NOAA Contract Report NMFS-NWFSC-CR-2023-08

https://doi.org/10.25923/tzc1-s304

Habitat Utilization by European Green Crab in Willapa Bay as Measured with Acoustic Telemetry: A Pilot Study

Project **22-1995 OPS**, European Green Crab Emergency Measures

September 2023

U.S. DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northwest Fisheries Science Center

NOAA Contract Report Series NMFS-NWFSC-CR

Recommended citation:

(Roegner et al. 2023)[1]

[1] Roegner, G. C., Z. Forster, and D. Beugli. 2023. Habitat Utilization by European Green Crab in Willapa Bay as Measured with Acoustic Telemetry: A Pilot Study. U.S. Department of Commerce, NOAA Contract Report NMFS-NWFSC-CR-2023-08.

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Habitat Utilization by European Green Crab in Willapa Bay as Measured with Acoustic Telemetry: A Pilot Study

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Executive summary

We monitored European green crab Carcinus *maenas* and Dungeness crab *Cancer magister* at two intertidal sites and the adjacent subtidal area in Willapa Bay, WA. One intertidal site was an bivalve aquaculture farm and the other a less modified public oyster ground. The two sites were separated by a marina channel and a rock jetty. We mapped prominent habitat features of the sub- and intertidal zones and quantified crab activity at those features.

Crabs were tagged with acoustic transmitters, and their dispersal patterns were monitored using a telemetry receiver array that we installed, as well as an existing bay-wide receiver network. Our receiver array successfully accounted for the 60 tagged crabs at sub- and intertidal habitats over the 3.5-month study period. Most of the Dungeness crab and a portion of the European green crab were also detected on the bay-wide network.

Dungeness crab mostly remained subtidal, had high activity across the subtidal zone, and dispersed from the release sites within <2 weeks. Dungeness crab moved both north and south of the release site. European green crab extensively utilized both sub- and intertidal habitats and moved readily between habitats. They dispersed less than Dungeness crab and about half were detected three months post release.

In the intertidal, European green crab preferred structural elements in the environment. At the public oyster grounds, they occupied oyster reefs, the tidal creek, and to a lesser degree, high intertidal wetland and shallow subtidal areas. At the farm site, green crabs concentrated at and were often quiescent within aquaculture infrastructure, especially oyster cultch bags in the low intertidal zone. Transits over the infaunal clam grounds also occurred but residency there was low.

European green crab were also active in the subtidal habitat, but most movements were restricted to the shallow subtidal bank adjacent to the intertidal areas. This is presumably eelgrass habitat. Green crabs commonly moved along this narrow corridor, and many congregated at the rock jetty for various periods. About one-half of the green crabs moved northward from release sites at the public oyster grounds to the more northern aquaculture farm site or beyond.

The spatial patterns of European green crab behavior suggest target areas for crab eradication methods. These include enhanced trapping activity along the shallow subtidal migration corridor and in close proximity to aquaculture infrastructure. Redesigning the arrangement of culture elements, such as spacing of bags, may reduce the attractiveness as shelter or increase access for trapping. Note these observations are valid for adult European green crab in the autumn to winter period, and behaviors of younger crabs, gravid females, and adults outside this time frame may differ.

Contents

1.0 Introduction

1.1 Background

The European green crab, *Carcinus maenas*, is an exceptionally proficient invasive species with successful range expansions to five continents from its European origin (Carlton & Cohen 2003; Hidalgo et al. 2005). Wide tolerances to temperature, salinity, and aerial exposure enable the crab to exploit a range of subtidal and intertidal habitats in estuaries and embayments (Leignel et al. 2014; Young & Elliot, 2020). A medium length larval planktonic period allows potential for both wide dispersion by ocean currents as well as retention within larger and less flushed estuarine systems (Brasseale et al. 2019; Behrens Yamada et al. 2021). A diverse omnivorous diet (Leignel et al. 2014) and antagonistic and/or predatory interactions with resident crab species (McDonald et al. 2001; Jensen et al. 2002) confers competitive dominance for many successful invasions. Of particular concern are the destructive actions of green crab on bivalve beds (Dare et al. 1981, Poirier et al. 2017) and eelgrass meadows (Matheson et al. 2016, Howard et al. 2019). Estimated negative economic impacts of the European green crab invasion are widespread (Lovell et al. 2007; Mach and Chan 2014).

Recent proliferation of European green crab in Pacific Northwest estuaries, after decades of low level population presence, has become a major concern for aquaculturists, fishers, and resource managers. A key mitigation method is intensive extractive fishing to physically remove ECG from the system. Knowledge of habitat preferences and migration patterns may aid these mitigation actions.

1.2 Objectives

This study was designed to test the effectiveness of intertidal acoustic telemetry and compare the sub- and intertidal habitat use of European green crab at Nahcotta in Willapa Bay, WA. Secondarily we contrasted habitat use at a bivalve aquaculture site to less modified intertidal habitat. While our focus was on green crab, we also released tagged Dungeness crab *Cancer magister* for comparative purposes. Our specific objectives were as follows:

- Confirm effectiveness of acoustic tagging and monitoring design for crab tracking
- Compare fine-scale habitat use at two adjacent intertidal/subtidal sites
- Ascertain large-scale crab migration patterns within Willapa Bay
- Evaluate findings for statewide eradication and control measures

2.0 Methods

2.1 Site description-habitat types

The Willapa Bay study area is composed of two intertidal sites separated by the dredged Nahcotta marina channel and a rock jetty (Figure 1). The north site is an active bivalve aquaculture farm. The south site is public oyster grounds. Both intertidal sites grade upland into a vegetated wetland bank, while the seaward edge forms a bank or edge at about the mean lower low water level that slopes abruptly seaward. The subtidal area ranges in depth from 1-3 m at the lower portion of the bank to 10-15 m in the main channel. The southeastern edge of the channel borders on a shallow intertidal mudflat island that terminates adjacent to the public oyster grounds, and the channel broadens to the north.

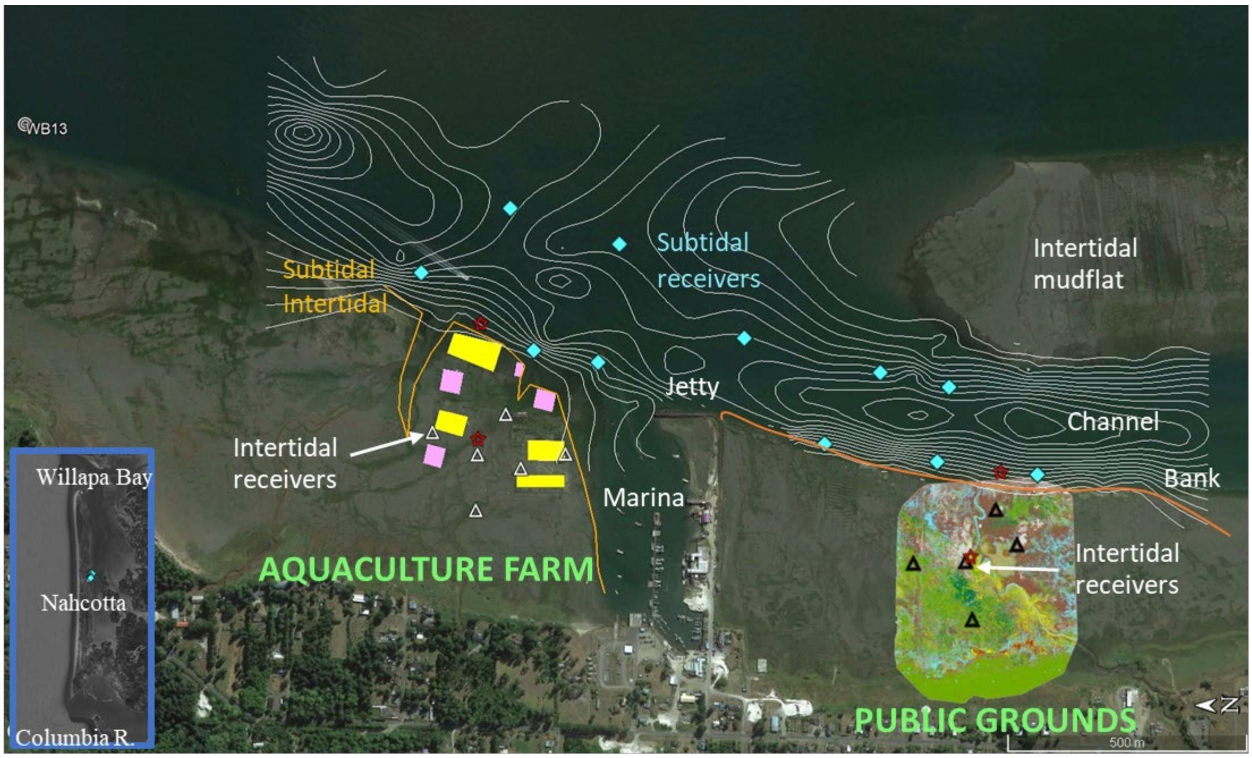

Figure 1. Site map showing features at sub- and intertidal monitoring areas. Note the north orientation; inset shows regional location in unrotated frame. At the aquaculture farm, yellow and pink rectangles denote show oyster cultch and flip bags, respectively. Triangles indicate intertidal receivers, while diamonds indicate subtidal receivers. Isobaths at 1-m intervals highlight steep channel banks; orange line is approximate position of inter-subtidal boundary. Sub- and intertidal crab release sites are indicated by red stars. At upper left, WB13 shows a receiver from the Willapa Bay network. Scale is in lower right corner.

The two sites differ in structural complexity and substrate modification due to bivalve culture practices (Figure 2). Dominant habitat types at the public oyster grounds are burrowing shrimp beds (*Neotrypea califorianus*), seasonally abundant eelgrasses (*Zostera marina* and introduced

Zostera japonica), and Pacific oyster (*Crassostrea gigas*) reefs (shell plus live oysters). Unmodified sediments are fine muds mixed with random shell. A prominent shallow tidal creek extends from the wetland to the subtidal bank.

At the aquaculture farm, habitat is modified by infaunal Manilla clam beds (*Venerupis philippinarum*) in a mud-gravel matrix, and structural elements of oyster culture that include stacks of cultch bags (shells in plastic mesh bags used for larval collection and early grow-out) and flip bags (vertical PVC poles with plastic mesh bags strung along horizontal lines). Between the aquaculture elements are patches of eelgrass, burrowing mud shrimp, and/or bare substrate. Eelgrass and burrowing shrimp density have been suppressed at the aquaculture farm compared with the public ground site.

Habitat characteristics of the two sites were mapped separately. At the farm site, a GPS was used to determine positions of the three culture types (clam beds, culch bag stacks, and flip bag racks). At Public Grounds, habitat was mapped using UAV-based hyperspectral imaging and LiDAR remote sensing techniques during August 2019 (Coleman et al. 2020). We assumed that broad ecological features remained similar between years, with the exception that the intertidal eelgrass imaged in the summer senesces during the autumn-winter period of the tagging study. The observed senesced eelgrass area was mostly bare mudflat with small patches of eelgrass (in depressions) and low densities of burrowing shrimp burrows.

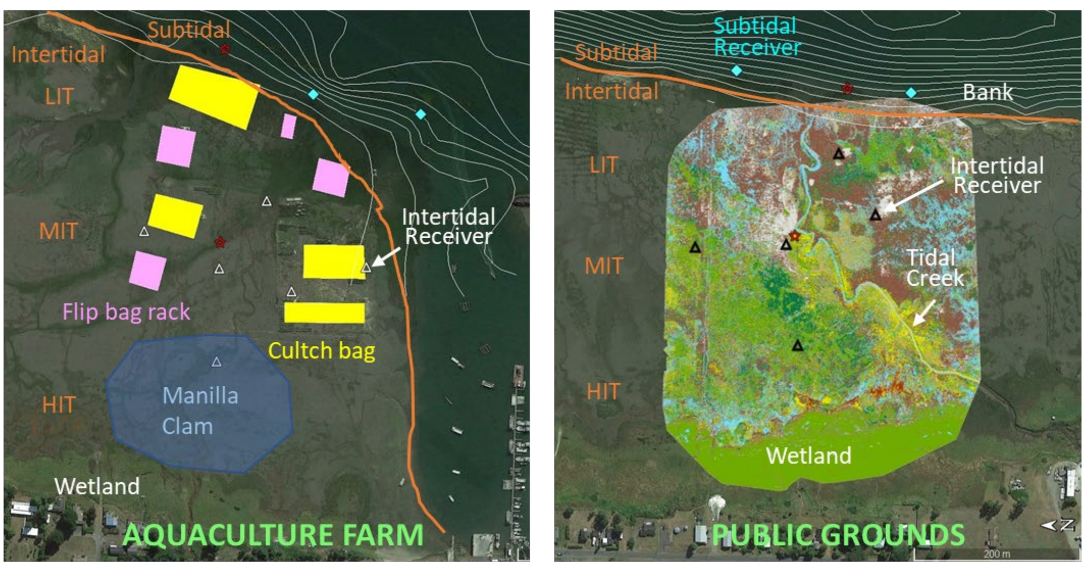

Figure 2. Habitat maps for the Aquaculture Farm (AF, left) and Public Grounds (PG, right) showing positions of acoustic receivers, the sub- and intertidal boundary, locations of culture infrastructure at AF, and other prominent features. The map of PG is a categorized habitat map based on hyperspectral imagery. White: oyster reefs. Brown, dense burrowing shrimp. Blue; water. Yellow, algae, Light and dark green; eelgrass when mapped but mostly mudflat during the experiment. Solid green; wetland. Approximate tidal zonation is also provided. Sub- and intertidal crab release sites are indicated by red stars. Google Earth image of intertidal zone is from 2016.

2.2 Acoustic system

The acoustic telemetry system consisted of 69-Hz acoustic receivers (models VR2AR and VR2Tx, Innovasea, Nova Scotia, Canada) and individually coded transponder tags (model V9-2x-BLU-1). Tags were 9 × 5 mm and were programmed with a variable ping rate of 150-250 s. The variable rate helps prevent signal "collisions" that reduce detection efficiency (www.innovasea.com). Tags had an estimated battery life of ~300 d, which exceeded the study period of 139 d. Crabs were not expected to molt and shed their tags during the study.

Acoustic receivers can be deployed in various arrangements reflective of experimental design objectives and receiver availability (Figure 3). Three basic receiver arrangements are "sentinel" (single receiver), "gate" (a line of two or more receivers in close proximity) and "array" (three or more receivers in acoustic contact). We used both the sentinel and array configurations in this study (Figure 3). Individual receivers provide timed presence-absence data and are used to infer residency and larger scale movement patterns or migrations based on residence time, direction, and absolute (or transit) velocity. Arrays provide time-referenced spatial data (positions) used to construct small scale movement patterns and movement metrics, and here, to infer habitat use.

We deployed an array of the acoustic receivers at intertidal and subtidal locations to establish an acoustically connected network, allowing us to track fine-scale movements of crabs across the tidal gradient. We called this the "European green crab array," or *EGC array*. In the intertidal zone, receivers were fitted into 10.2-cm-diameter plastic sleeves and positioned in the sediment to maintain line-of-site with neighboring units (Figure 4).

Receiver height above the sediment ranged 5-10 cm due to local topography. An array was composed of five receivers oriented roughly as a cross aligned north-south. At the aquaculture site, an additional receiver was attached to a pole where oyster bag stacks might have interfered with transmissions. This receiver was ~25 cm above the sediment. In the subtidal zone adjacent to the sites, eleven receiver units were deployed on subtidal moorings ~1.5 m above the bottom (Figure 4). Receivers closest to the intertidal arrays were positioned just seaward of the channel edge in 3-4 m of water, with the deepest deployed at a ~15-m depth on the channel thalweg..

Line of site was established wherever possible to enable continuity between sub- and intertidal units when inundated. Together, the sub- and intertidal receivers were positioned with overlapping detection areas (<300 m) to allow hyperbolic positioning telemetry with the Innovasea *Vemco Positioning System* or VPS (http://innovasea.com). Based on the VPS system, a single transmission must be received by at least three receivers for position to be determined..

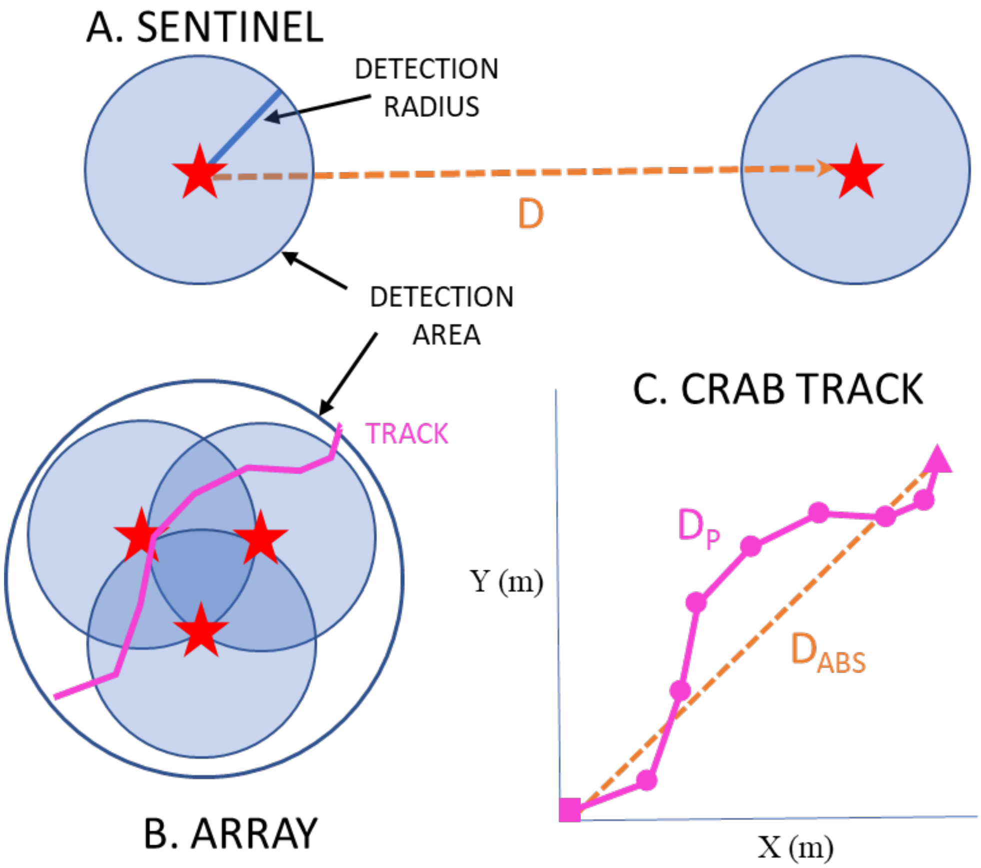

Figure 3. Schematic of sentinel and array characteristics and track metrics. A. Movement between sentinels (transit). B. Overlapping detection radii of acoustic receivers for fine-scale positioning of tags. C. A hypothetical crab track showing absolute (D_{ABS}, orange) and path ($D_{P,}$ pink) distances.

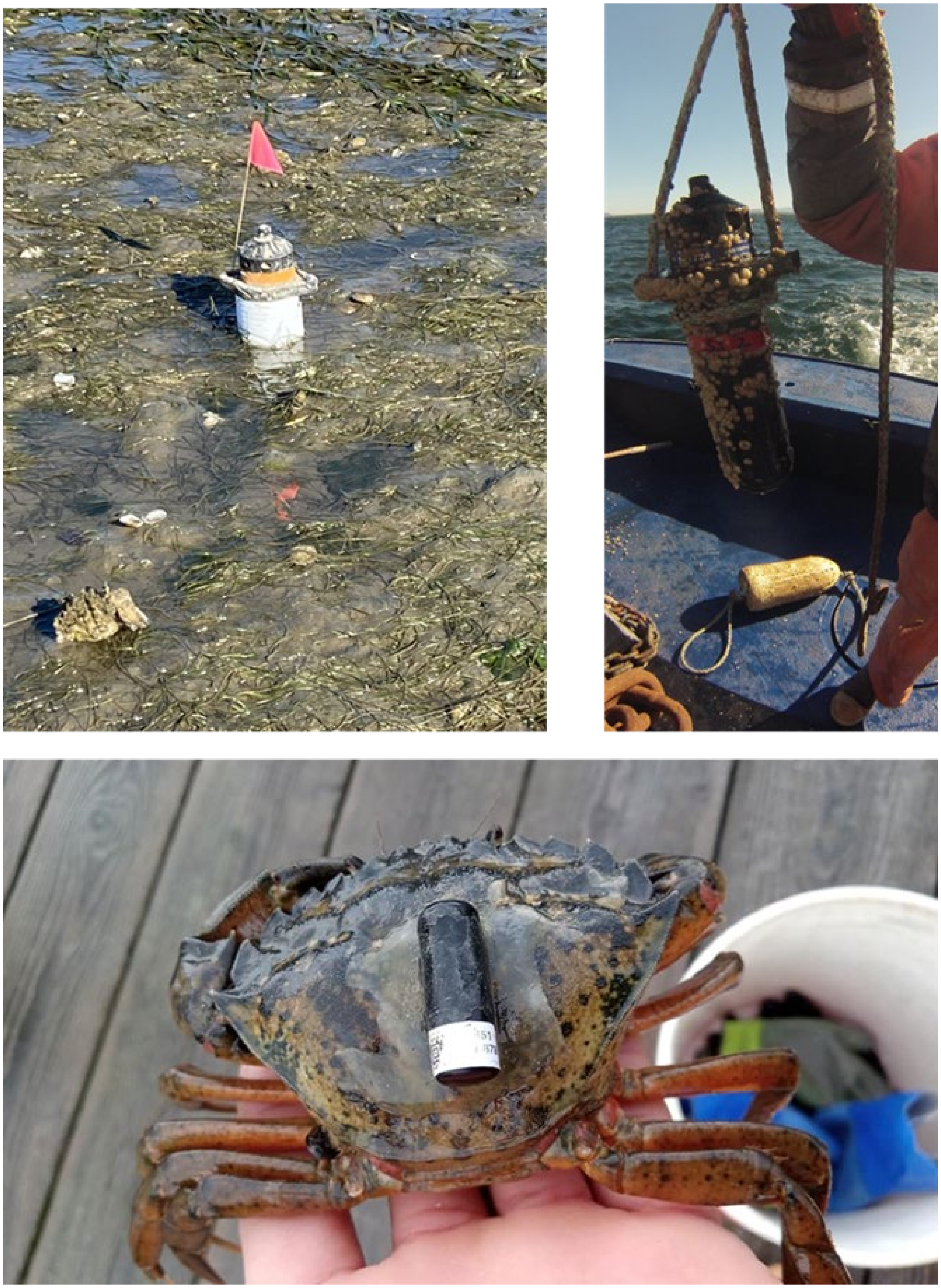

Figure 4. Upper left: Intertidal receiver at the Public Ground. Upper right: Recovery of subtidal receiver. Lower: A tagged European green crab captured in an eradication trap. Note eroded label indicative of burrowing.

2.3 Willapa Bay green sturgeon network

In addition to the EGC array, timed detection data (presence/absence) was also acquired from an existing bay-wide green sturgeon receiver network: the Willapa Bay network (Figure 5; Heironimus et al. 2023).

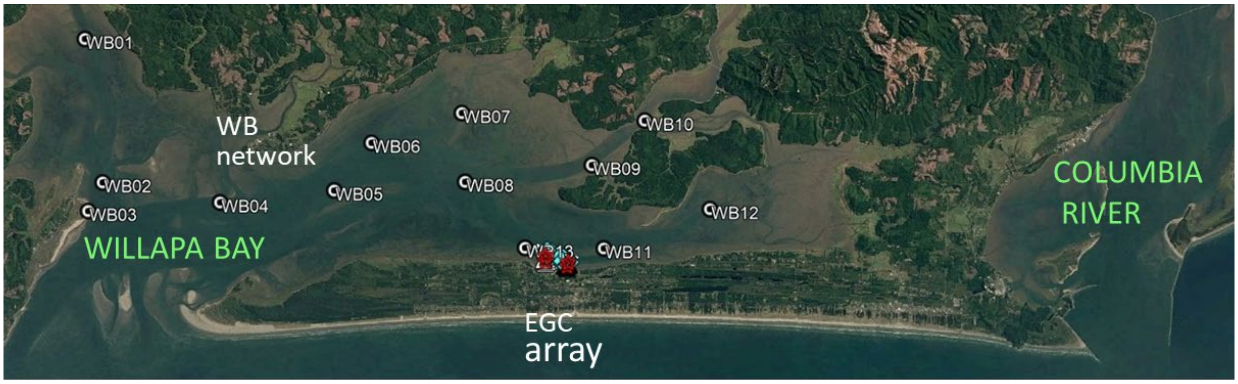

Figure 5. Location of receivers WB01-WB13 in the green sturgeon detection network (Willapa Bay receiver network) in relation to the European green crab study location near receiver WB13.

2.4 Crab tagging procedure and releases

European green crab were caught in baited recreational crab pots set in the intertidal zone (1 m diameter × 0.3 m high); Dungeness crab were caught in the nearby subtidal zone. For tagging, captured crabs were graded by size and sex into treatment groups. For European green crab, undamaged and lightly fouled individuals were used. Fewer Dungeness crab were available, and some individuals were missing appendages. Tags were affixed to the dorsal carapace with fast-curing epoxy glue (Figure 4). Handling of crabs was minimized during the tagging procedure, and crab respiratory currents were monitored in shallow-water trays as the adhesive cured. These techniques follow Roegner and Fields (2014).

We tagged four groups of 10 European green crab and released them at intertidal and subtidal sites (red stars in Figures 1 and 2) during high tide. There was an equal sex ratio of European green crab, with sizes ranging 68-92 mm (79.1 ± 7.3 mm) for males and 61-81 mm (68.1 ± 6.0 mm) for females. No females had extruded eggs.

We also tagged two groups of 10 Dungeness crab and released them at the subtidal locations (Figures 1 & 2). There was an uneven F:M sex ratio of 3:7, with males 91-181 mm (122.9 ± 32.9 mm), and females 76-105 mm (92.8 ± 10.5 mm). Inter- and subtidal reference tags were deployed at both sites, as were four loose tags used to simulate tag loss. Receiver deployment and crab tagging occurred 12-13 October 2022. Receivers were recovered from 28 February to 1 March 2023 for a monitoring period of 139 d.

3.0 Acoustic detection analysis methods

Both detection and position data were used to understand crab movements and habitat use. Detections were more numerous and served to determine residency at the EGC Array and also movement from the Nahcotta site to receivers in north and south Willapa bay. Position data were used to track crab movements and infer habitat use at sub- and intertidal locations. The primary data for detections and positions are described below:

3.1 Detections

Detections are time-stamped measurements from a coded transponder tag within the receiver reception radius (~0.28 km^2 at r = 0.30 km). For single receivers, the tag position was assigned to the receiver location. We grouped all receivers in the EGC Array to a single location. Given the relatively high transmission cycle of the tags (20 pings/h) relative to crab motility, multiple sequential detections (a time series) were usually recorded, and single detections were ignored.

For each time series of detections at a receiver or the array, we filtered the data for gaps of more than 24 h. Where gaps existed, the time series segments were partitioned and numbered, with transit 1 being the initial time period, transit 2 for the second segment, and so on. This allowed for analysis of initial metrics with subsequent movement.

Note that gap duration ranged from a few transmission cycles (< 10 min) to several weeks. Signal gaps can have many causes, including movement from reception range, behaviors like burrowing or sheltering that disrupt signal transmission, or environmental conditions such as waves that increase acoustic noise. Additionally, gaps in reception occurred in the intertidal zone when inundation was below the receiver transponder/hydrophone height. Gaps can thus occur on tidal frequencies, be set by behavioral activities, or be aperiodic.

Basic metrics from detections include:

- Residency or duration (R, days), based on a single time series of near-continuous detections. Residency at a site was determined as the time difference between last and first detections. The residency index (RI) was duration / observation period (139 d).
- Gaps in the time series, suggesting movement out of reception range, followed by a return to the detection radius. Gaps of days to weeks were observed, indicating residency within the immediate area.
- Detection time series at two or more receivers. Ordering the detections by date revealed directed movements, which could be unidirectional or exhibit regional residency.
- Transit time and velocity. From the time gap of detections and distance between receivers, absolute transit time (T_T) and transit velocity (U_T) were calculated. Transit velocity $U_T = D/ T_T$, where D is the distance between receivers (km). Velocities are expressed as m/h or km/d.

Note that uncertainties arise due to the unpredictability of the receiver detection radius, which is rarely precisely known. Error was associated with this unknown but generally decreased as a function of the distance between receivers. Thus, T_T and U_T are considered rough estimates.

3.2 Positions

From the VPS analysis, the primary data for each transponder (tagged crab) was a time-stamped X-Y coordinate (a position, P). The sequence of positions comprised a 'track" of the movements of individual crabs, from which kinematic (movement) metrics can be calculated (Figure 3). Gaps of over 24 h in a time series, the horizontal position error (HPE; Smith 2013), and sequential movements in position exceeding 100 m were considered thresholds for determining track length and number.

We analyzed each intertidal crab track and quantified the time crabs spent in relation to several categories: 1. Activity level; 2. Intertidal location; and 3. Habitat type. Information on subtidal habitat characteristics was lacking, so we concentrated on intertidal and shallow subtidal locations. Details for each analysis follow.

3.2.1 Activity level

Crabs were observed to engage in three basic movement behaviors:

- Quiescence – Periods of limited movement (<10 m) around a position.
- Meandering – Weak or non-directional movements of low velocity. Sometimes associated with high position error readings.
- Transit – Directed and often linear movements.

We tabulated the hours individual crabs spent during each movement category during intertidal occupancy. Gaps in the time series were often accompanied by significant position change (>100 m), indicating undetected movement (probably at low water levels when signals were not received). However, in other cases, crabs were detected over long periods with limited position change. These data could infer sheltering or tag loss/mortality.

When significant movement occurred after a quiescent period, sheltering was assumed; for periods of very long quiescence without subsequent movement, the possibly of tag loss could not be discounted. Gaps of over 24 h were subtracted from total occupancy time because crabs could make significant forays in a 24-h period. Time estimates were restricted to periods of direct observation and were thus conservative measures of activity.

For transits, we calculated track path length (D_P), track absolute distance (D_{ABS}) from endpoints, the track velocity ($U_P = D_P / \Sigma t$), and the Linearity Index (LI). Linearity index, or inverse sinuosity, is the straight line distance traveled divided by the path distance traveled ($LI = D_{ABS} / D_P$). LI approaches 1.0 during straight line transit while deviating from unity during nonlinear (curved) movement, meandering, or periods of quiescence.

3.2.2 Intertidal zonation

We estimated tidal levels from habitat maps and tallied the hours occupied by European green crab at each zonation category. Definitions are shown in Table 1. All movement activities were included in the zonation calculations.

Table 1 Description of categories used in tidal zonation assessment. Ab, abbreviation.

Tide Code	Zonation	Ab	Aquaculture Farm	Public Ground
1	Subtidal Channel	SC	Main subtidal channel	Main subtidal channel
2	Shallow subtidal bank	SSB	Shallow sub/intertidal bank	Shallow sub/intertidal bank usually w/eelgrass
3	Low intertidal	LIT	Oyster bag and rack	Mud w/varied oyster/shrimp/eelgrass
4	Mid intertidal	MIT	Oyster bag and rack	Mud w/varied oyster/shrimp/eelgrass
5	High intertidal	HIT	Clam grounds	Mud w/eelgrass
6	Vegetated marsh bank	VMB	High intertidal edge of wetland	High intertidal edge of wetland
7	Across zones	AZ	Transits across two or more zones	Transits across two or more zones

3.2.3 Habitat use

We used GIS to estimate crab positions related to habitat characteristics. As described above, the aquaculture and non-cultured sites differed fundamentally in spatial complexity and habitat composition, and so were considered separately. Table 2 lists the habitat categories used for the two sites. We computed the time crabs spent occupying the intertidal and shallow subtidal zones. Only data from the quiescent and meandering behaviors were used, as transits were relatively rapid and generally spanned intertidal zones and habitat types.

Table 2. Classifications used for habitat use assessment. Abbreviations: AF, aquaculture farm site; PG, public oyster ground site.

HabCode	Habitat	Site	Dominant organism/structural component
0	Shallow ST- Eelgrass	AF	Located on shallow subtidal/intertidal bank. Vegetated w/eelgrass
1	Bare ground - Eelgrass	AF/PG	Mostly bare mud / light burrowing shrimp during study period; vegetated with eelgrass in summer
2	Oyster reef	PG	Clumps of live oysters and shell matrix
3	Burrowing shrimp	AF/PG	Medium to high density burrowing shrimp
4	OY-BS	PG	A mix of oyster and shrimp
5	Tidal creek	PG	Tidal creek draining upper intertidal marsh, associated with oysters, eelgrass, and burrowing shrimp (depending onloocation)
6	Vegetated bank	AF/PG	High intertidal marsh edge
7	Oyster cultch bag	AF	Bags of oyster shell and spat piled ~1.0 m high on PVC pipes
8	Oyster flip bag	AF	“Flip bags” of oysters suspended on wooden frames that float with tide.
9	Clam ground	AF	Gravel-augmented sediment and planted clams
10	Across habitats	AF/PG	General movement across habitats w/o long access (usually a transit)
11	Aquaculture substrate	AF	Presence on modified aquaculture substrate (denuded of shrimp and eelgrass); firmed up
12	Asc w/culture structure	ACS	Activity associated around oyster bags or racks; not necessarily within structure

4.0 Results

4.1 Objective 1: Confirm effectiveness of acoustic monitoring design for EGC tracking

All receivers were successfully recovered and the data downloaded on 1 March 2023. Receivers and reference tags had good linkage with the array architecture. As expected, intertidal receivers lost detection capacity at low water, but when inundated the receivers communicated with subtidal and reference transponders effectively. Horizontal position error (HPE) tended to be higher in intertidal than subtidal areas, probably due to signal interference with topographic features especially aquaculture structures. Overall, we found 91% of HPE measurements were below 30 (36% <5).

All 60 tagged crab were recorded on receivers. There were 509,772 detections of Dungeness crab (82,564 excluding tag losses) and 12,439 positions were determined. There were 1,170,851 detections of European green crab, and 132,953 green crab positions were calculated. We found that one Dungeness crab had immediate tag loss, and a second crab's signal became immobile after ~2 weeks of movement. One European green crab tag had only 27 detections; and no VPS positions could be computed for this individual, but all others had sufficient detections to provide spatial data.

Several EGC became immobile after extensive transits; the main locations were at the rock jetty, within oyster culture structure, at intertidal oyster shell, or in subtidal areas. However, other EGC in the same areas were quiescent for days to weeks before subsequent movements; thus we could not definitively ascertain whether the immobile crabs were sheltering or had lost their tag.

Four tagged green crabs were recaptured at the aquaculture farm as part of removal mitigation efforts. We asked that trapped tagged crabs be photographed and released. Days at liberty (or days post release, dpr) ranged from 61 dpr (two crabs) to 134 dpr. One of the early recaptures was trapped again at 160 dpr, after the monitoring period had ended. Curiously, all these trapped crabs were initially released at the subtidal site adjacent to the farm, and not released at the intertidal site itself. It is possible some tapped crabs were not identified in mitigation samples and were inadvertently removed from the study.

We analyzed detections and individual tracks from 39 EGC and 19 DC within the Nahcotta Array. We also analyzed movements from crabs detected on the Bay-wide WB network. Crab positions and habitat use were summarized for both sub- and intertidal movements. We concluded that the acoustic monitoring design was successful.

4.2 Objective 2: Compare fine-scale habitat use at two adjacent intertidal/subtidal sites

We first used detection data to tally detections on sub- and intertidal receivers, and then used position data to evaluate activity, intertidal zonation, and habitat use.

4.2.1 Comparative crab distribution patterns

Dungeness crab and European green crab had contrasting distribution patterns (Figure 6). Based on detection data, DC largely remained in the subtidal zone, with only 3153 of 82,564 detections recorded on intertidal receivers (3.84 %; range 0 to 26.5%). These detections were from only four of 19 crabs (> 8%). In contrast, EGC had extensive occupation at both sub- and intertidal locations. Considering all EGC detections, 31.5 % were from intertidal receivers. All crabs were detected at subtidal sites.

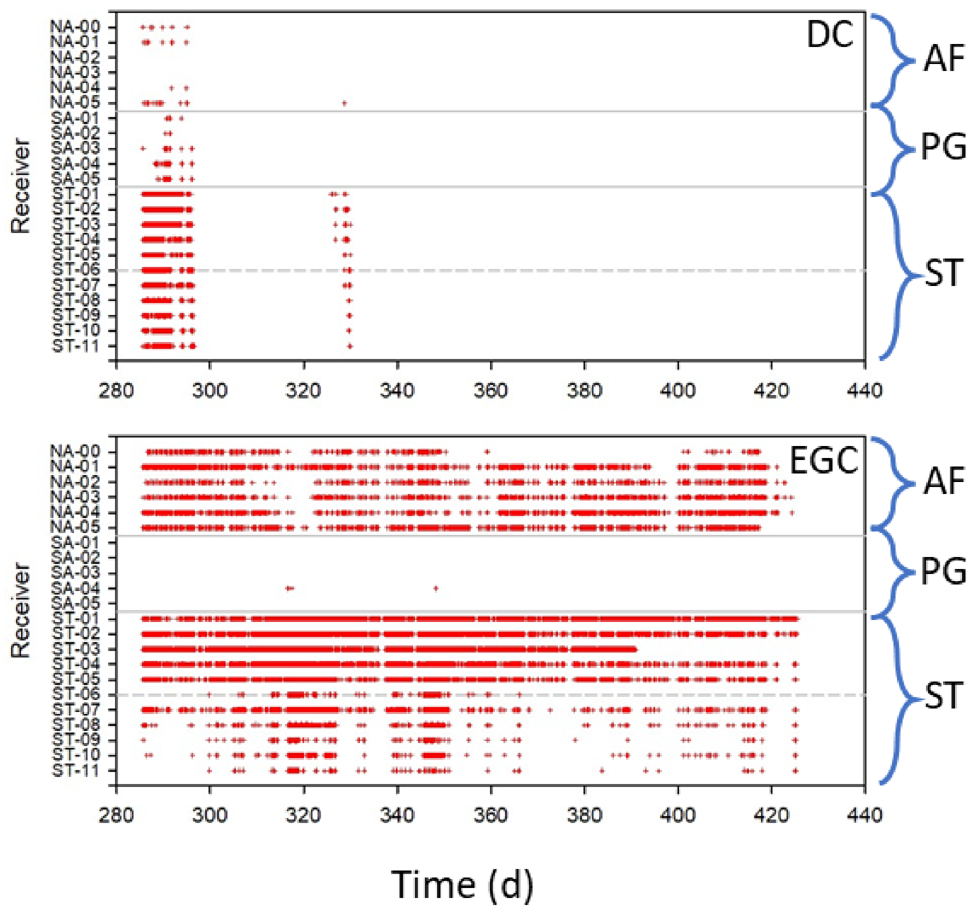

Figure 6. Example time series of detections from a Dungeness crab (upper) and an European green crab (lower) over the monitoring period, emphasizing differential intertidal use and duration at the EGC Array. Receivers are grouped by intertidal (AF and PG) and subtidal (ST) locations. For the Dungeness crab, note the gap in detections, suggesting migration away and return to the EGC Array.

Vemco positioning system (VPS) analysis revealed that both species had periods of quiescence, meandering, and transits (Figure 7). Dungeness crab were more motile, and tracks were largely composed of mostly linear transits punctuated by short quiescent periods. Only three tracks were observed in the intertidal zone. In the subtidal zone, Dungeness crab traversed along contours of the shallow intertidal bank but also traveled across the channel in deep water. In contrast, European green crab extensively occupied both sub- and intertidal areas, but in the subtidal areas they mainly traversed along the contours of the subtidal bank with few transits into deeper water. Periods of quiescence and meandering were common, especially at the rocky jetty. Both intertidal areas were extensively traveled by European green crab.

Interestingly, 10 of 19 European green crab released at the public oyster grounds moved north along the subtidal jetty. Of these crabs, four continued north and traveled to the aquaculture farm site, three lingered at the jetty before moving on, and two were last detected at the jetty. In contrast, three European green crab moved south to the jetty, with one remaining. No European green crab released in the northern part of the array moved definitively to the south.

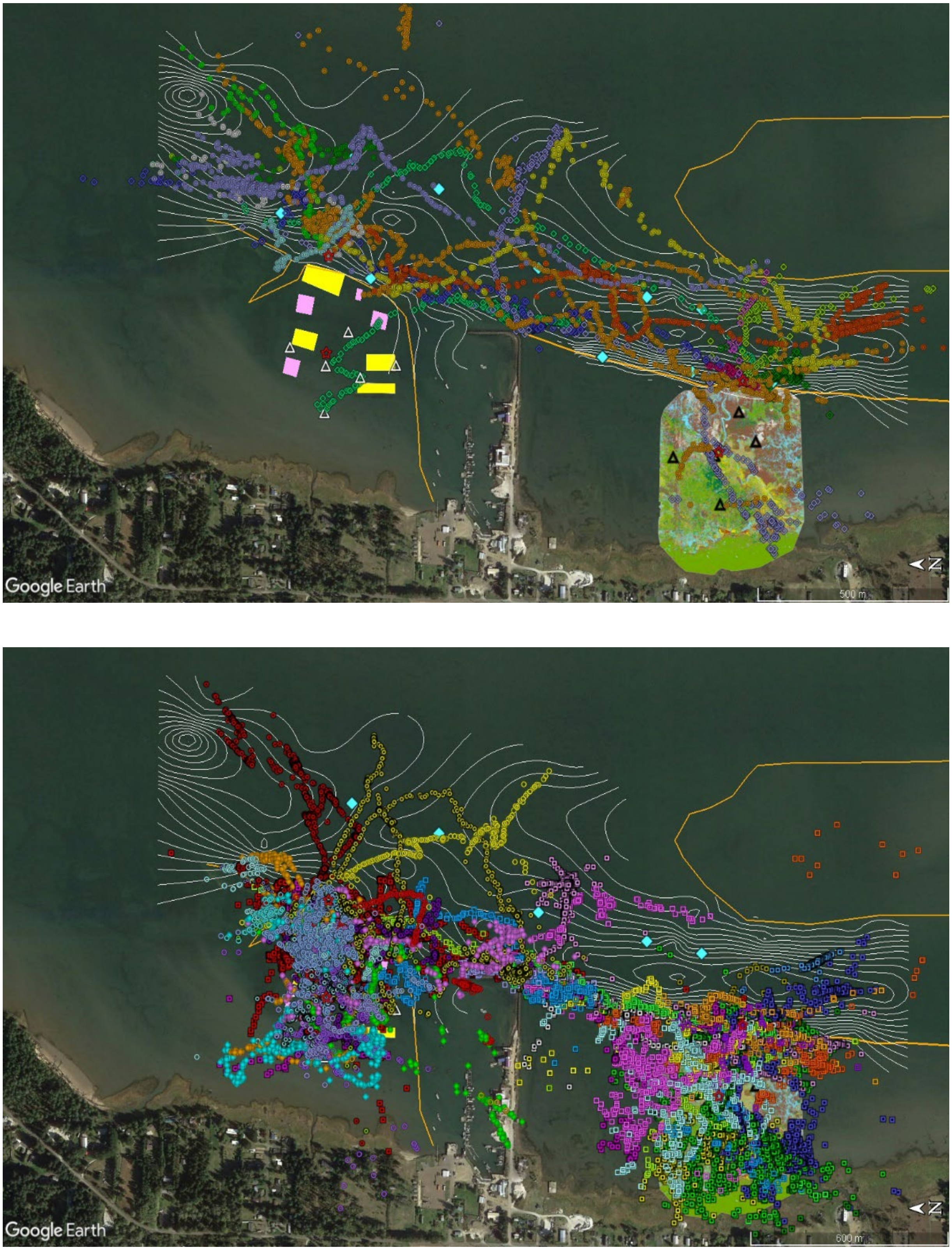

Figure 7. Cumulative movements of Dungeness crab (upper) and European green crab (lower) during the monitoring period. Each color/shape is an individual crab track.

4.2.2 Comparative residency patterns

Based on residency index (range of days detected/monitoring period), all Dungeness crab left the Nahcotta area after about 14.1 d (Figure 8). In contrast, one-half of the European green crab remained in detection range for more than 80% of the experimental period (113 d). Thus, Dungeness crab dispersed from the tagging site, while many European green crab remained on site for an extended period. There was no clear difference between male and female crabs.

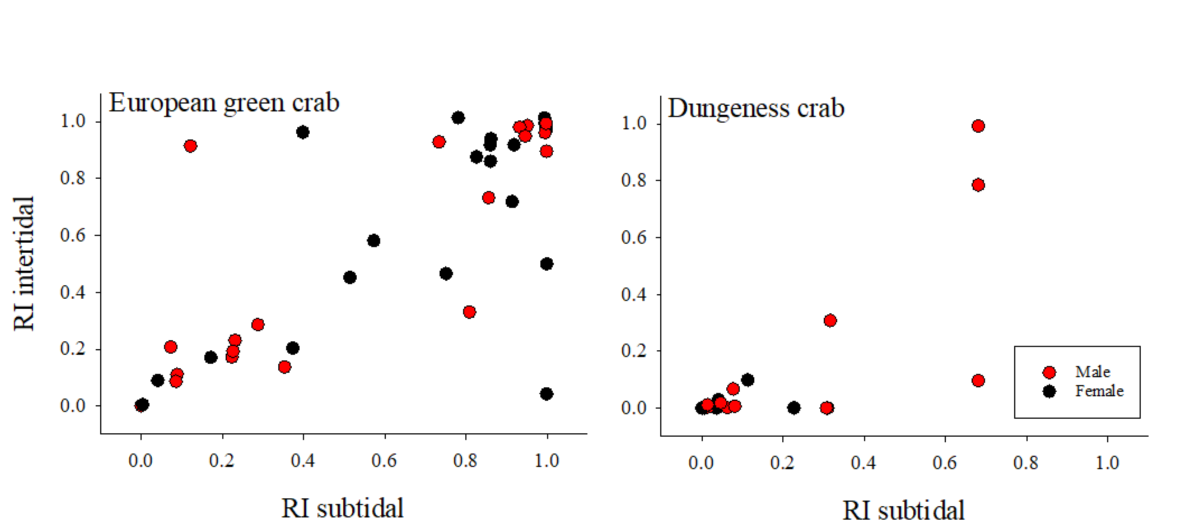

Figure 8. Residency index (RI) of crabs based on detections at sub- and intertidal receivers showing relatively rapid dispersal of Dungeness crab from the release site.

4.2.3 Activity (EGC)

At the aquaculture farm site, European green crabs were mostly quiescent or meandering, while at the public oyster ground, crabs were mostly meandering or transiting. We ran a three factor ANOVA to examine differences in standardized proportion by movement category, site, and crab sex (Figure 9), and found significant main effects with site (p=0.005) and the site × movement interaction term (p<0.001). Crab sex was not a significant variable. Post-hoc analysis indicated significantly higher quiescence at aquaculture farm than at the public ground. Crabs spent 3.1 times more time transiting habitats at the public ground, but the effect was not significant. Meandering at both sites was at similar levels.

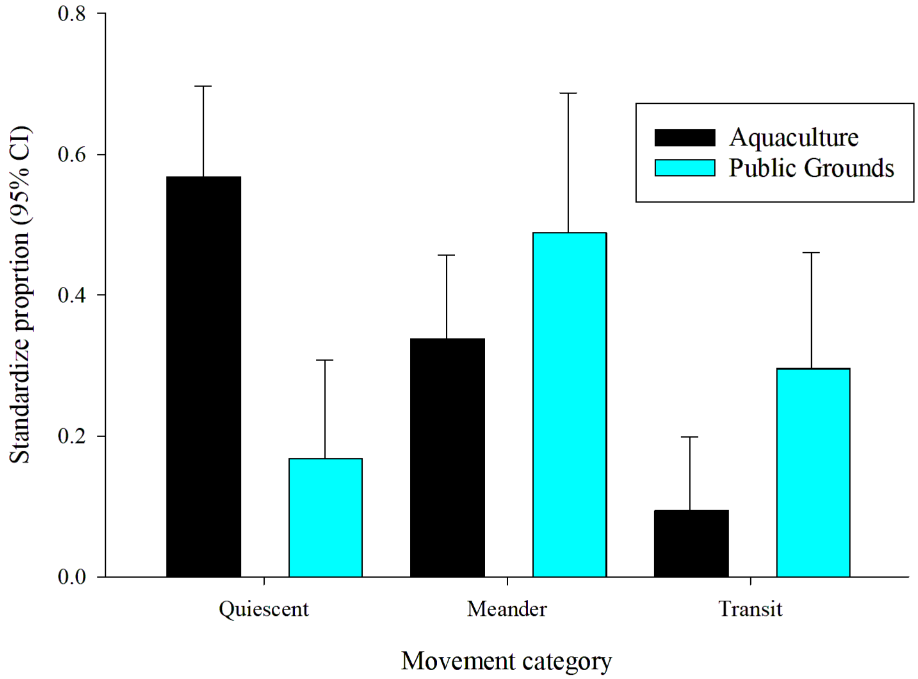

Figure 9. Mean percent activity at aquaculture farm and public oyster ground intertidal sites.

4.2.4 Transits

We compiled metrics on European green crab transits to evaluate the potential for crab to access intertidal environments (Figure 10). With two exceptions, metrics were similar between the aquaculture farm and public oyster grounds sites. Most transits were of < 6 h duration, likely due to ~6 h semidiurnal tide periods. Other continuous transits > 6 h were probably during neap periods of extended inundation. Future analyses will clarify these patterns.

Path distances broadly ranged from <50 to >400 m per excursion with a maximum of over 600 m. Note the length of the intertidal zone was ~ 470 m at the aquaculture farm and ~380 m at the public oyster grounds, meaning crabs were capable of transiting the entire intertidal zone within a high tide period. Transit velocities ranged from <10 to >200 m/h, and velocities were higher at public oyster grounds than the aquaculture site. Most transits were highly linear (LI> 0.8), with more curvy paths taken at the public oyster grounds site.

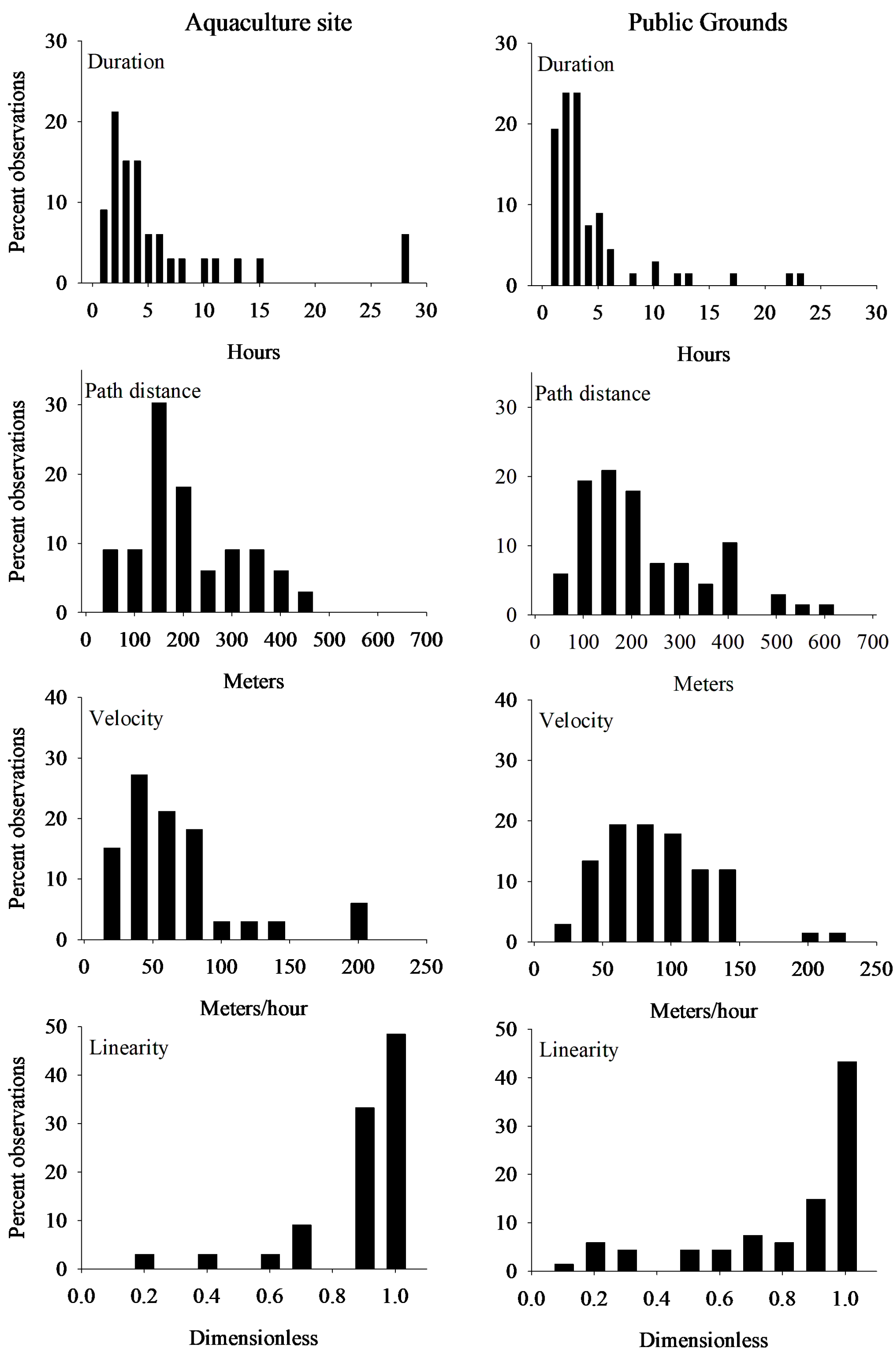

Figure 10. Frequency analysis of transit metrics for European green crab at the aquaculture farm (left) and public oyster grounds (right).

4.2.5 Intertidal zonation

There were 126 tracks from 35 European green crabs observed in the intertidal zone for a cumulative total of 15,610 h occupancy (Table 3; Figure 11). The majority of European green crab activity at the aquaculture farm site was in the low intertidal zone (68.9%) followed by the mid-intertidal (19.3%). At the public oyster grounds, European green crab activity was more widespread and was most concentrated in the mid-intertidal zone (44.6%), followed by the high intertidal zone (19.5%). Shallow subtidal and low intertidal sites had similar occupancy (~12%).

There were also detections in the vegetated marsh; however, position error readings were often high and outside selection criteria. Note there was limited reception at the highest shore levels at the farm site, perhaps because of out-of-range receivers. Total occupancy was nearly four times greater at the aquaculture farm than at the public grounds, in part because four crabs released at the southern part of the array moved north and onto the aquaculture farm site.

Table 3 Cumulative occupancy (hours) of European green crab by estimated tidal zonation. N; Number of observed tracks.

	Aquaculture farm			**Public oyster grounds**		
Tidal zone	N	Duration	Time	N	Duration	Time
Shallow subtidal bank	10	819.3	6.5	11	351.4	11.7
Low intertidal	21	8679.9	68.9	15	391.9	13.0
Mid intertidal	13	2438.7	19.3	12	1340.7	44.6
High intertidal	7	337.7	2.7	7	584.9	19.5
Wetland	0	0.0	0.0	7	182.5	6.1
Across zones	8	331.1	2.6	10	152.4	5.1
Totals	59.0	12606.6		62.0	3003.7	

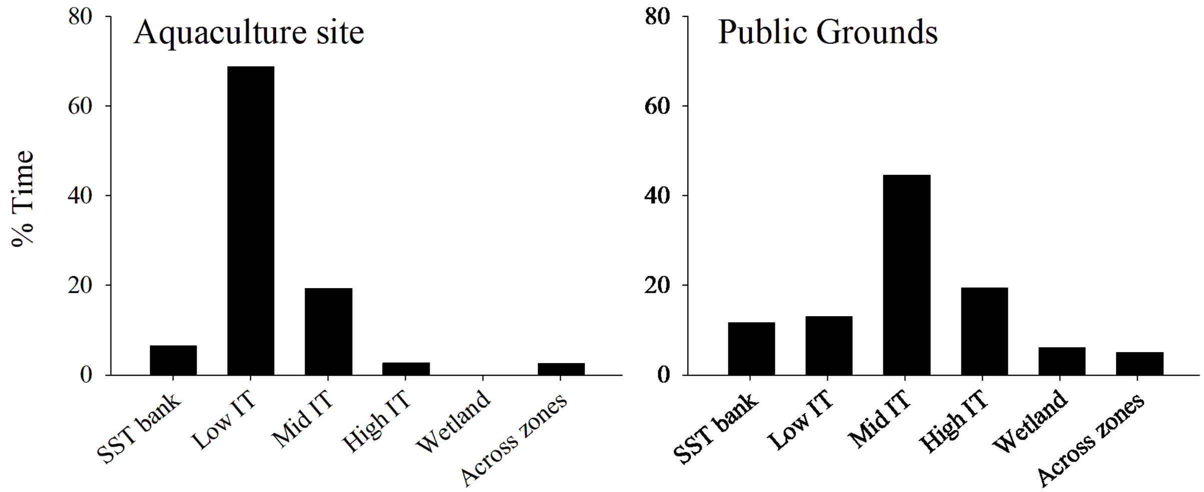

Figure 11. Percent occupancy by intertidal zonation. SST, shallow subtidal; IT, intertidal.

4.2.6 Habitat use

To assess the activity of European green crab on intertidal substrates, we categorized habitat types at the aquaculture farm and public oyster ground sites and tallied the combined hours crabs spent at the various habitats. Tallies for quiescent and meandering activities were determined separately. Transits were ignored as crabs often moved rapidly across habitats.

During quiescent periods at the aquaculture site, over 62% of measurements were recorded at oyster culture structures, with an additional 24% of time spent at areas near culture structure (Figures 12; Table 4). Crab meandering activity was primarily around oyster bags (23%) or areas near culture structure (39%). In total 79% (9797 h) of crab activity was at or near oyster culture structure locations. In contrast, cumulative activity at clam grounds was limited to 426 h (3%).

At the public oyster grounds, European green crab utilized a variety of habitat types (Figures 12; Table 4). Periods of quiescence were low (285 h) with oyster reef accounting for the highest percent time (28.8%), followed by mixed oyster and burrowing shrimp areas (OY-BS; 19.1%) and the BG-eelgrass beds (17.2%). Crabs were also found to shelter in the tidal creek and vegetated bank (26.2 % combined). European green crab spent more time meandering at the public grounds, and again were present across all substrate types. The dominant habitat during meandering was oyster reef (45%) followed by activity around the tidal creek (16%). Slow movement around the vegetated bank (12.7%) and shallow subtidal eelgrass beds (10.7%) also occurred.

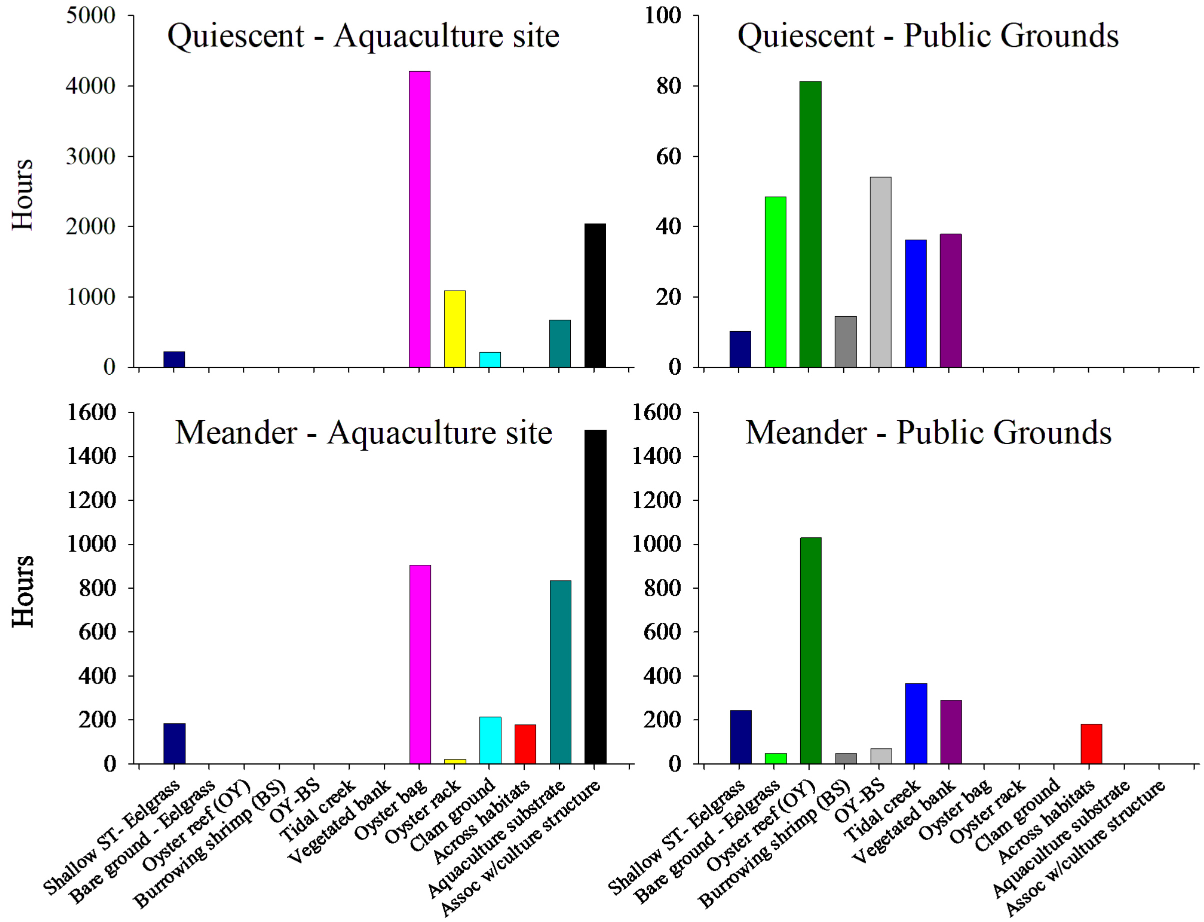

Figure 12. Total hours of European green crab occupancy by habitat category. ST, subtidal; OY, oyster reef; OY-BS, oyster and burrowing shrimp.

Table 4. Hours of habitat use by European green crab during quiescent and meandering activity at the aquaculture site and at the public grounds. See text for habitat category descriptions. N = number of activity periods; Sum in hours (h); Total habitat use (%).

Habitat category	**Quiescent (8,745)**						**Meandering (6,139)**					
	Aquaculture farm			Public oyster ground			Aquaculture farm			Public oyster ground		
	N	Sum (h)	Total (%)	N	Sum (h)	Total (%)	N	Sum (h)	Total (%)	N	Sum (h)	Total (%)
Shallow subtidal-eelgrass	9	219.4	2.59	4	10.2	3.6	10	185.4	4.8	8	243.6	10.7
Bare ground-eelgrass	1	2.3	0.03	16	48.5	17.2	0		0.0	12	48.5	2.1
Oyster reef	0		0.00	14	81.4	28.8	0		0.0	5	1,029.4	45.2
Burrowing shrimp	0		0.00	2	14.6	5.1	0		0.0	9	48.8	2.1
Oyster reef-burrow shrimp	0		0.00	6	54.2	19.1	0		0.0	7	69.1	3.0
Tidal creek	0		0.00	5	36.2	12.8	0		0.0	14	366.9	16.1
Wetland	0		0.00	3	37.9	13.4	10		0.0	0	290.3	12.7
Oyster bag	80	4,214.0	49.80	0		0.0	2	905.0	23.4	0		0.0
Oyster flip rack	31	1,094.0	12.93	0		0.0	3	21.9	0.6	0		0.0
Clam ground	4	212.6	2.51	0		0.0	4	214.1	5.5	7		0.0
Across habitats	1	1.8	0.02	0		0.0	19	179.0	4.6	0	181.2	8.0
Aquaculture substrate	11	677.4	8.00	0		0.0	32	834.1	21.6	0		0.0
Assoc w/culture structure	38	2,041.1	24.12	0		0.0	5	1,521.7	39.4	0		0.0
Totals	175	8,462.6		50	282.9		85	3,861.2		62	2,277.9	

4.3 Objective 3: Determine large-scale crab migration patterns within Willapa Bay

Dungeness crab had limited residency at the EGC array, and all eventually left the reception area (Figure 13). Seventeen of nineteen Dungeness crabs that departed were detected at sentinel receivers of the Willapa Bay receiver network. Eleven crabs were detected at receiver WP13 (869 m from ST01, the most northern subtidal receiver in the EGC array) but five of these had overlapping time stamps with the EGC array, indicating movement just north of the EGC array receivers. (These crabs were subsequently detected again in the EGC array).

Another five Dungeness crabs were last detected on receiver WB13 and were presumed to have moved north. A final Dungeness crab moved north to WB11 and was subsequently detected at several northern receivers beginning 61 d post release. Six crabs exited the array to the south (to WB11), and four of these transited ~7.2 km further upstream to receiver WB12. One crab returned from WB12 to the EGC array.

Nineteen European green crabs were detected on Willapa Bay network receivers. Nine of these detections were at receiver WB13, and as with the Dungeness crab, six of these had overlapping time periods and were last detected at the EGC array, while the other three presumably moved north and out of detection range. Four European green crab moved south and were last detected at receiver WB11, and two other European green crab were last detected at WB12 (33 and 44 d post-release, respectively) after bypassing WB11. One crab moved briefly to WB11 and then returned to the EGC array 15 d post-release.

Of the 16 European green crab with low residency indices (RI < 0.80), 9 were not detected on Willapa Bay network receivers (i.e., they likely moved from the release site but were not subsequently detected). These data show that like Dungeness crab, European green crab dispersed to subtidal areas both north and south of the release site, with 9 of the 19 crabs moving away from the EGC array and others returning to the release site detection area.

Transit times and velocities are shown in Table 5. Dungeness crab transits were relatively rapid and exhibited velocities ranging from 0.2 to 1.9 km/d (Table 5). With one exception, European green crab had much longer transits with most transit velocities below 0.2 km/d.

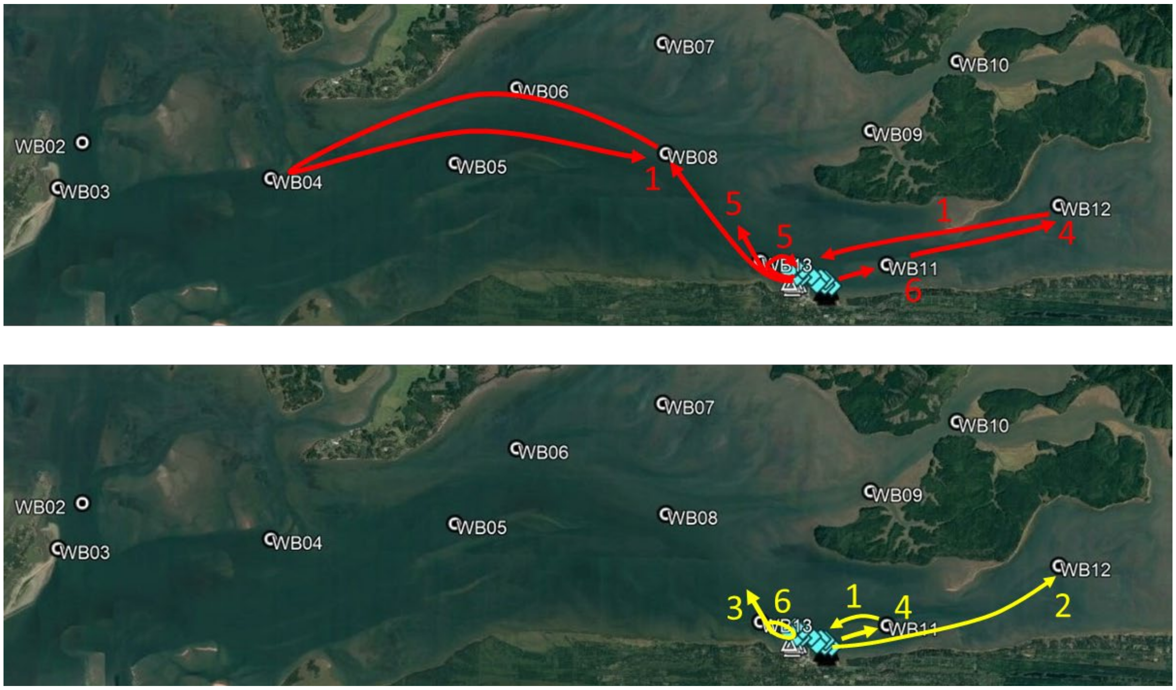

Figure 13. Summary of movement based on detection timing for Dungeness (red tracks, upper panel) and European green crab (yellow tracks, lower panel).

Table 5. Transit time and velocity estimates for Dungeness (DC) and European green crab (ECG) between receivers of the EGC array and Willapa Bay receiver network (WB1-WB13). R = indicates movement from at release site.

Dungeness crab				European green crab			
Transit	Crab ID	Transit time (d)	Transit velocity (km/d)	Transit	Crab ID	Transit time (d)	Transit velocity (km/d)
R>WB11	DC803	7.7	0.3	R>WB11	EGC027	2.2	0.9
	DC806	1.8	1.1		EGC028	10.5	0.2
	DC807	2.2	0.9		EGC031	20.9	0.1
	DC811	1.1	1.9		EGC036	82.8	<0.1
	DC813	5.9	0.3	R>WB12	EGC024	64.5	0.1
	DC818	3.9	0.5		EGC040	32.1	0.2
WB11 >WB12	DC807	7.0	0.8				
	DC811	5.2	1.0				
	DC813	25.6	0.2				
WB12 > R	DC812	7.7	1.0				
WB13 >WB08	DC819	6.1	0.9				

4.4 Objective 4: Evaluate findings for statewide eradication and control measures

We evaluated the European green crab movement patterns for spatial or temporal concentrations that may aid focused eradication efforts using baited crab pots. Several concentrations of European green crab were identified.

1. ***Natural structural components in the intertidal zone***. European green crab concentrated around structural elements in the environment (Figures 14 and 15). At the public oyster grounds, the main features were oyster reefs, the tidal creek, and the vegetated wetland area (with high horizontal position error). However, European green crab traversed widely across the entire intertidal area.

2. ***Aquaculture structures in the intertidal zone.*** European green crab were highly concentrated at low intertidal oyster bag and flip-bag structures (Figures 14 and 16).

3. ***Migration corridor along the shallow subtidal bank***. European green crab transited and resided in shallow subtidal areas, presumably in eelgrass beds. They made limited forays into deeper water (Figures 14-16).

4. ***Subtidal structure: movement to and quiescent or meandering patterns at the jetty.*** European green crab (and Dungeness crab) appeared attracted to the jetty for both short and long time periods (Figure 14-16).

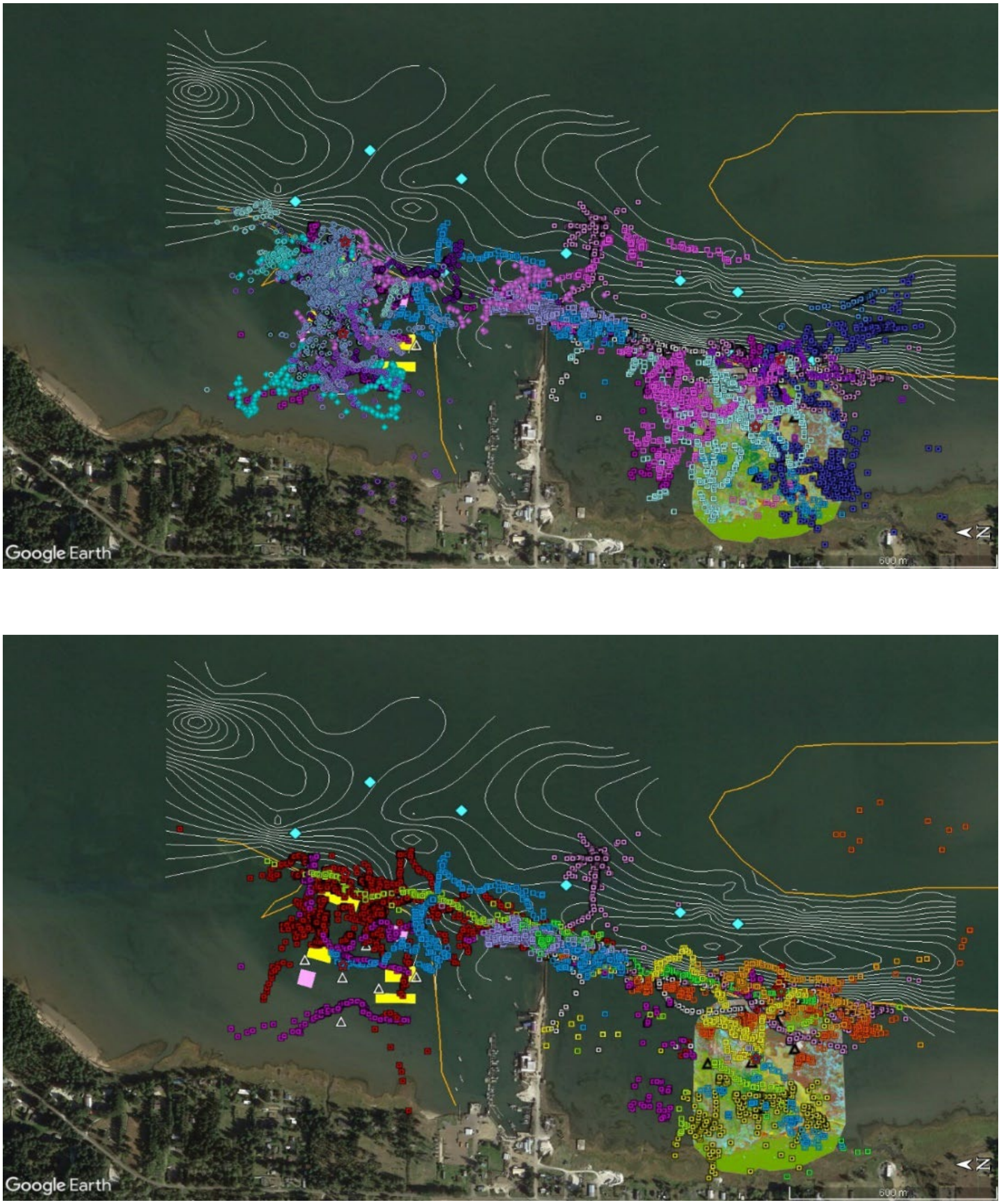

Figure 14. Comparison of European green crab female (upper) and male (lower) movements highlighting concentration of activity along subtidal bank and jetty. Each color/shape is an individual crab track.

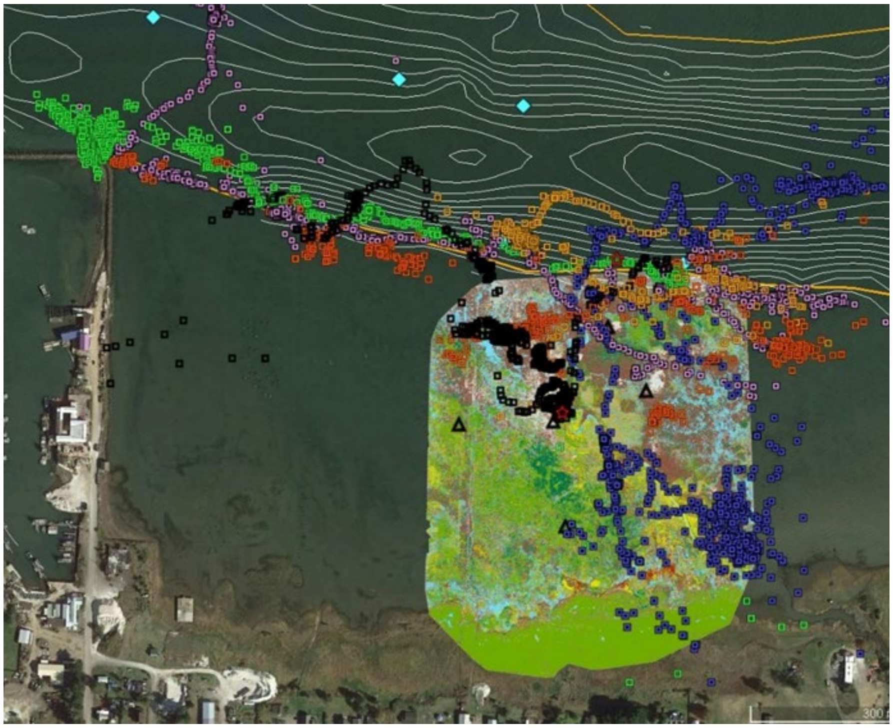

Figure 15. Example tracks of European green crab at the public oyster grounds site showing varied occupation of intertidal habitat, trajectories along the shallow subtidal berm, and a concentration at the jetty. Each color/shape is an individual crab track.

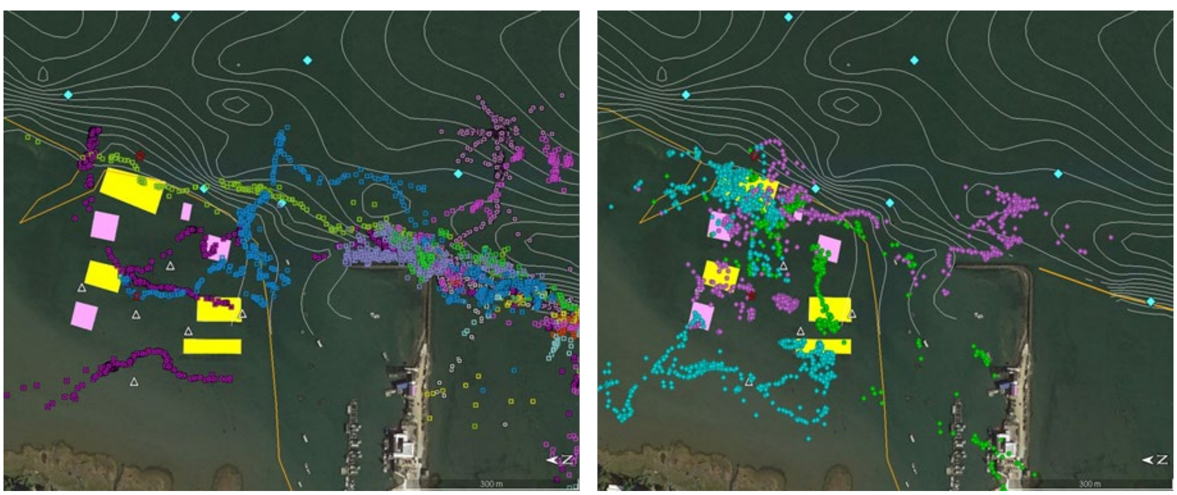

Figure 16. Example tracks of individual European green crab at the aquaculture farm site showing moderate (left) and high (right) occupation of aquaculture infrastructure. Note also the concentration of crab at the jetty. Each color/shape is an individual crab track.

5.0 Summary

There were fundamental differences in residency and sub- and intertidal habitat use between species. Dungeness crab were primarily subtidal with only three individuals tracked onto intertidal habitats. Subtidal tracks tended to be long, linear movements and overall distributions spanned the channel. Group residency was less than 15 d, with a single crab retuning (after a gap of >30 d). Seventeen of nineteen crabs were detected on the Willapa Bay receiver network, moving both north and south of the release site.

In contrast, fewer European green crab appeared to migrate from the release site, and about half were detected throughout the 139-d monitoring period. European green crab made extensive use of both intertidal and shallow subtidal habitats (~30% of detections were intertidal), and commonly transited sub- and intertidal zones. In the intertidal zone, European green crab exhibited quiescent, meandering, and transit activity patterns that appeared to vary between intertidal sites.

At the public oyster grounds, European green crab appeared to be more active and to prefer oyster reef and tidal creek channel. At the aquaculture farm, many crabs were quiescent or meandering and were strongly associated with aquaculture infrastructure, particularly oyster cultch bags in the low intertidal areas. Crabs were observed to reside for days or weeks within these structures, while sometimes making forays to surrounding habitat.

While Dungeness crab had a wide subtidal distribution, most European green crab remained and moved along the narrow subtidal bank and were less commonly detected in deep channel environments. Crabs could transit rapidly along this bank (not quantified for this report), but they also were observed to meander or remain relatively quiescent at subtidal locations. Of the 20 crabs released at southern release sites, 10 moved north along the bank, where they often congregated at the rocky jetty.

European green crab showed a mixed propensity for site fidelity. While residency was high for some individuals, there was frequent movement between sub- and intertidal regimes, and about half migrated from the release area during the study. Transit rates in intertidal areas could be substantial, and while movement at the bay-scale appeared lower for European green than for Dungeness crab, wide dispersal or replenishment of favorable areas was possible.

Given the subtidal occupation and relatively rapid transit rates of European green crab, "fishing out" a particular intertidal area may confer limited long term benefit without a system-wide effort. Prioritizing high value areas where green crab are likely to cause greater ecological and economic damage may provide the greatest benefit.

This pilot study confirms the usefulness of acoustic telemetry for discerning crab movements at sub- and intertidal habitats. However, the results are confined to adult crabs in the autumn-winter season. It may be warranted to repeat the experiment (with augmented receiver distribution) during the warmer months when invertebrate recruitment peaks. This may, for example, provide evidence of increased crab activity on infaunal clam beds. Targeting gravid females (which become common in November) may be another effective management option. A study to document their habitat preferences is warranted.

5.1 Recommendations for enhanced trapping/trap placement strategies

Based on these observations of tagged European green crab movement and behavior, we have identified two strategies that could be effective for enhanced trapping/trap placement:

1. ***Trap in shallow subtidal habitats***. European green crab spent more time at subtidal than intertidal locations, and both resided and transited in a relatively narrow spatial zone along the channel bank. Rocky substrate perhaps used as shelter (like the jetty) could also be targeted for concentrated fishing effort.

2. ***Prioritize high value areas likely to reduce economic damage.*** Possibilities include increasing trap density or reducing shelter opportunity at intertidal oyster culture structure. European green crab clearly preferred oyster culture structure and especially the dense oyster grow-out bags. Redesigning the geometry of the bag arrangement and increasing fishing pressure within/around oyster bags could aid eradication.

Other structural elements, such as oyster reefs and intertidal/shallow subtidal channels, are also preferred habitat that could be targeted for removal.

6.0 Acknowledgements

We thank the Washington Department of Fish & Wildlife, Washington State Recreation and Conservation Office (Project: 22-1995 OPS, European Green Crab Emergency Measures), the Willapa Bay Oyster Reserve Board, and NOAA Fisheries for providing the funding and in kind support for this effort. Tagging and receiver deployments were aided by Joe Vinarcsik (NOAA), and WDFW’s Brian Turner, Hanna Robinson and Shelby Gentry. Thanks to Warren Cowell, Willapa Bay Shellfish, who provided crab for tagging as well as data on tagged crab recaptures, and Steven Corbett (NOAA) for crab detection data from the WB network. We thank the local shellfish growers and property owners who allowed access to their tidelands including Pacific Shellfish, Wiegardt & Sons, Heckes Clam Co. and the Port of Peninsula. Joanne Butzerin (NOAA) edited the document, and Kym Jacobsen (NOAA) reviewed the report. We appreciate their contributions.

7.0 Literature cited

Behrens Yamada, S, WT Peterson, PM Kosro. 2015. Biological and physical ocean indicators predict the success of an invasive crab, *Circinus maenas*, in the northern California Current. Mar Ecol Prog Ser 537: 175–189.

Brasseale, E, EW Grason , PS McDonald, J Adams, P MacCready. 2019. Larval transport modeling support for identifying population sources of European green crab in the Salish Sea. Estuaries and Coasts: 42:1586–1599.

Carlton JT, Cohen AH. 2003. Episodic global dispersal in shallow water marine organisms: the case history of the European shore crabs *Carcinus maenas* and *C. aestuarii*. J Biogeogr 30: 1809−1820

Coleman, A, GC Roegner, A Borde, I Gonzalez-Hirshfeld, T Saltiel, S Zimmerman, S Hendrickson, J Aga, G Pierce. 2021. Remote sensing of burrowing shrimp density on intertidal substrates with an Unmanned Aerial System. Ground-truth and calibration surveys. Report of research to the Pacific Conservation District, Washington State Conservation Commission by the Pacific Northwest National Laboratory, Richland, Washington 99354. DOI: 10.13140/RG.2.2.34414.54083

Dare, PJ, DB Edwards. 1981. Underwater television observations on the intertidal movements of shore crabs, *Carcinus maenas*, across a mudflat. Journal of the Marine Biological Association of the United Kingdom 61:107–116.

Heironimus, L.B., M.T. Sturza, and S.M. Schade. 2023. Tagging green sturgeon with acoustic transmitters for evaluation of habitat use along the Washington Coast. Interim Report. Prepared for: U.S. Navy, Commander, Pacific Fleet. Prepared by Washington Department of Fish and Wildlife under Cooperative Agreement #N62473-20-2-0005. 06 March 2023. 78 pp

Hidalgo, F.J.; Baron, P.J.; Orensanz, J.M. A prediction come true: 2005. The green crab invades the Patagonian coast. Biol. Invasions 7: 547–552.

Leignel, V, JH Stillman, S Baringou, R Thabet, I Metais. 2014. Overview on the European green crab Carcinus spp. (Portunidae, Decapoda), one of the most famous marine invaders and ecotoxicological models. Environ. Sci. Pollut. Res. 21: 9129–9144.

Lovell, S. J., E. Y. Besedin, and E. Grosholz. 2007. Modeling economic impacts of the European green crab. Selected Paper prepared for presentation at the American Agricultural Economics Association Annual Meeting, Portland, OR, July 29-August 1, 2007

Mach, ME, KM Chan. 2013. Trading green backs for green crabs: evaluating the commercial shellfish harvest at risk to European green crab invasion. F1000Research 2:66; doi.org/10.12688/f1000research.2-66.v1

Matheson, K. CH. McKenzie, RS Gregory, DA Robichaud, IR Bradbury, P. V. R. Snelgrove, GA Rose. 2016. Linking eelgrass decline and impacts on associated fish communities to European green crab *Carcinus maenas* invasion. Mar Ecol Prog Ser 548: 31–45.

McDonald, PS, GC Jensen, DA Armstrong. 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.

Poirier, L. A., L. A. Symington, J. Davidson, S. St-Hilaire, and P. A. Quijón. 2017. Exploring the decline of oyster beds in Atlantic Canada shorelines: potential effects of crab predation on American oysters (Crassostrea virginica). Helgoland Marine Research 71:1-14.

Roegner, GC, SA Fields. 2014. Mouth of the Columbia River beneficial sediment deposition project. Benthic Impact Study. Report of research from NOAA Fisheries to US Corps of Engineers Portland District.

Smith, F. 2013. Understanding HPE in the VEMCO Positioning System (VPS) V1.0. VEMCO Document# Doc-005457–07. VEMCO Inc., Halifax. 31pp.

Young, AM, JA Elliott. 2020. Life History and Population Dynamics of Green Crabs (*Carcinus maenas*) Fishes 5: 4; doi:10.3390/fishes5010004

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