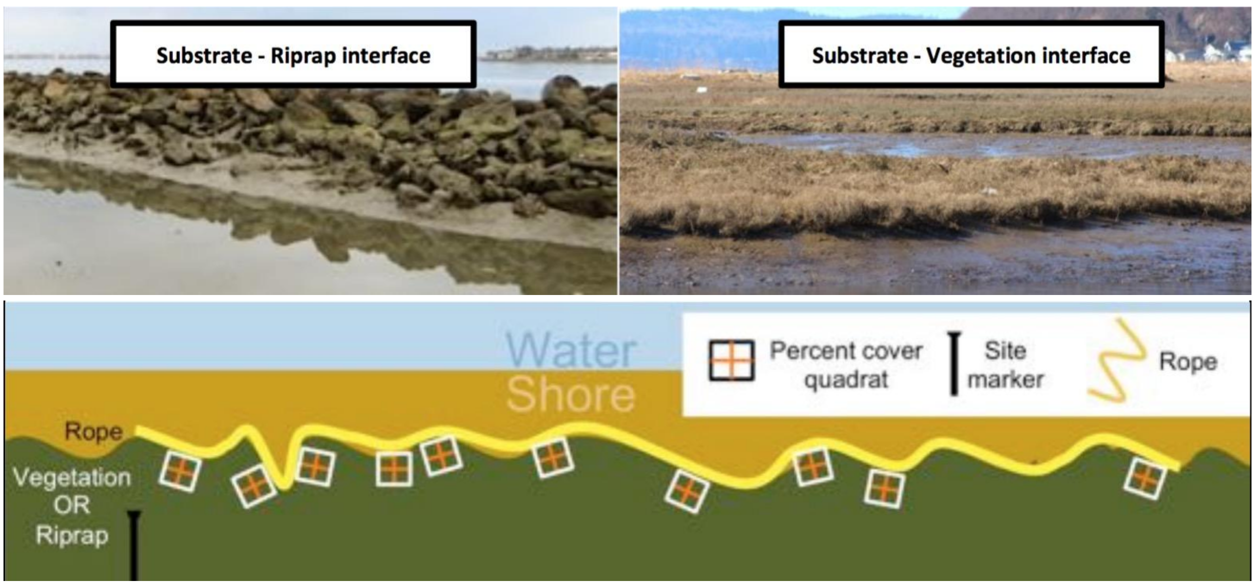

Figure 19. Examples of habitat survey transect line placement at Crab Team monitoring sites, which are typically characterized by riprap (left) or marsh vegetation (right).

Molt survey

All crabs must molt to grow, and the molted exoskeletons are often deposited by the high tide onto the upper beach with seaweed and other beach wrack and debris (Figure 20). In addition to the live trapping, searching for molts provides another modality by which volunteers look for evidence of European green crabs in nearby waters. Indeed, several range expansions of this species have been identified first through molts rather than through capture of live crabs.

Volunteers begin at the established site marker, then have 20 total person minutes (20 minutes for one molt collector, 10 minutes for each of two molt collectors, etc.) to collect as many molts as possible. Volunteers are instructed to target the highest concentrations of molts in the general area but pick up any molts they see. Once the time is up, volunteers identify, count and record the species of all the individual molts collected.

Figure 20. Crab molts, including green crab carapace (top left) in beach wrack. Photo: Jeff Adams

Equipment cleaning and maintenance

To prevent any transfer of biological material and to maintain the integrity of the equipment, volunteers are instructed to rinse, inspect and clean their monitoring equipment and boots as much as possible before leaving the site. Once home, the volunteer in charge of the equipment cleans the traps, bait jars, tubs and quadrat with fresh water, then stores the equipment in a dry location until the next month's monitoring event.

Volunteer Training

At the heart of Crab Team's success and impact is the dedicated cadre of trained volunteer and institutional partners who monitor sites throughout the Puget Sound. Recruiting, training and supporting those volunteers is Crab Team's first priority. Crab Team volunteers expand the geographic and temporal scope of monitoring and data collection far beyond what would be possible using professionals on the same budget. To ensure the quality and reliability of the volunteer-collected data and to increase the general level of knowledge about green crabs among people who are likely to frequent Puget Sound shorelines, Crab Team offers training workshops in March of each year.

The corps of Crab Team volunteers expanded dramatically during the first two full years of the program (2016-2017) as the network of monitoring sites grew substantially. During that period, Crab Team developed and refined a training workshop for new volunteers with no prior experience. Crab Team hosted several full-day classroom workshops in March of each of those years, at geographically distributed sites around the Puget Sound. In 2018, the number of regularly monitored sites was not expected to increase significantly and the majority of Crab Team volunteers returned to monitor from previous years. Crab Team therefore adopted a new strategy for training: 1) target a more limited number of new volunteer trainings to geographies where new team members are most needed and 2) provide original content that enhances training and opportunities for feedback to returning volunteers. The 2018 training was also preceded by a webinar update for returning volunteers and partners in which Crab Team staff shared updated information on findings from the previous year and on plans for the year ahead. The webinar is also available online (*https://youtu.be/RFXKwCNiL0I*).

Crab Team staff also developed several distance learning resources to serve as a primer or refresher for new or returning volunteers. These resources are available on the Crab Team volunteer toolbox webpage (http:/*/wsg.washington.edu/crabteam/getinvolved/toolbox/*) under the section titled Learning Resources. These were created in response to feedback from volunteers on the need for support in organism identification as well as to provide tools to refresh familiarity with protocol details:

- Video series on protocol components, with questions to assess understanding,
- Practice decks of "tricky ID" flashcards, designed based on the Cornell Lab of Ornithology's Snap ID tool, (*https://academy.allaboutbirds.org/product/feeder-birds-identification-and-behavior/*)
- Crowdsourced list of tips and tricks provided by volunteers based on their experience in the field, with the goal of increasing the enjoyment, efficiency and accuracy of Crab Team sampling.

Training for New Volunteers

The day-long volunteer training workshops for new participants provide background on green crab, introduction to Crab Team protocols and time for protocol demonstration and practice. Workshop topics included:

- Crab Team staff, background and partners
- What makes the European green crab invasive
- What is threatened by a green crab invasion
- What is being done about the threat
- Step-by-step protocols in the classroom
- Hands-on protocol practice at a simulated Crab Team site
- Identification training on mobile pocket estuary fauna
- Discussion of team selection, map and possible monitoring sites

In 2018, three training events for new volunteers were held in March, to prepare for the April start of the sampling season (Table 1). Workshops were primarily advertised through existing networks of marine and watershed stewardship volunteers throughout Puget Sound. A few participants at each workshop had attended the training in previous years but were repeating the new volunteer class just to reinforce the concepts and have more time interacting with Crab Team Staff and volunteer colleagues. In total, 62 new participants took part in Crab Team trainings in 2018.

Enhanced volunteer training

All returning volunteers were invited to attend an enhanced training workshop, and Crab Team offered four at regionally distributed locations (Table 1). Though the enhanced training was not designed for new volunteers, accommodations were also made in the enhanced training for a small number of individuals who otherwise would not have been able to attend a workshop. The goal of these workshops was to refresh returning volunteers on Crab Team protocols after the winter break, clarify and reinforce some protocol elements and provide opportunities for volunteer interaction and group learning, as well as feedback. Training components included:

- What's new from Crab Team: news and a review of all pocket estuary data from 2017
- Protocol review and refinement
- Enhanced crab identification
- What's been your experience? (opportunity for feedback on natural history observations, tips and tricks and other thoughts)
- Bait and equipment distribution

A total of 109 Crab Team members returned for training workshops in 2018. Crab Team staff required that at least one member from each team attend the workshops, though all were welcome and more than half of the returning volunteers took part.

Lastly, training does not stop with the classroom. Crab Team staff visit as many sites as possible during the sampling season, and in particular will visit new sites or new teams at the beginning of the season. This one-on-one attention is a critical component of preparing volunteers to sample independently and for maintaining strong relationships between volunteers and staff. In 2018, Crab Team launched two new monitoring sites—Jimmycomelately Creek in Sequim Bay and Hancock Lake near Admiralty Inlet—by visiting them with returning volunteers. Staff completed 26 additional site visits to ongoing sites (for a total of 28) working side-by-side with volunteers to reinforce protocol details and answer site-specific questions.

Table 1. New and returning volunteer participation in 2018 Crab Team trainings. Bold text indicates training workshops primarily aimed at new volunteers. For trainees new to Crab Team, the number in parentheses denotes how many joined a Crab Team monitoring site. The number of trainees involved in Poulsbo and Port Townsend trainings also include volunteers who are involved in green crab removal efforts at Dungeness National Wildlife Refuge.

Location	Date	New (Joined)	Returning	Total
Poulsbo	3/12/18	24 (19)	4	28
Padilla Bay	3/13/18	22 (18)	-	22
Port Orchard	3/16/18	-	19	19
Padilla Bay	3/19/18	-	44	44
Friday Harbor	3/23/18	4 (4)	10	14
Port Townsend	3/26/18	2	32	34
Seattle	3/28/18	10 (10*)	-	10
	Total	62	109	171

*At the Seattle training, six new participants from WA DNR's Puget Sound Corps program attended. The Corps volunteers work in the Aquatic Reserves program to monitor two Crab Team sites, and a new group is trained annually for this work, a relationship Crab Team looks forward to continuing.

Temperature loggers

Based on the first two years of monitoring data and feedback from volunteers, Crab Team began to consider gathering additional environmental data at regularly monitored sites. Temperature is a logistically tractable parameter to measure, with reasonably low cost and time investment relative to the quality and value of data that can be obtained. In 2018, iButton temperature loggers (DS 1921 by Thermochron) were placed at approximately half (26) of Crab Team's sites (Figure 21). Prior to deployment, all iButtons were logged by serial number, and their real time temperature readings were validated with a NIST-traceable thermometer to assure they were accurate within 1.0 degree Celsius. The loggers were, with a few exceptions, placed on site prior to April 1 and retrieved after September 30, and programmed to capture observations at even intervals during this period. Based on the data capacity of this model of iButton, we were able to observe temperature every 128 minutes. Loggers were sealed in waterproof capsules designed for iButtons (DS9107 by Dallas - Maxim), which were in turn inserted into 1.5-inch diameter PVC pipe such that seawater could surround the capsule on both ends. The PVC tube provided a way to attach, via plastic zip ties, the logger to a stable, removable structure at the site—either a small cinder block or longer section of PVC inserted in the mud, as was most likely to be stable at a given site. The set up was labeled with the WSG

Crab Team research tag and deployed adjacent to the rebar site marker, and placed so the logger would remain submerged for the entire sampling period, capturing only water temperature.

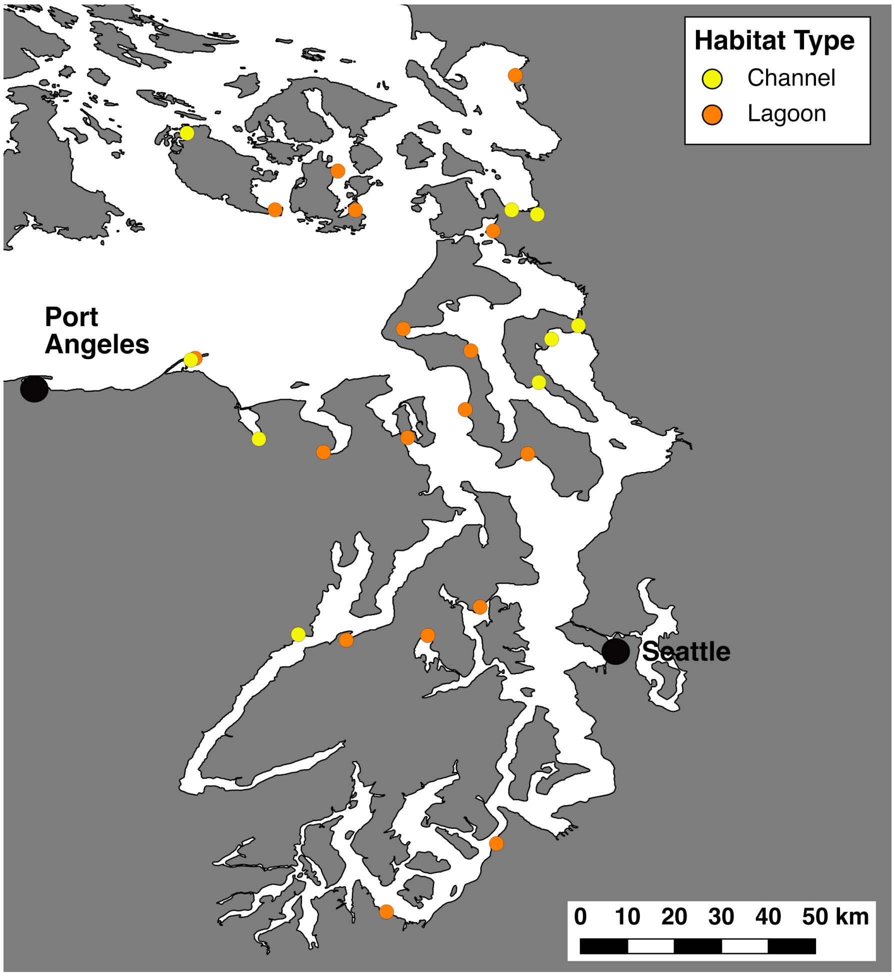

Figure 21. The 26 Crab Team sites at which temperature loggers were deployed in 2018, where point color denotes habitat type of the site.

Quality Assurance

Because the changes in protocol were minimal from the quality assurance (QA) plan used during the initiation of the Crab Team, the same QA measures that were already in place have been used to ensure the value and utility of Crab Team data. Training is required of all volunteers and site visits are conducted by Crab Team staff to reduce the likelihood of errors in collection. At least one returning volunteer from each existing monitoring site was required to attend a new or returning volunteer training. Additionally, by teaming volunteers together, having multiple trained participants increases the likelihood that any mistakes will be caught by another team member. Continuing education, including newsletters, emails and online resources, also help keep volunteers current and reinforce proper protocols.

Photo documentation is key to quality checks of recorded data. Crab Team staff review data sheets and relate them to trap photo documentation with questions in mind:

- Do the datasheets and photos match?
- Do the recorded data generally make sense?
- Are the data sheets legible and are there any questions of interpretation?

In addition to images of trap catches, volunteers will photograph unknown or questionable specimens or situations they have and send those with the data sheets for confirmation and feedback to Crab Team staff. Also, if a green crab is suspected, volunteers contact Crab Team staff immediately via cell phone with photos for confirmation so the crab can be retained and dealt with properly.

For the use of temperature loggers, Crab Team followed the guidance of Ecology's Standard Operating Procedure (SOP) for continuous temperature monitoring (Ward 2011) with only minor modifications.

Volunteer monitoring data management

Crab Team data is currently entered and managed in spreadsheets, while WSG Communications and project staff are completing a Crab Team database in MySQL. Hard copies of volunteer information and monitoring data documents are retained at WSG as part of the data record. The Pacific States Marine Fisheries Commission is currently developing a database to house green crab data from the entire West Coast. Crab Team is providing input into the design of the database, and will contribute the relevant information when it is complete. All georeferenced data on captures of European green crab are available for download on the Crab Team site map (*www.tinyurl.com/wagreencrab*).

Larval source modeling background and approach

As critical as it is to have an early detection system in place and to try to remove green crabs when found, it is also important for effective management to understand where the green crabs are coming from and how they could arrive in the Salish Sea. Gathering evidence on these questions was the topic of two research projects coordinated by Crab Team during winter 2018. The projects used two very different modes of investigation—larval transport modeling and genomics—to ascertain which known populations of European green crab were most likely contributing larvae into the Salish Sea. The larval transport modeling effort was supported as a component of this grant and is detailed below and in the results section of this report.

The goal of the larval transport modeling was to investigate the spatial and temporal patterns of the dispersal of simulated larvae in a computer model of past ocean conditions. Given known potential source populations, we sought to evaluate support for each of those sites as the origin of the individual green crab captured in the Salish Sea during 2016 and 2017. The Transboundary European Green Crab working group (TEGC) met with, provided feedback to and learned from Elizabeth Brasseale, UW oceanography doctoral student and modeler, during project development and after the modeling work was completed. Approaches and outputs were also iteratively reviewed by TEGC members throughout the development and implementation of the model to ensure the resulting information was as biologically realistic and meaningful as possible. The results of this work are currently under revision with *Estuaries and Coasts* (Brasseale et al. 2019).

Ocean conditions and weather from 2014 to 2016 were simulated using the LiveOcean Model (*https://faculty.washington.edu/pmacc/LO/LiveOcean.html*), a realistic ocean model developed by Parker MacCready, UW Oceanography, and colleagues. Larvae were simulated within this ocean model as "particles" released at four selected locations, timed based on published observations of larvae in the water column at or near each location. Each larva also was programmed to exhibit depth changes consistent with regional observations for this species.

We selected four known locations of green crab populations in the region that could serve as a source for advection into the Salish Sea: Coos Bay, Willapa Bay, Barkley Sound and Sooke Inlet (Figure 22). Release dates differed depending on the site, based on observations of seasonal peaks in abundance of first stage zoeae in the water column. For Coos Bay (Shanks et al. 2011), green crab larvae show a late winter and smaller late summer peak, so release dates were set for January, February, March, April and August. However, at the more northern sites, larvae are not apparently abundant in winter, and release dates were simulated during April, May, July and August. The date of release was the same for each month for all four sites, and was selected during the biggest magnitude of swing (ebb) tide, i.e., highest-high, to lowest-low for that month. Though green crabs can release larvae over successive days, release on a nighttime ebb is the most common time, and we selected the most extreme ebb tide because it should maximize the dispersal distance from the release site.

Each release simulated 10,000 particles from a single location and tracked the simulated larvae for 75 days. Temperature has a strong influence on the developmental rate of larvae (de Rivera et al. 2007), but the precise relationship between temperature and development is not sufficiently well characterized to be incorporated into the model. However, we established a wide "competency window" for larvae that ranges from the fastest possible development to the megalopal stage, when settlement could occur, under warm conditions (30 days), to the longest duration we would expect a zoea could survive without being able to metamorphose based on cool temperatures (75 days).

We evaluated the “success” of a cohort of larvae at reaching the central Salish Sea (beyond Port Angeles, WA), as the proportion of that cohort that spent any time in the eastern Salish Sea during the competency window (30-75 days). Thus we parameterized the simulations with observational data, where it exists, and in cases where there were no published data, we selected parameters that would favor success of larvae at invading, so as to establish a “worst case scenario” for larval incursion into the Salish Sea. Results are best interpreted as relative probabilities (i.e. which site is a more likely source) rather than absolute probabilities (i.e., what is the chance that a larva from Sooke Basin could end up at XY location).

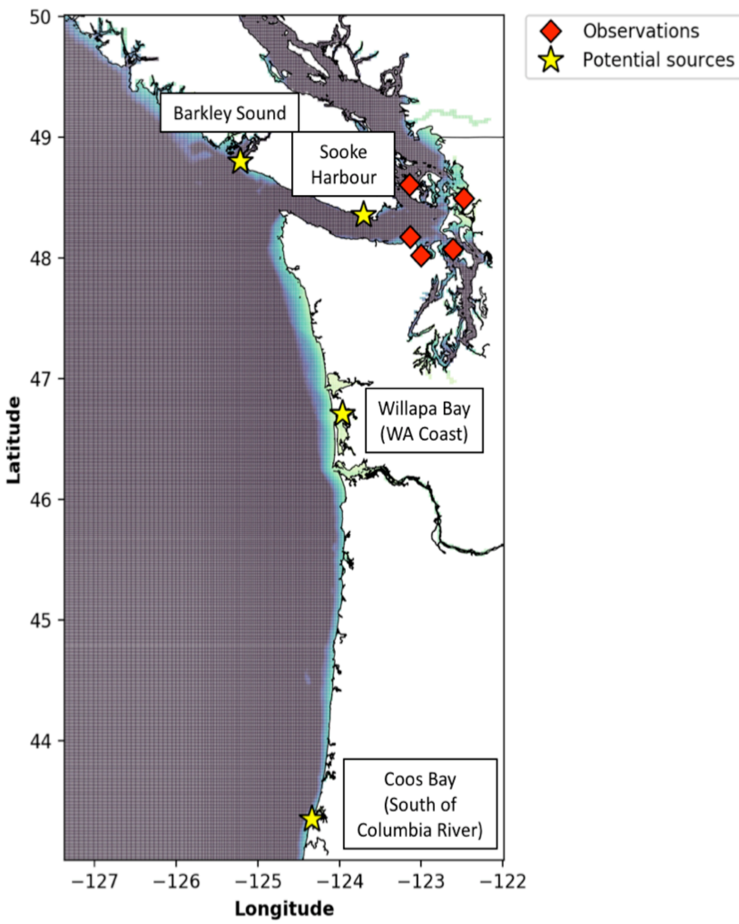

Figure 22. Map of simulated larval release locations (yellow stars). The map represents the geographic extent of the ocean model used in the experiments. Red diamonds indicate green crab detections within the Salish Sea as of 2017. (Reproduced from Brasseale et al. *2019*).

RESULTS: MONITORING DATA SUMMARY

(meets requirements of *Deliverable 2.2: 2018 Monitoring data summary*)

Crab Team Monitoring Summary

After the monitoring season ends in late September, Crab Team staff finalize data entry and quality assurance, then perform a preliminary analysis and develop and distribute a one-page infographic (Figure 23) to volunteers, stakeholders and other interested groups to communicate the year's results. This relatively coarse analysis focuses on the three most accessible areas of data: level of effort, species- and site-specific data and green crab captures. In 2018, temperature observations were also gathered at half the Crab Team sites, and a description and summary of the resulting data are provided below.

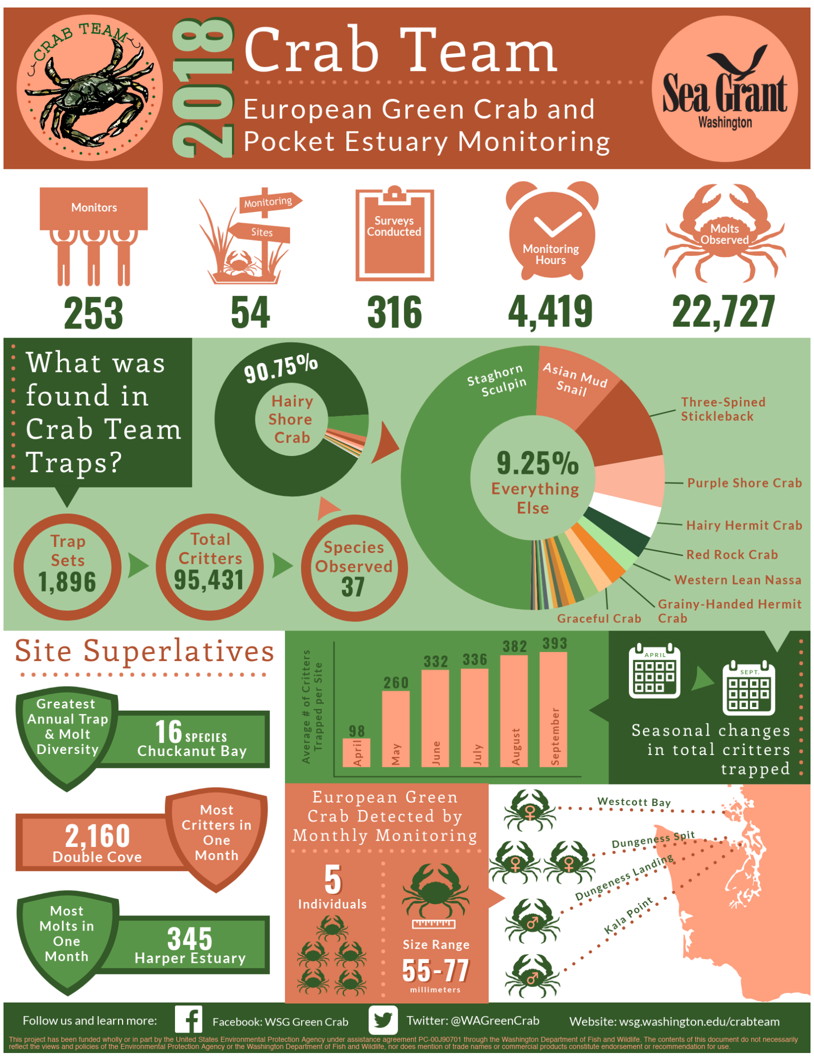

Figure 23. Crab Team's 2018 monitoring summary infographic

Effort

The Crab Team network now consists of 54 sites, which have been monitored between five and 20 times since the program began (Figure 24). Critical to the success of a community science program of this scale are the volunteers and partners who contribute time and resources to collect data. In 2018, 253 individuals participated in monthly monitoring at the 54 Crab Team sites, contributing nearly 4,500 hours.

- **253** Total Individual Monitors at Crab Team Sites
  - **204** Volunteers
  - **2** Crab Team Staff
  - **9** Partner Volunteers
  - **40** Partner Staff
- **4,419** Total Monitoring Hours (does not include Crab Team staff site training visits)
  - **3,576** Volunteer Hours (valued at **$111,145.49** according to independentsector.org annual valuation of volunteer time)
  - **66.5** Crab Team Staff Hours (regular site monitoring)
  - **72.9** Partner Volunteers Hours
  - **703** Partner Staff Hours

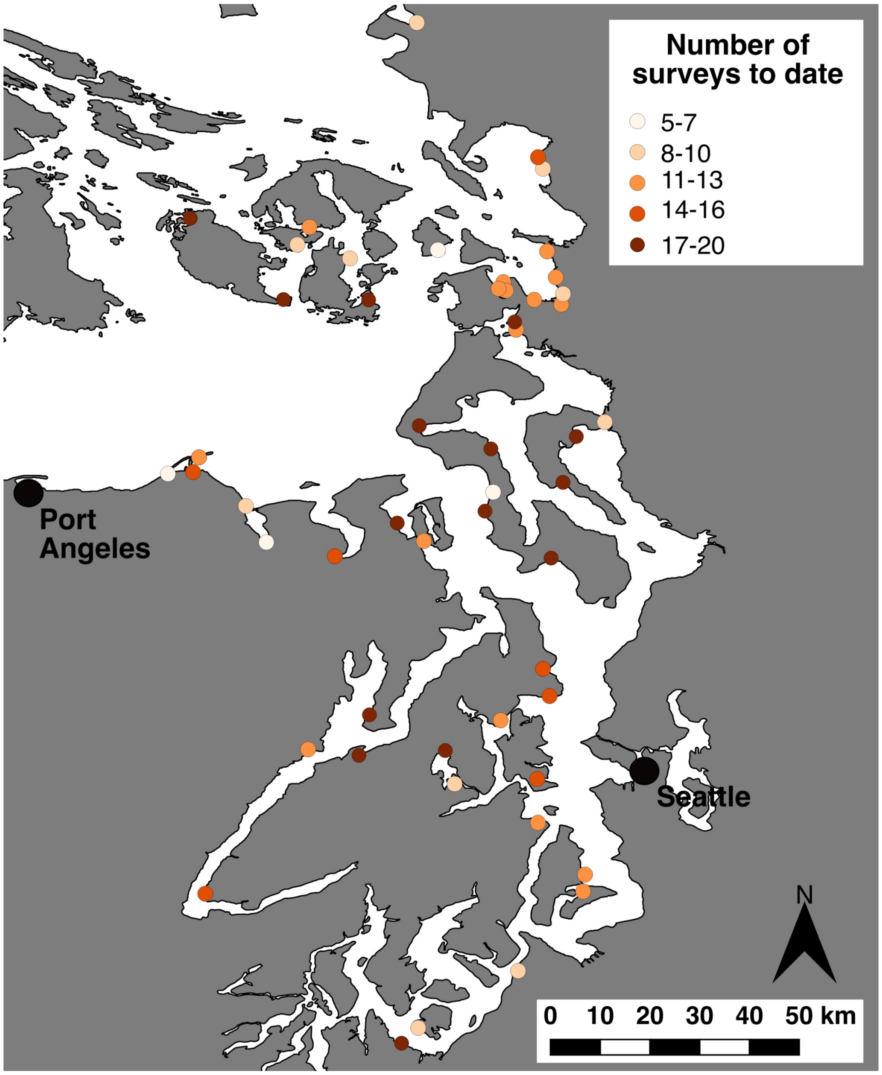

Figure 24. Crab Team regular monitoring sites as of 2018, color coded for the total number of surveys conducted since the Crab Team pilot year in 2015. A typical sampling year includes six monthly monitoring events, but on occasion, due to logistics, fewer sampling efforts are undertaken each year

Since Crab Team started in 2015, volunteers and partners have observed and identified nearly a quarter of a million individual animals that were collected during the approximately 100,000 hours that traps were fishing (Table 2). Thousands of molts have also been collected and identified and hundreds of meters of pocket estuary shoreline assessed. The scope of the network, combined with the rigorously validated data, is contributing to the development of a long term pocket estuary monitoring data set, the value of which will increase greatly over time.

Table 2. Crab Team trapping effort summary for 2015 to 2018. Monitoring trap soak hours for 2018 were not available at the time of this report and are estimated based on the ratio of 2017 monitoring trap hours per trap set.

	Number of sites monitored	**Trap sets**	**Monitoring trap soak hours**	**Total number organisms recorded**	**Total number of taxa trapped**
2015	7	84	2,230	7,902	9
2016	26	828	18,696	44,216	25
2017	52	1,698	37,359	76,298	31
2018	54	1,896	41,715 (est.)	95,431	37
To Date	**57**	**4,506**	**100,000 (est.)**	**223,847**	**37**

Site- and Species-Specific Data

Trap data

From trapping protocol data, Crab Team can learn about the mobile fauna that live in pocket estuaries. Though the organisms observed in Crab Team traps are generally limited to those that are attracted to bait, the consistency with which the protocols are implemented over space and time permit inference about patterns of abundance and diversity in this subset of the ecological community.

Across the entire Crab Team network, and consistent with previous monitoring seasons, trap catches were dominated by a single native crab species, the hairy shore crab (*Hemigrapsus oregonensis*), which made up more than 90 percent of the total trap catch in 2018 (Table 3). A number of rarities were also observed this year, bringing the total number of species that have been captured in Crab Team traps to 37.

Table 3. Total species captured in Crab Team trapping across all sites in 2018.

Common Name	**Species Name**	**Crab Team species code**	**Annual total**	**Average per survey**
Hairy shore crab	*Hemigrapsus oregonensis*	HEOR	86,606	274.07
Pacific staghorn sculpin	*Leptocottus armatus*	LEAR	4,469	14.14
Asian mudsnail	*Batillaria attramentaria*	BAAT	961	3.04
Three spined stickleback	*Gasterosteus aculeatus*	GAAC	930	2.94
Purple shore crab	*Hemigrapsus nudus*	HENU	568	1.80
Hairy hermit crab	*Pagurus hirsutiusculus*	PAHI	347	1.10
Red rock crab	*Cancer productus*	CAPR	243	0.77
Western lean nassa	*Nassarius mendica*	NAME	194	0.61
Grainy handed hermit crab	*Pagurus granosimanus*	PAGR	191	0.60
Graceful crab	*Cancer (Metacarcinus) gracilis*	MEGR	181	0.57
Eel-like fishes	Various pricklebacks and gunnels	ELFS	177	0.56
Sand shrimps	Crangonidae spp.	SAND	91	0.29
Dungeness crab	*Cancer (Metacarcinus) magister*	MEMA	76	0.24
Brokenback shrimps	Pandalidae and Hyppolytidae	BROK	60	0.19
Japanese nassa	*Nassarius fraterculus*	NAFR	59	0.19
Prickly sculpin	*Cottus asper*	COAS	51	0.16
Shiner perch	*Cymatogaster aggregata*	CYAG	43	0.14
Nassa species	*Nassarius spp.*	NASS	41	0.13
Tidepool sculpin	*Oligocottus maculosus*	OLMA	26	0.08
Skeleton shrimps	Caprellidae	SKEL	22	0.07
Hairy helmet crab	*Telmessus cheiragonus*	TECH	18	0.06
Sand dollar	*Dendraster excentricus*	DEEX	14	0.04
Flatfishes (exc. starry flounder)	Various flatfishes	FLAT	13	0.04
Spider crabs	Majidae	SPID	11	0.03
Bubble shell	*Haminoea spp.*	BUBB	7	0.02

Common Name	Species Name	Crab Team species code	Annual total	Average per survey
Bay pipefish	*Syngnathus leptorhynchus*	SYLE	7	0.02
European green crab	*Carcinus maenas*	CAMA	5	0.02
Carinate dove snail	*Alia carinata*	ALCA	4	0.01
Starry founder	*Platichthys stellatus*	PLST	4	0.01
Pygmy rock crab	*Glebocarcinus oregonensis*	GLOR	2	0.01
Black-clawed crab	*Lophopanopeus bellus*	LOBE	2	0.01
Hooded nudibranch	*Melibe leonina*	MELE	2	0.01
Plainfin midshipmen	*Porichthys notatus*	PONO	2	0.01
Amphissa snail	*Amphisssa columbiana*	AMCO	1	<0.01
Gobies	Multiple from Gobiidae	GOBY	1	<0.01
Opalescent nudibranch	*Hermissenda crassicornis*	HECR	1	<0.01
Whitespotted greenling	*Hexagrammos stelleri*	HEST	1	<0.01

Crab Team captures an increasing number of organisms per survey as the season progresses (Figure 25), with the average number of organisms captured across all six traps peaking at nearly 400 per survey in August. The low catch numbers early in the season suggest that the Crab Team sampling season captures the front end of the effective period for trapping mobile organisms in the targeted habitats. Trap catches late in the season remain high, but tides and daylight make sampling beyond September unsuitable for Crab Team monitoring protocols.

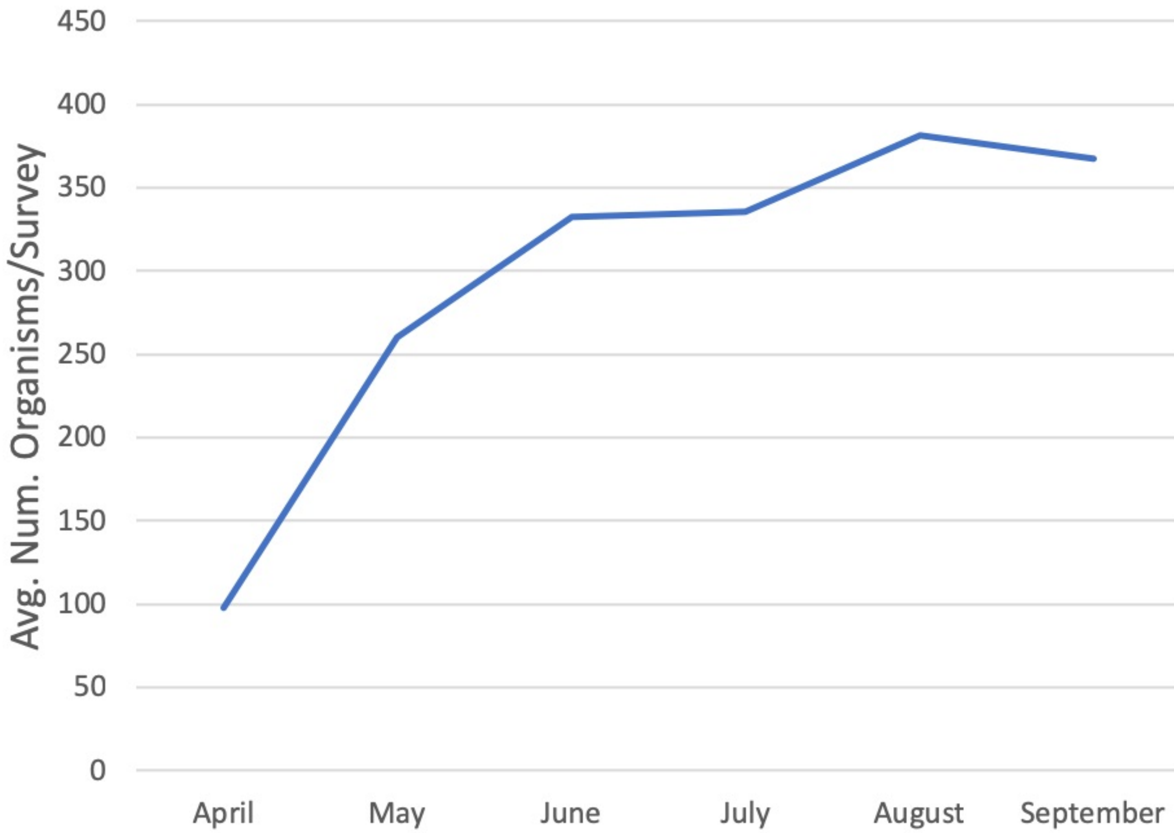

Figure 25. Average number of organisms trapped per site, of all species, across the Crab Team network for each month of sampling in 2018.

Molt data

In 2018, no green crab molts were found during regular sampling. One Crab Team member (who was part of the Washington Department of Natural Resources Puget Sound Corps) found one green crab molt near Crab Team monitoring sites in Fidalgo Bay, separate from the regular site monitoring. The find prompted a rapid assessment that yielded no additional green crabs. The molt was further evidence that the Padilla Bay area was broadly exposed to green crab larvae in recent years.

Although no green crabs were discovered through regular monthly molt collections, nearly 23,000 molts from 13 crustacean taxa were gathered, identified and recorded (Table 4). As in the baited traps, an order of magnitude more hairy shore crabs were found than any other crustacean. The next most common was the purple shore crab, which was, in turn, an order of magnitude more abundant than the four large crab species (Dungeness, hairy helmet, graceful, and red rock crabs). Other crustaceans accounted for a very small proportion of the overall sample.

Due to time constraints between the end of the sampling season and the due date of this report, further analysis of molt data is not currently available. At a glance, the taxa and average numbers of individuals gathered from the three different dominant habitat types monitored by Crab Team appear to reflect similar taxa richness and relative abundance between channel and lagoon habitats but differs in tideflat habitats, in which molts of larger crab species are more abundant (Table 4). Crab Team staff intend to explore such patterns as well as seasonal variations and differences within and among species and habitat types.

Table 4. Crustacean molts collected by taxon and habitat type during 2018 Crab Team monitoring, including average number of individuals per site for each of the three habitat types, and total numbers of molts for each species across all 54 sites.

Taxon	**Channel (average # per site)**	**Lagoon (average # per site)**	**Tideflat (average # per site)**	**Total (# across all 54 sites)**
Hemigrapsus oregonensis	398	371	307	19,464
Hemigrapsus nudus	44	58	16	2,186
Cancer (Metacarcinus) magister	13	8	29	575
Telmessus cheiragonus	8	12	26	241
Cancer (Metacarcinus) gracilis	2	3	6	100
Cancer productus	3	3	19	94
Burrowing shrimps (*Thalassinidea spp.*)	1	8	0	25
Amphipods	2	2	3	17
Spider crabs (Majidae)	1	1	0	12
Pea crabs (Pinnotheridae)	0	2	0	5
Hermit crabs	1	3	0	4
Brokenback shrimps (Pandalidae and Hyppolytidae)	1	0	0	3
Lophopanopeus bellus	0	0	1	1
Total abundance by habitat type and for all 54 sites	**7,112**	**11,917**	**3,698**	**22,727**
Taxa richness for by habitat type and for all 54 sites	**11**	**11**	**8**	**13**

Green crab captures

In 2018, five green crabs were captured at four locations in Washington's inland marine waters as a part of regular Crab Team monthly monitoring protocols:

- **Two at Dungeness Spit**. Control efforts led by USFWS have been ongoing at the refuge since discovery of green crabs here in 2017. In total, 69 green crabs were captured as a part of this effort (a total of 2,679 trap days) in 2018. To track the status of green crab populations in a consistent, rigorous way, Crab Team protocols are still implemented at three Crab Team regular monthly monitoring sites established within the National Wildlife Refuge. At the channel site on Graveyard Spit, which is the site with the highest density of green crab at the refuge, two female crabs (55mm and 67mm) were captured in separate monthly monitoring efforts.
- **One at Dungeness Landing**. Established as a volunteer-monitored Crab Team site in 2016, Dungeness Landing sits just outside the Dungeness Spit National Wildlife Refuge property. Following the detection of green crabs at the refuge in 2017, Crab Team supported an assessment trapping effort at Dungeness Landing, in addition to continuing monthly monitoring, but no green crabs were captured that year. A single male (55mm), the first at the site, was captured by volunteers during monthly monitoring in June 2018. A follow up assessment effort by WDFW failed to detect any additional evidence of green crabs.
- **One at Westcott Bay, on San Juan Island**. Green crab was first detected in the inner Salish Sea in 2016 by Crab Team volunteers. No live green crabs were captured there in 2017, including during a rapid assessment effort. However, this year, during a training workshop with managers from the US and Canada, two additional green crabs were captured at the site. This was followed by a single capture of a female (58mm) during regular monthly monitoring by Crab Team volunteers, and one additional individual captured during a follow up assessment trapping effort by WDFW. These captures indicate that Westcott is an important location to continue monitoring and assessment efforts.
- **One at Kala Point, near Port Townsend.** Late in the monitoring season, a male green crab (77mm) was captured by volunteers during their final monthly monitoring effort of the season. This site has been monitored consistently since our pilot year in 2015. Based on the large size of the crab captured, it had likely been there for more than a year. This underscores the value of repeated monitoring efforts at sites where we have previously failed to detect green crab.

Along with Lagoon Point on Whidbey Island, where four green crabs were collected in 2017 and 2018 during monitoring and rapid assessment efforts, Kala Point represents the furthest intrusion of green crabs into the southern portion of the Salish Sea. Continued monitoring and control as necessary is critical at Lagoon and Kala Points since they are adjacent to the Admiralty Inlet mixing zone and the entrance to Puget Sound and Hood Canal. Since green crab monitoring was reestablished in Washington's inland marine waters in 2015, green crabs or evidence of green crabs (molts) have been collected at six locations plus two larger complexes (Padilla Bay and Dungeness Spit, Figure 26).

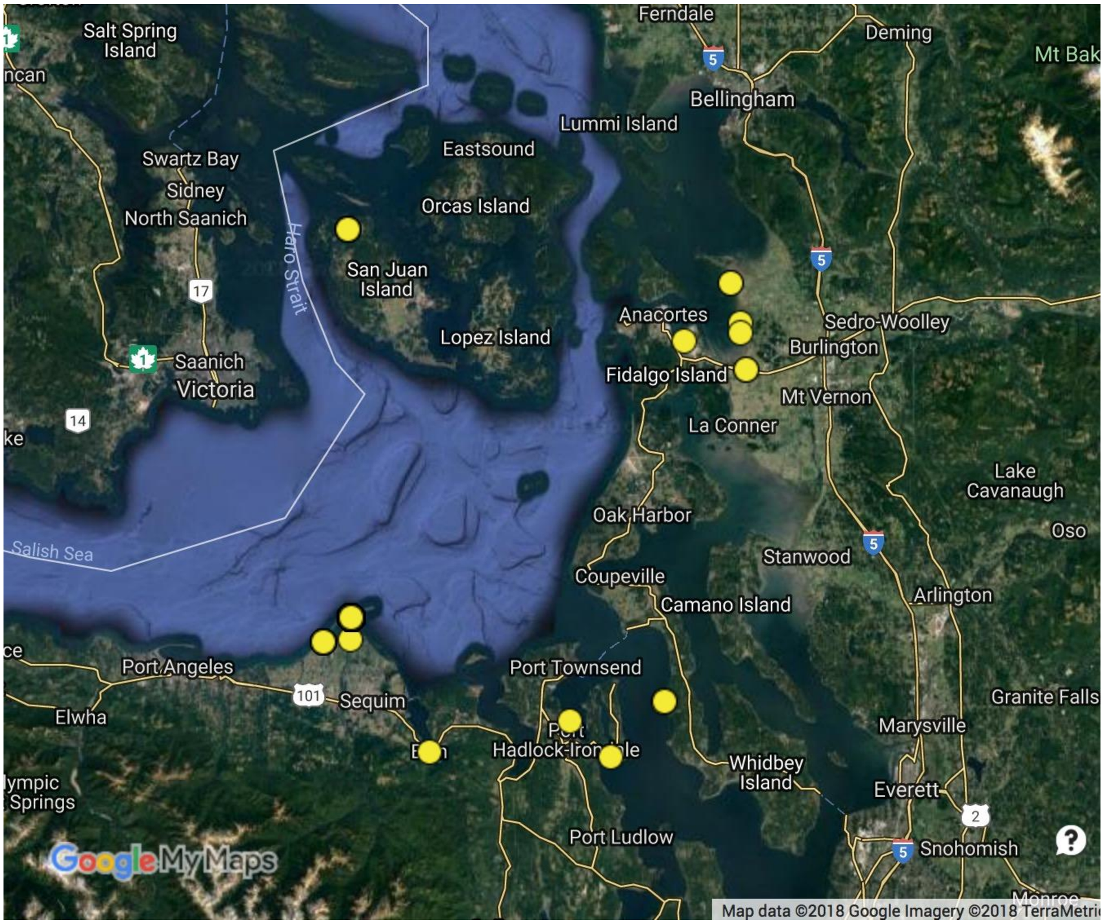

Figure 26. All locations in Washington's inland marine waters where European green crab have been collected.

Temperature monitoring

Temperature data were successfully retrieved from 24 of the 26 sites at which loggers were deployed for 2018, eight of which were in sites characterized as marsh channels (example Figure 27), and 16 of which were lagoons (example Figure 28). Two of the loggers (Table 5) appear to have been corrupted for unknown reasons, but we will continue to try to retrieve data from them. All 24 loggers passed the post-deployment temperature validation. While analysis on temperature data is ongoing, we have extracted some preliminary summary information (Table 6) from each site and can start to explore trends in temperature differences between the two site types at which loggers were deployed (i.e., channels and lagoons). Interestingly, temperature in lagoons and channels did not differ significantly in terms of either the average or maximum temperature reached during the observation period (Table 6). By contrast, temperature variance was significantly greater in channels than lagoons (Table 6, $F_{1, 22} = 5.427$, $p = 0.30$). This is likely because volume of retained/impounded water in channels is lower than that of lagoons, and therefore carries less thermal inertia. A next step will be to evaluate whether differences in temperature variance across sites are correlated with community metrics such as diversity and abundance of organisms trapped at the sites.

We also anticipate using temperature data to conduct preliminary assessments for "scope for growth" of European green crabs across sites and site types. The analysis will take a bioenergetics approach to estimate green crab growth rates for each site, and will provide insight into which sites and site types might be most vulnerable to impacts by green crabs and might therefore be prioritized for removal if green crab are found there.

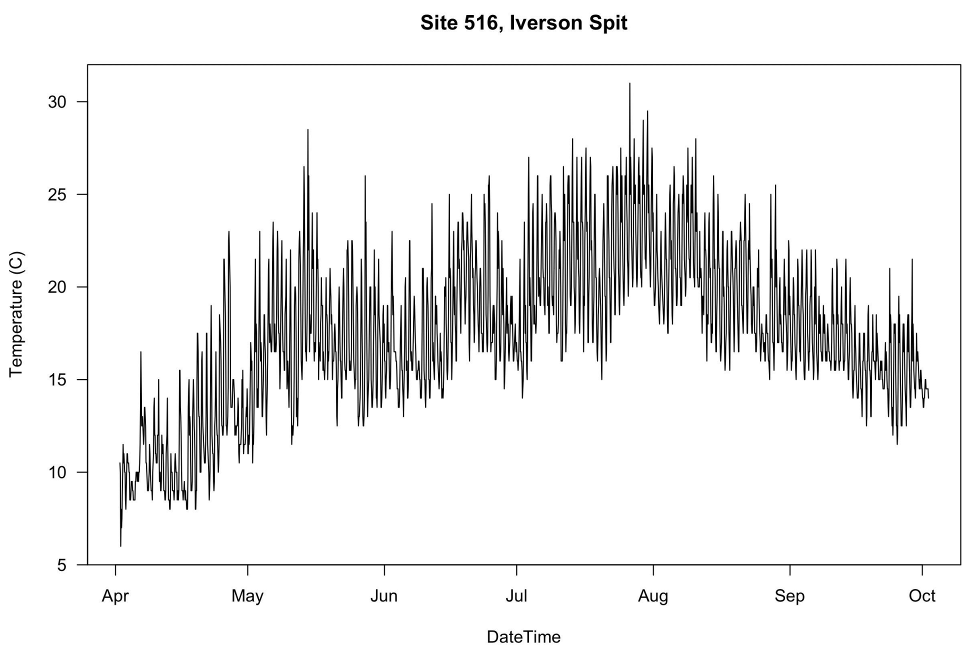

Figure 27. Sample temperature profile from a channel site, 516, Iverson Spit on Camano Island.

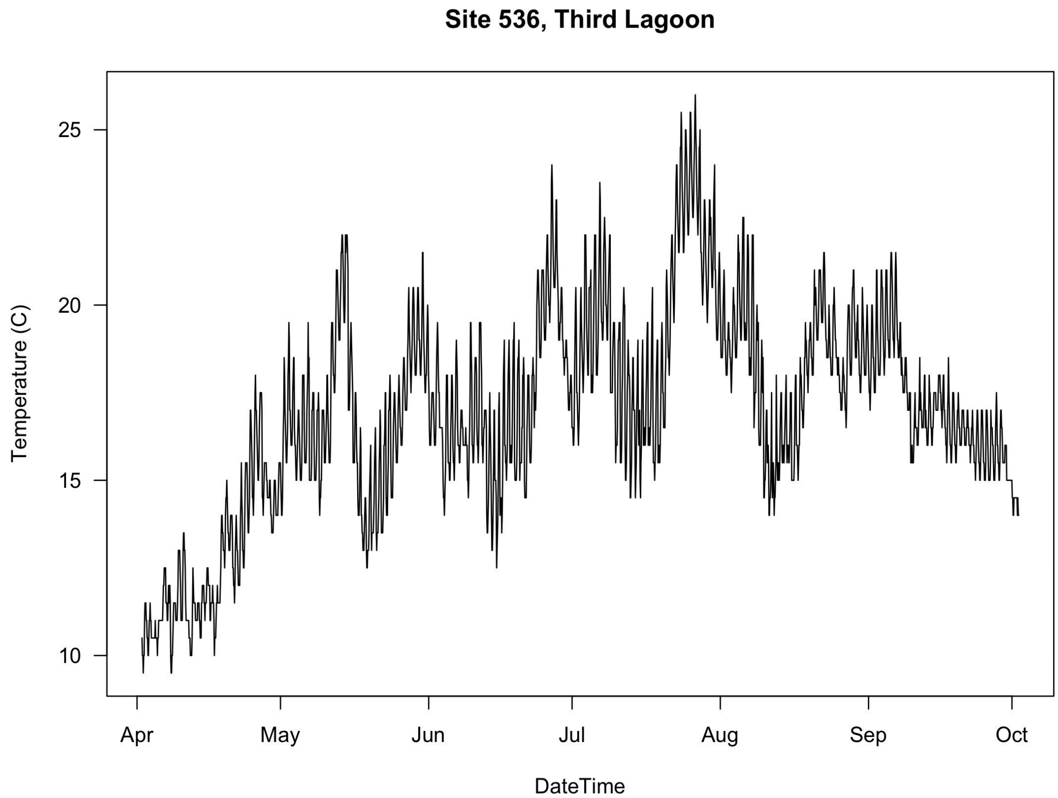

Figure 28. Sample temperature profile from a lagoon site, 536, Third Lagoon, on San Juan Island.

Table 5. Temperature data summary for the 26 Crab Team sites with temperature loggers in 2018. The data were not recoverable from the loggers at two sites (199 and 323).

Site	Site Name	County	Site Type	Average (C)	Maximum (C)	Variance (C)
128	Nicks Lagoon	Kitsap	Lagoon	19.4	36.5	23.4
133	Best Lagoon	Kitsap	Lagoon	17.3	31.5	16.0
138	Duckabush	Jefferson	Channel	14.4	26.0	18.1
153	Kiana Lodge	Kitsap	Lagoon	14.4	25.5	7.6
198	Discovery Bay	Jefferson	Lagoon	17.6	29.0	13.0
199	Jimmycomelately	Clallam	Channel	Data	Not	Recovered
201	Indian Island	Jefferson	Lagoon	16.8	26.0	9.8

Site	Site Name	County	Site Type	Average (C)	Maximum (C)	Variance (C)
250	Butterball Cove	Thurston	Lagoon	15.5	26.0	10.7
277	Titlow Lagoon	Pierce	Lagoon	12.8	22.0	6.0
306	Deer Lagoon	Island	Lagoon	16.1	29.5	17.0
311	Penn Cove	Island	Lagoon	15.6	24.5	7.4
323	Kiket Lagoon	Skagit	Lagoon	Data	Not	Recovered
330	Mud Bay	San Juan	Lagoon	15.5	26.0	12.0
362	Post Point	Whatcom	Lagoon	18.9	26.0	6.9
378	Big Indian Slough	Skagit	Channel	17.3	24.5	11.9
383	Graveyard Spit East (Lagoon)	Clallam	Lagoon	15.2	29.0	6.4
384	Graveyard Spit West (Channel)	Clallam	Channel	18.1	31.5	16.0
508	Race Lagoon	Island	Lagoon	17.5	30.5	13.5
516	Iverson Spit	Island	Channel	17.6	31.0	17.7
527	Swinomish Casino	Skagit	Channel	15.7	28.5	12.4
533	Westcott Bay	San Juan	Channel	17.3	32.0	20.0
536	Third Lagoon	San Juan	Lagoon	17.0	26.0	8.8
540	Spencer Spit	San Juan	Lagoon	18.4	30.5	22.0
552	Elger Bay	Island	Channel	16.9	29.5	20.5
590	Lagoon Point	Island	Lagoon	15.3	21.0	5.6
599	Davis Slough	Island	Channel	17.6	31.0	16.2

Table 6. Comparison of temperature parameters (C) from sites categorized as either marsh channels (n = 8) or lagoons (n = 16). Variance is the only factor that is significantly different between site types.

Site Type	Average Temp			Maximum Temperature			Temperature Variance	
	Mean	SE		Mean	SE		Mean	SE
Channel	16.85	0.43		29.25	0.97		16.61	1.12
Lagoon	16.44	0.43		27.47	0.96		11.64	1.39

Larval source modeling results and discussion

Of the 380,000 simulated green crab larvae in the study, fewer than 2 percent were advected into the eastern portions of the Salish Sea during the time period when they might be competent to settle, and it generally required favorable weather and ocean conditions for larvae from coastal sources to do so. This suggests green crab larval access to the Salish Sea is a relatively rare phenomenon. Still, larvae from each site were successful on more than one occasion and were particularly successful in late summer 2014 (Table 7).

Due to proximity, Sooke Basin had originally been thought to be the most likely source because of its location within the Salish Sea. In the course of these experiments, some larvae from Sooke did drift east, but overall, successful transport from Sooke Basin to the Salish Sea was relatively low, since most larvae were swept to the Pacific Ocean on the prevailing outward surface currents of the north side of the Strait of Juan de Fuca by the time they were mature enough to settle. Larvae from Sooke Basin released in August 2014 had the greatest success reaching the inner Salish Sea (Figure 29), while most releases resulted in little or no success (Figure 30) regardless of release location or date.

Table 7. Success of transport into the eastern Salish Sea of simulated larvae, by release date source location. Cells with variable saturation are colored yellow to highlight numerical trends: darker yellow cells indicate greater relative successful transport into the Salish Sea. Percentages represent the portion of larvae released that reached the eastern Salish Sea during the period they could settle from the plankton. Grey indicates no release for that location at that date. (reproduced from Brasseale et al. 2019)

Date	**Sooke, BC**	**Barkley Sound, BC**	**Willapa Bay, WA**	**Coos Bay, OR**
10 Aug 2014	11.38%	4.10%	27.46%	0.22%
27 Jan 2015				0%
22 Feb 2015				0%
22 Mar 2015				0%
19 Apr 2015	0.81%	0%	0%	0%
18 May 2015	0.03%	0%	0%	
3 July 2015	0%	0%	0%	
1 Aug 2015	0.09%	0.03%	0.02%	0%
17 Jan 2016				0.08%
13 Feb 2016				0%
12 Mar 2016				0%
9 Apr 2016	1.90%	0%	0%	0%
8 May 2016	0.68%	0%	0%	
2 July 2016	0%	0%	0%	
2 Aug 2016	0.64%	0.01%	0.05%	20.16%
AVERAGE	1.73%	0.46%	3.06%	1.86%

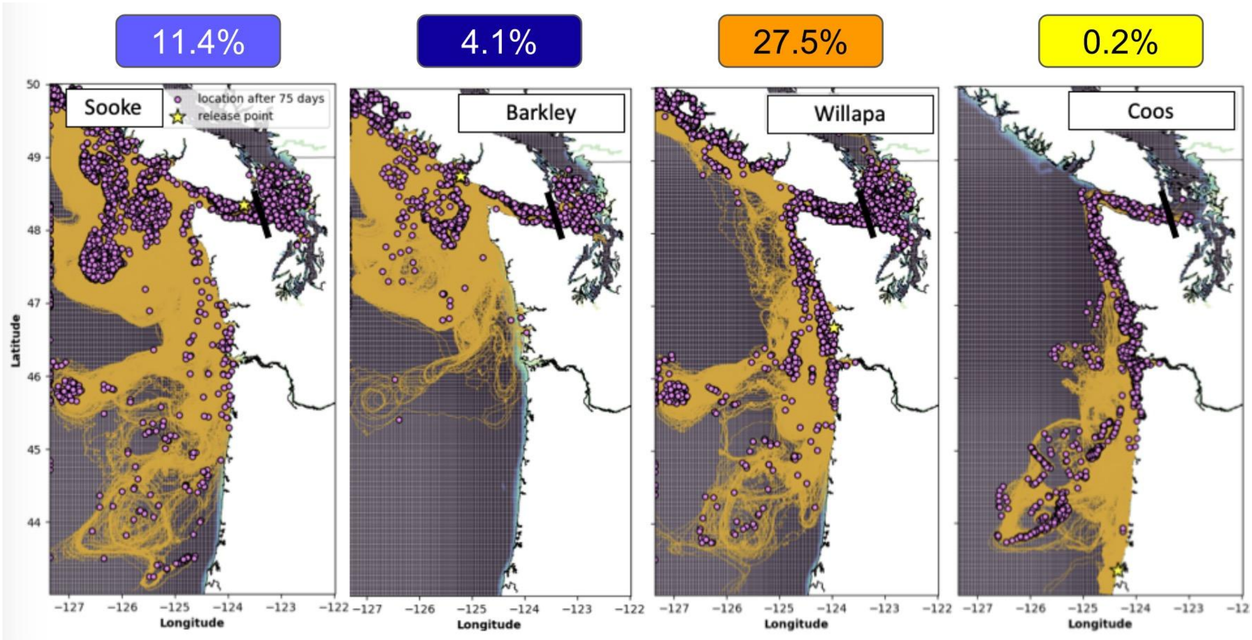

Figure 29. Examples of particle tracking experiments in which simulated larvae, released August 10, 2014, were successful reaching the Salish Sea after a 75 day period in the water column. (reproduced from Brasseale et al. 2019)

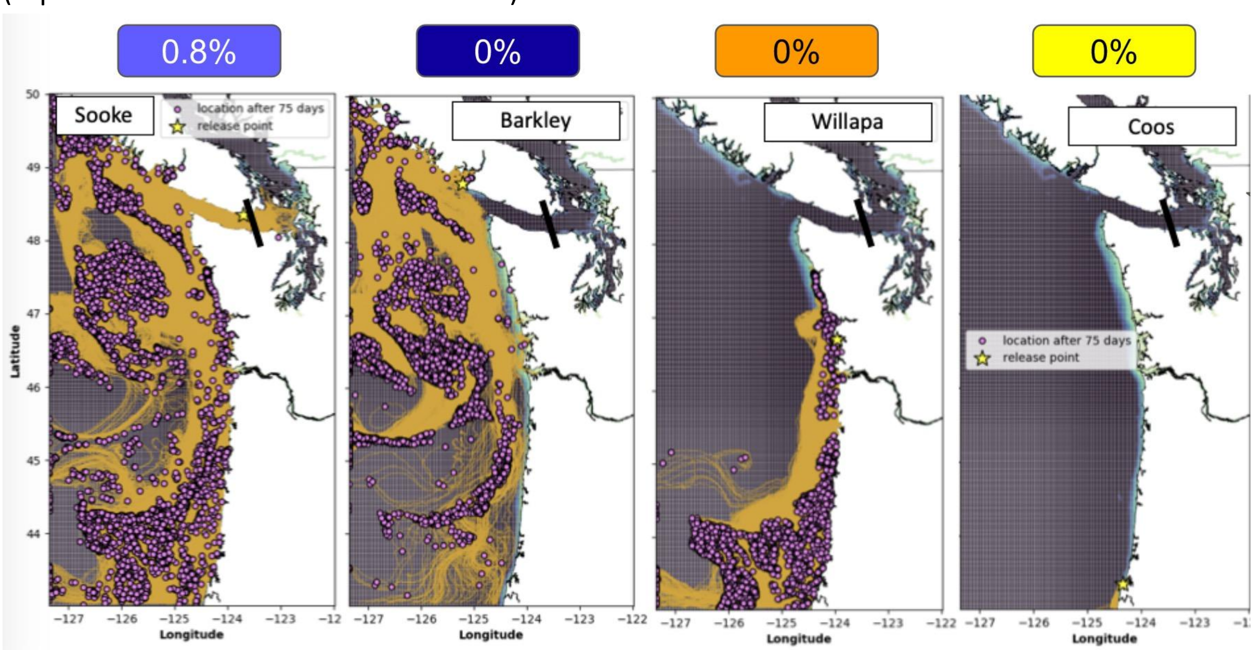

Figure 30. Examples of particle tracking experiments in which simulated larvae, released April 19, 2015, were largely unsuccessful reaching the Salish Sea after a 75 day period in the water column. Yellow stars represent release points, yellow lines are tracks followed by simulated larvae and purple dots represent the final location of simulated larvae after 75 days. (reproduced from Brasseale et al. 2019)

Larval transport model discussion

The model results indicate that typical oceanographic conditions likely keep green crab larvae from Pacific coastal estuaries out of the Salish Sea and support the idea that flow reversals into the Strait of Juan de Fuca facilitate larval dispersal into the Salish Sea (Behrens Yamada et al. 2017). Flow reversals occur when the dominant flow of surface water along the southern side of the Strait is directed into the Salish Sea instead of out to the Pacific Ocean. With the exception of Sooke Basin, larvae did not reach the inner Salish Sea without concurrent flow reversal events. When flow reversals overlap with green crab larvae being abundant in Pacific plankton, the possibility of those larvae reaching the eastern waters of the Salish Sea increases. This overlap appears to be infrequent and could be informative to managers as a tool with which to direct monitoring efforts. In addition, predominant currents that drive waters on the northern part of the Strait of Juan de Fuca to the west also help flush larvae produced in Sooke Basin out into the Pacific, providing a partial natural barrier to further range expansion within the Salish Sea. As stated earlier, El Niño-Southern Oscillation (ENSO) conditions have been documented to favor the survival and nearshore retention of green crab larvae from central California north (Behrens Yamada et al. 2015), and those conditions were also in place in 2014-2016 for even greater chance of green crab larvae being pushed into the Salish Sea.

Additional larval source support: Genomics

Though not supported by this grant, the genomics research conducted by Carolyn Tepolt at Woods Hole Oceanographic Institution, concurrent with larval modeling, confirmed that green crabs from the population at Dungeness Spit came from one of the coastal populations (CA, OR, WA or BC), not from Sooke Basin and also not from somewhere else in the world, supporting the model results. Interestingly, the green crabs from Sooke are genetically distinct from those sampled on the coast, likely because the population started with only a small number of individuals and has remained isolated (Figure 31). It is thanks to partners who provided additional funding to support the genomics project (Friends of Dungeness National Wildlife Refuge, the Lower Elwha Klallam Tribe, the Port Gamble S'Klallam Tribe, WDFW and WSG) that we have this very helpful additional line of evidence.

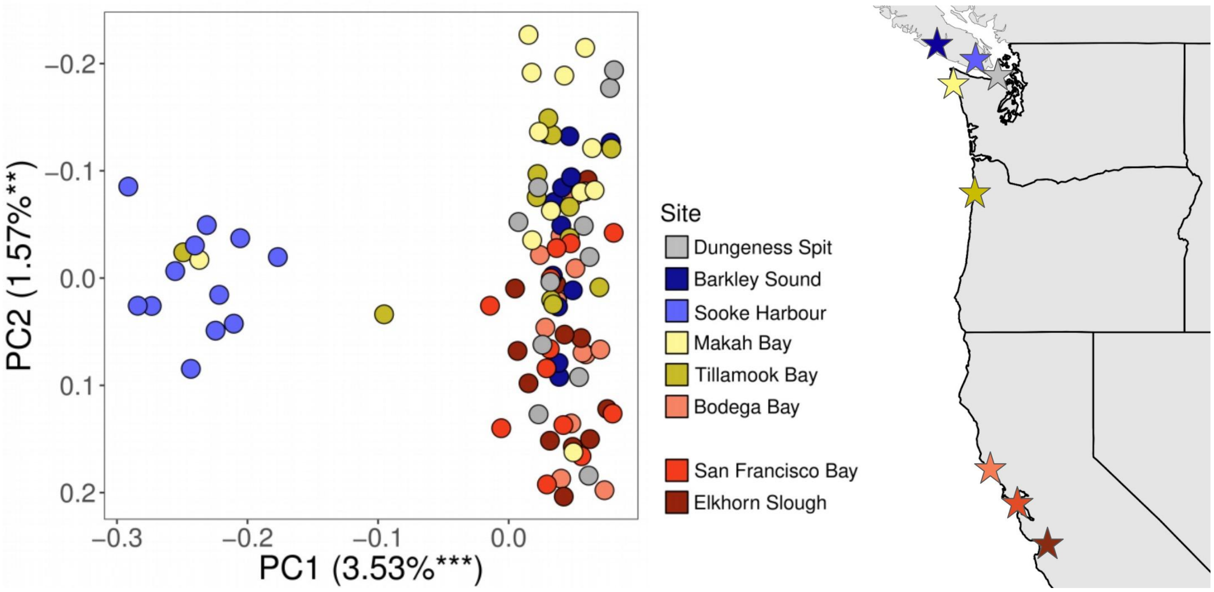

Figure 31. Genomic characterization of individual green crabs collected from sites along the US West Coast. Of particular note is the unique signature of Sooke Basin—indicated by the spatially separated cluster of dots in the plot—and that a few individuals originating from Sooke Basin were likely among those analyzed for Makah and Tillamook Bays. (Carolyn Tepolt, in prep)

Larval Source Conclusions

Identifying, through two separate lines of evidence, Sooke Basin's limited role in contributing larvae to the Salish Sea was surprising, and makes a very important contribution to management planning. The larval modeling research made clear that green crab larva can be naturally transported into the Salish Sea. The genomics study confirmed that observations of green crab from the field do indeed support this surprising pattern. In terms of management, if somewhat rare but predictable events deliver larvae into the Salish Sea, we have an opportunity to keep ahead of the invasion through regular monitoring and a robust infrastructure for rapid assessment and response. By contrast, if the evidence had suggested that Sooke (in particular, but also Pacific coastal sources) was frequently flooding the Salish Sea's shorelines with green crab larvae, the situation would have been significantly more difficult to manage.

TECHNICAL SUPPORT & TRANSBOUNDARY MANAGEMENT

(Meets requirements of *Deliverable 4.1: Technical support information integrated as section of Final Report*)

As a member of the Transboundary European Green Crab (TECG) working group, WSG Crab Team worked with WDFW, DFO and the Puget Sound Partnership, separately, on different aspects of green crab monitoring and control, and as a team, to host two special session on green crab status and management at the 2018 Salish Sea Ecosystem Conference and to develop a transboundary green crab management plan. Crab Team technical expertise and project experience made a number of contributions to regional efforts, helping to identify highly suitable habitats for targeted monitoring and response, providing training to regional partners, and conducting outreach that connects communities to the issues associated with green crab and paves the way for support and access for Crab Team and TEGC partners.

Rapid Assessments

When a green crab is captured during regular monitoring or stumbled upon and reported to Crab Team or WDFW, a rapid assessment process is initiated. With the capture location as a focal point, staff and equipment resources are mobilized for assessment trapping of the location and nearby suitable habitat to determine if multiple green crab are present and control measures should follow.

In Washington's portion of the Salish Sea, WDFW provides leadership for the rapid assessment process. Also, with the addition of a field technician specifically working on green crab in 2018, WDFW had the capacity to lead most rapid assessments. Crab Team staff supported this technician with initial training in trapping practices, as well as with site location and trap placement guidance and a limited amount of field assistance.

During the 2018 season, assessments were conducted at six locations (partly detailed in Table 8). Three of these assessments were in response to evidence of green crabs at a new detection site and led by WDFW. A molt was found on the shoreline in Fidalgo Bay (not during regular Crab Team site monitoring), but rapid assessment trapping did not capture any live green crabs. Crab Team volunteers captured a green crab at Dungeness Landing where a rapid assessment survey by Crab Team in 2017 did not capture any green crabs. After the new capture, WDFW repeated the assessment and again didn't capture any additional green crabs. Both Fidalgo Bay and Dungeness Landing are adjacent to locations (Padilla Bay and Dungeness Spit respectively) where green crabs had been previously captured, so evidence of green crabs at these locations was not entirely surprising. Fortunately, because the assessment trapping didn't collect any additional green crabs, there are not likely to be large populations in these areas. The third location with a new capture was at Kala Point, south of Port Townsend. The location's proximity to the southern portions of the Salish Sea identified this location as particularly concerning. Rapid assessment in the area resulted in just one additional crab in a nearby but separate marsh (Scow Bay).

Three other assessments repeated rapid assessments from previous years to check again for additional green crabs. Fortunately, the assessments at Westcott and Padilla Bays, led by WDFW and Washington Department of Ecology staff at the Padilla Bay National Estuarine Research Reserve, as well as a survey at Lagoon Point coordinated by Crab Team staff captured only one additional green crab (Westcott Bay, described above) indicating green crabs remain rare at these locations.

Rapid assessment is a very important tool for identifying priorities and allocating resources and monitoring known locations to prevent further spread. It is also resource-intensive and benefits from strong collaboration and public understanding of the issue.

Table 8. WDFW 2018 European green crab supplemental monitoring trapping effort summary by region.

Region	Sites	Trap-days	Type
Brinnon	3	36	Early Detection
Disco Bay	3	18	Early Detection
Hood Canal Bridge	3	148	Early Detection
Fidalgo Bay	2	59	Rapid Response
Marrowstone/Indian Island	12	600	Rapid Response
Dungeness Landing	1	64	Follow Up assessment
Padilla Bay	2	116	Follow Up assessment
San Juan Island	6	221	Follow Up assessment
Total	**32**	**1,262**	

Control

Though green crabs have been found in very small numbers (1 to 6 individuals) after regular monitoring and rapid assessments at several sites, more substantial control efforts are activated where larger numbers of green crab have been found. Within Washington's portion of the Salish Sea, the Dungeness National Wildlife Refuge is the only location where such numbers have been found. Significant numbers of green crabs were also captured in Makah Bay in late 2017, just south of the mouth of the Strait of Juan de Fuca. Significant control efforts have been established at Dungeness NWR, led by the USFWS, and in Makah Bay, led by the Makah Tribe, since green crabs were discovered at those sites. Crab Team's input has been sought in both cases to provide expertise and technical support.

Dungeness National Wildlife Refuge Control Effort

Though the leadership and monumental effort required to trap green crabs at Dungeness NWR has been addressed by the USFWS and Refuge volunteers, Crab Team has contributed with expertise on green crab related to stakeholder and outreach efforts, trapping strategy and analysis of effort (Figures 4, 32 & 33). Some takeaways from the 2018 trapping effort at Dungeness include:

1. There was no evidence of a strong 2018 cohort at Dungeness Spit. Indeed there was only a single crab that was clearly from the 2018 cohort.
2. The catch per unit effort (CPUE) and numbers did not increase in 2018 vs 2017, despite the high potential for population growth evidenced by the captures in 2017.
3. There was no evidence that green crabs are expanding to other areas around Dungeness Spit. Volunteers collected a single individual at nearby Dungeness Landing, but the rapid assessment did not catch any additional green crabs.

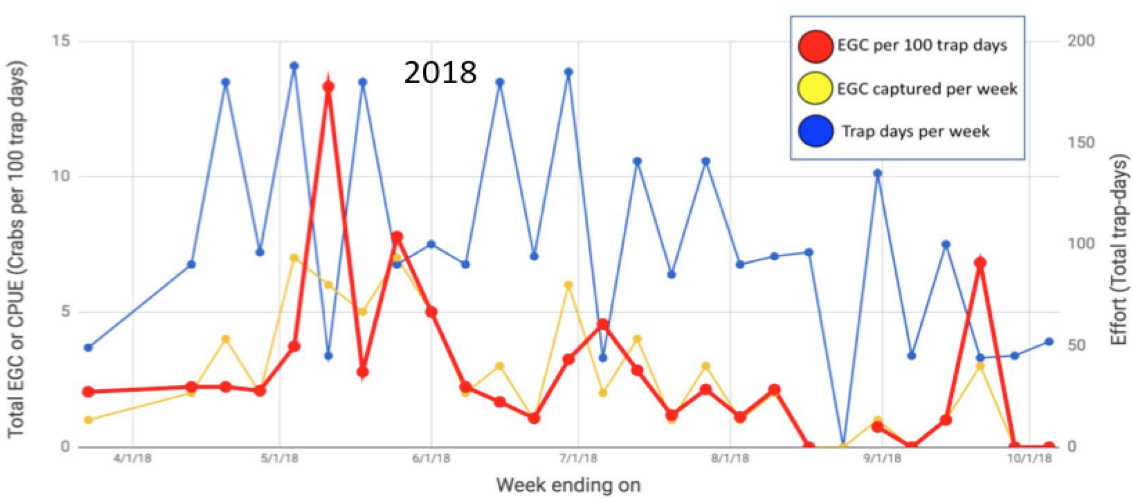

Figure 33. Trapping effort, green crab captures and catch per unit effort (CPUE) over time for 2018 green crab control efforts at Dungeness National Wildlife Refuge.

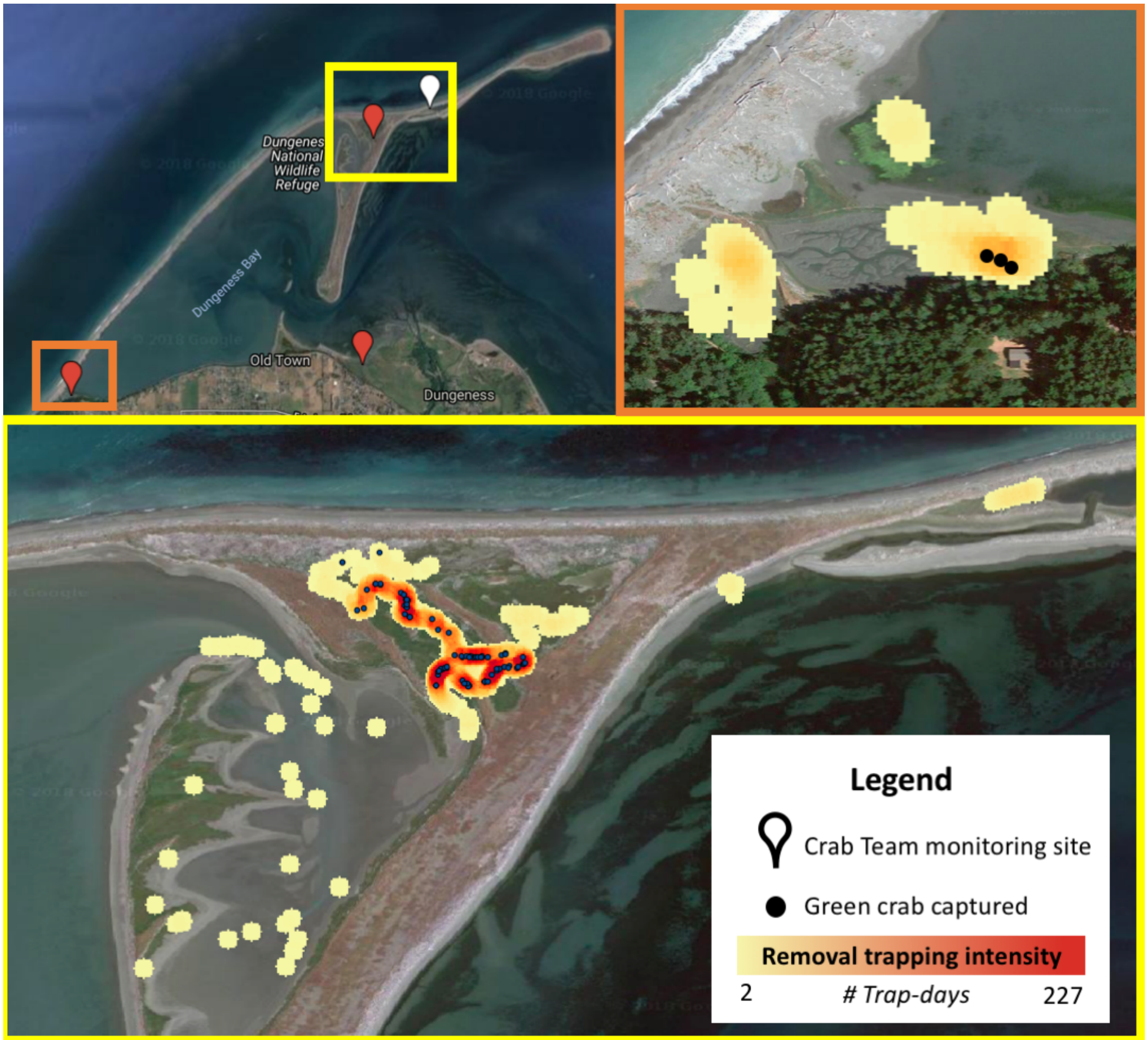

Figure 32. Heat map representation of the 2017 Dungeness National Wildlife Refuge green crab control effort, including location of captured green crabs.

Makah Bay Control Effort

In late 2017, a live green crab was photographed and reported to Crab Team from Makah Bay, just south of the Strait of Juan de Fuca. Though just outside of the Salish Sea, the Bay is very close and assessment trapping by Makah biologists and volunteers included both Salish Sea (Neah Bay) and Pacific Coast locations (Wa'atch and Tsoo-Yess River estuaries). No green crabs have been captured in Neah Bay, but trapping at Makah Bay captured 1,029 green crabs from April through September 2018. Suitable habitat was identified in two estuaries that contribute to Makah Bay and a trapping strategy was established by Makah Tribal biologists with support from Crab Team, WDFW and USFWS. For 2018, the catch per unit effort (CPUE) for Tsoo-Yess, which enters Makah Bay from the south, was 42 green crabs per 100 traps set for approximately 24 hours each. For Wa'atch, the larger estuary that enters from the east, 22 green crabs were captured per 100 traps set. Catches at both locations were an order of magnitude higher than anywhere in Washington's portion of the Salish Sea.

Thanks to the Makah Tribe's commitment to understanding and addressing green crab in Makah Bay, control and monitoring efforts will continue and our understanding of green crab impacts and control will improve.

WDFW Supplemental Green Crab Monitoring

For the 2018 field season, WDFW received support from the Pacific States Marine Fisheries Commission for seasonal staff to monitor for green crab at locations identified as most suitable for green crab and to conduct rapid response assessments and trapping at sites where evidence of green crab was found. The additional resources allowed WDFW to set traps at 32 additional sites—factoring in rapid assessments as well as early detection trapping—on at least one occasion (Figure 34). Crab Team staff supported this position and the efforts of WDFW to survey additional sites by providing training to WDFW staff and by providing guidance on suitable habitats and site access.

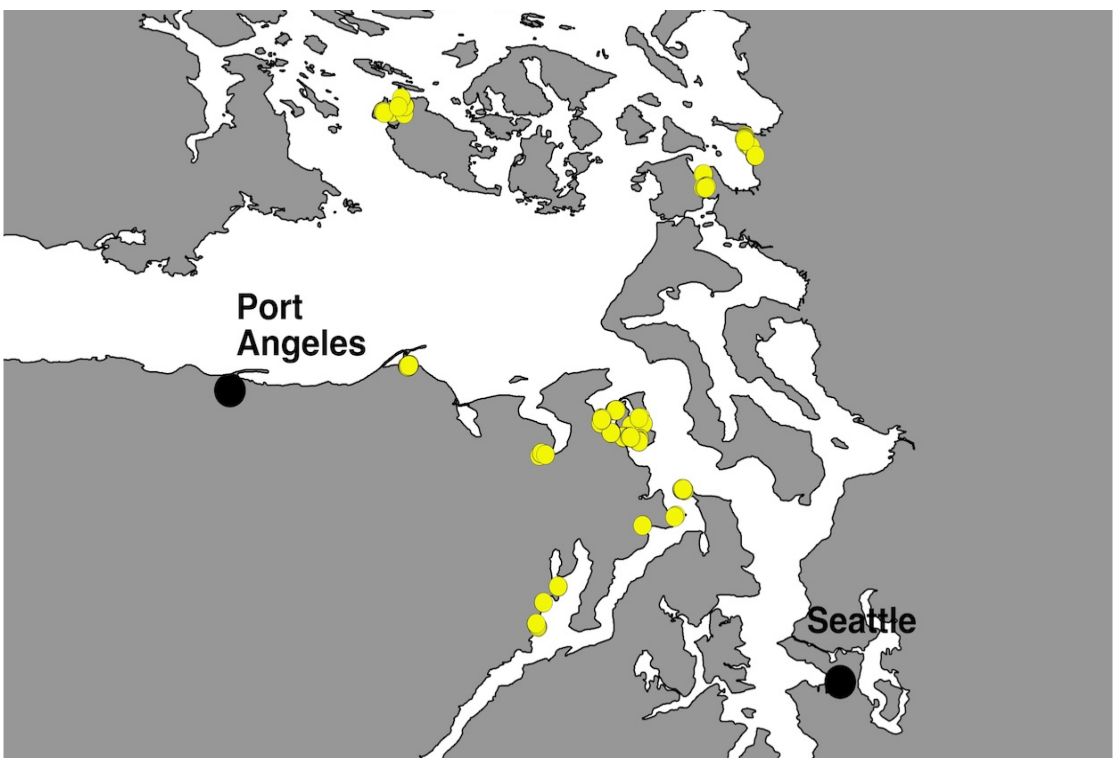

Figure 34. WDFW 2018 European green crab supplemental monitoring locations.

WDFW staff set a total of 1,262 traps over the course of the 2018 season (Table 8). Of these, 202 traps were set for exploratory early detection efforts, 401 represented follow-up assessments of sites where green crabs had been detected in previous seasons and 659 were set as part of rapid response efforts associated with evidence of green crabs found during regular 2018 Crab Team monitoring or after public reports.

Fisheries and Oceans Canada (DFO)

In 2018, Fisheries and Oceans Canada research and management staff expanded their monitoring efforts for green crab along shorelines of the Canadian portion of the Salish Sea. Crab Team staff both learned from DFO staff, participating in a green crab collection effort in Sooke Basin, and contributed to DFO's expanded monitoring efforts. Crab Team staff provided a two day training workshop, with field and classroom components, on monitoring approaches and protocols to DFO resource management staff and contributed to the DFO's habitat suitability mapping effort. (Figure 35).

Figure 35. Crab Team, DFO and WDFW staff workshop Crab Team sampling protocols on san Juan Island, June 2018.

Transboundary Management Plan development

The transboundary European green crab work group has convened three times since late 2017 to enhance interaction and collaboration across the international border of the shared Salish Sea waters. The ultimate goal has been to formalize the collaboration into a transboundary action plan (Figure 35) in order to guide efforts and resources to most effectively prevent further spread and harm by green crab to the Salish Sea. TEGC work group meetings initiated, and the PSP financially supported, drafting and further development of an action plan and an accompanying brief. The PSP contracted with Joan Drinkwin of Natural Resources Consultants, Inc. to draft the plan by summer 2018, then the work group finalized a draft Transboundary Action Plan by early autumn. The work group also distilled the plan into an accompanying white paper (Figure 36).

These documents outline a collaborative, science-based, consistent approach to managing green crab in the Salish Sea, and set the tone for successful prevention of further harm and spread of green crabs in the Salish Sea for years to come. The primary objectives outlined in the Transboundary Action Plan are:

1. Collaboratively manage the response to European green crab
2. Prevent human-mediated introduction and spread of the European green crab
3. Detect European green crab presence at earliest invasion stage
4. Rapidly eradicate or reduce newly detected populations
5. Control persistent infested site populations to eliminate or minimize environmental, economic and human resource harm
6. Conduct research to develop increasingly effective management strategies

Figure 36. Cover pages for TEGC work group documents.

CONCLUSION

Washington Sea Grant's Crab Team has had an expanded role and impact each year since its pilot in 2015. In 2018, expansion was not in the number of sites monitored and volunteers, but in a combination of transboundary planning support, collaboration for assessment and control, and by addressing research needs. The success of this particularly ambitious year was possible only because of strong partnerships and thanks to the financial support of Puget Sound Marine and Nearshore Grant Program and EPA.

The Transboundary Action Plan now provides a guide for Crab Team's future involvement and direction. While Crab Team will by necessity continue to seek funding to support its efforts, the focus will continue to be on:

- maintaining a strong volunteer monitoring core at regular Crab Team monitoring sites,
- providing expertise to support partner efforts in early detection and control,
- leading and partnering in research that addresses prevention, detection and management of green crab in the Salish Sea and,
- continuing multiple lines of outreach to engage Salish Sea communities and partners in the relevance, status and understanding of the green crab issue on the West Coast and in the Salish Sea.

Crab Team, from staff to partners to volunteers, has used the first four years of development and support to become an established program that is prepared to continue to play an important role in protecting Salish Sea resources from the threat of invasive species.

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