The 2021 European green crab (*Carcinus maenas*) Invasion in Lummi Sea Pond

Technical Report

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March 2023

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ABSTRACT

European green crab (*Carcinus maenas*; hereafter "EGC") were first discovered on Lummi Nation tidelands in 2019 and were captured in north Lummi Bay and Lummi Sea Pond (LSP); the latter a fully enclosed 750-acre seawater pond situated in Lummi Bay, built in the 1970s and historically used to cultivate salmon, clams and oysters for commercial harvest. Increased trapping effort by Lummi Natural Resources (LNR) Department and Washington Department of Fish and Wildlife (WDFW) staff in 2020 suggested EGC densities were growing at a rapid rate in LSP relative the rest of the tidelands. In 2021, coordinated trapping effort across multiple agencies led by LNR and the implementation of a new trap type, greatly increased EGC captures in LSP. By August 2021, EGC captures in LSP surpassed the entire years' captures in 2020 (>2,500 EGC), which galvanized an emergency-level trapping effort in LSP for the remainder of the trapping season.

The goal of this report is to summarize the 2021 EGC trapping effort in LSP and document the change of relative abundance across years (2019-2021), months (April-December 2021), and by trap types (fukui-style, minnow, shrimp). Trapping data was standardized to calculate catch per unit effort (CPUE), defined as number of EGC per 100 trap sets, and describe relative abundances of EGC in LSP. The influence of increased soak nights on number of captured EGC was also explored to identify methods of standardizing CPUE and increasing trapping efficiency.

At the end of 2021, a total of 85,803 EGC were captured inside Lummi Sea Pond, the majority of EGC captured using shrimp traps (brand Promar) which had not been used in Lummi Sea Pond prior to 2021. Despite controlling for uneven effort between years, temporal patterns revealed heightened CPUE in September 2021 compared to the same period in 2020. Catch rates were elevated in September and October, when CPUE tripled in less than a month of trapping effort. Shrimp traps were the most effective trap style and reached an average of more than 2000 CPUE by late September. Increasing soak nights increased total EGC captures; however, capture efficiency reduced as soak length increased.

EGC size distributions during the 2021 trapping season suggest at least three different size classes or cohorts were present in LSP. In the first few months of the 2021 trapping season, EGC carapace widths were either near or above the threshold for juvenile EGC (49 mm). Beginning in July, a young cohort of EGC emerged (<30 mm) which dominated the size distribution before the end of the year.

The strong young of year cohort observed in 2021 trapping efforts, suggests conditions were optimal for EGC settlement and growth in LSP and validates the predictions by Mueller and Jefferson (2019). Several trapping and control measures are discussed, including repair of the tide gates that have control over the water level in Lummi Sea Pond and will lead to greater control of EGC settlement in LSP.

Suggested citation for report:

Buzzell, B. (2023). The 2021 European green crab (*Carcinus maenas*) invasion in Lummi Sea Pond. Aquatic Invasive Species Division Technical Report. Lummi Natural Resources Department, Bellingham, Washington. Pp. 27+v.

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INTRODUCTION

In the last several decades the European green crab, *Carcinus maenas* (hereafter "EGC") has become a well-established invasive species on the U.S. east and west coasts (Klassen and Locke, 2007). In its non-native range, EGC are infamous for their aggressive, predatory behavior and adaptability to changing environments (Tepolt et al. 2020). EGC are a serious concern for Lummi cultural and economic resources, especially shellfish aquaculture where they will over-predate on juvenile bivalve species, diminishing future harvests. Often referred to as an "ecosystem engineer", EGC destroy essential eelgrass habitat that many nearshore marine species rely upon, including juvenile salmonids (Howard et al. 2019; Kennedy et al. 2018).

Introductions to the U.S. east coast from Europe and North Africa were likely due to trans-shipment activity in the 1800s, and then to the San Francisco Bay area in the 1980s from shellfish transplants (Cohen et al, 1995). Northward expansion of EGC along the U.S. west coast has been mainly through the transport of EGC larvae on ocean currents; strong settlements of EGC have been aided by intense El Niño events across the eastern Pacific Ocean in 1997/1998 and 2015/2016, causing conditions which extended the survival and distribution of larval stage EGC (Yamada et al. 2021). However, EGC introduction into the Strait of Juan de Fuca is thought to be from shellfish transplants into Sooke Basin (Curtis et al. 2015). Human mediated vectors coupled with altered ocean conditions increased opportunities for settlement in the Salish Sea, most notably in Drayton Harbor and Lummi Bay (Mueller and Jefferson, 2019).

EGC were first detected on the Lummi Nation tidelands in October and November 2019 (Mueller and Jefferson, 2019). Multiple sites on-reservation were trapped by Lummi Natural Resource staff (LNR), and 2 of 12 sites contained EGC, including the bay-side of the Northern Lummi River Distributary tide gate at the Sandy Point Heights neighborhood and the north shoreline within Lummi Sea Pond (Fig. 1).

Lummi Sea Pond (LSP) is a 750-acre, man-made aquaculture pond built into the shoreline of Lummi Bay and fully enclosed by a 3-mile-long dike road (Heath et al. 1975). Constructed in the 1970s, LSP was intended to aid Lummi Nation's economy and bolster community through the growth and harvest of salmon and oysters. Water level in LSP is controlled by a series of tide gates at 4 locations along the dike; however, the tide gates are not fully functional. Although in disrepair, the tide gates maintain at least 5 feet of water to supply saltwater for present-day shellfish aquaculture operations: oysters, manila clams, and geoduck. Tidal exchanges in Lummi Bay have a delayed influence on water level in LSP, and it takes several days to observe an overall change in water level. With minimal tide influence and protection from most predators, LSP is truly a unique environment specifically designed to maximize the growth of shellfish species.

After the first discovery of EGC on Lummi Nation Tidelands in 2019, LIBC passed Resolution #2020-032, declaring EGC a serious environmental threat. LNR led a multiagency response with Washington Department of Fish and Wildlife (WDFW) to increase trapping effort in LSP and the surrounding tidelands from April to November 2020[1]. At season's end, 2,730 trap sets were completed in LSP and 2,490 EGC were removed (only 7 EGC removed at Sandy Point Heights) –LSP was recognized as a hotspot of EGC densities within Washington State. Although no gravid ("egg-bearing") EGC were captured in 2020, mating pairs and young of year (i.e., juvenile EGC; hereafter, YOY) were observed, suggesting natural reproduction was occurring within LSP.

[1] Mueller, K., Jefferson, N. 2021. The 2020-2021 Lummi Nation European Green Crab Invasion Response: Final Report, Part 1, Contract No.20-15309, Amendment 1. Lummi Indian Business Council, Natural Resources Department.

Figure 1. Satellite view and maps of invasive European green crab (EGC), *Carcinus maenas*, sampling locations on Lummi Nation reservation tidelands within Lummi Bay (top) and Portage Bay (bottom), Whatcom County Washington; Lummi Sea Pond (LSP), and Sandy Point Heights (SPH) were the only two trapping locations containing EGC (Mueller and Jefferson, 2019).

EGC specimens from both inside and outside LSP in 2019 and 2020 were retained for genetic analysis to understand the population's origin[1]. Preliminary results from mRNA sequencing of 2019 EGC specimens indicated a mixed origin from outside the Salish Sea and from Sooke Basin on Vancouver Island, BC; however, the majority of 2020 EGC specimens suggested the emergence of a possible LSP genetic signature. These results provide further evidence that the EGC in LSP are a self-sustaining and naturally reproducing population.

In April 2021, LNR further increased trapping effort in LSP with assistance from WDFW. In July, a designated LNR team for EGC trapping was hired and a new trap style was introduced. By August, heightened effort resulted in the capture of more than double the EGC removed from LSP in all of 2020. Increased capture rates led to a largescale rapid joint response in September and October with multiple staff from WDFW, WSG, and the Northwest Straits Commission (NWSC)—the main goal being to remove as many EGC as possible from LSP. In November, LIBC passed Resolution #2021-158 and declared an EGC disaster after more than 70,000 EGC had been captured and removed from LSP. Trapping continued into December with a final count of *85,803* EGC removed from LSP—which at that time was the largest documented EGC population density in Washington State.

Given the astonishing escalation of green crab captures from 2019-2021, our goal for this report was to describe and quantify the magnitude and complexity of EGC trapping efforts in LSP. Therefore, the objectives for this report were to:

1) Quantify trapping effort and examine LSP EGC capture rates for the 2021 trapping season,

2) Assess efficiency of various trap types used in LSP,

3) Examine catch rate discrepancies with increasing fishing time,

4) Describe EGC population dynamics, sex ratios and total carapace width distributions,

5) Provide temporal-spatial snapshots of increased trapping effort and catch rates in LSP, and

6) Summarize capture of bycatch species.

Lastly, we expand and reiterate management implications and suggestions from Mueller and Jefferson (2019) for future EGC control in Lummi Sea Pond and Lummi Nation Tidelands.

MATERIALS AND METHODS

Trapping Protocols

The EGC trapping season in LSP took place from April 15- December 17, 2021, initially at bi-weekly intervals and then increased in frequency up to 5 days per week. Overall trapping protocols closely followed those of Washington Sea Grant's (WSG) Crab Team used by the citizen science monitoring program[2] but were modified as appropriate for EGC removal trapping in LSP.

Two predominant shoreline types exist in LSP; marsh and grasslands along the north central to eastern shoreline, and the boulder-armored dike wall. The marsh zone remains shallow (<1 m) with a gradual decline, but the dike wall has a steeper grade (Fig. 2). Trap types were chosen based on use in other EGC trapping programs (e.g.,

[2] Washington Sea Grant Crab Team Volunteer Toolbox. 2022 (updated). https://wsg.washington.edu/crabteam/getinvolved/toolbox/

WSG, WDFW) and trapping efficiency (Bergshoeff et al. 2018). Trap specifications and modifications are listed in Table 1 and the three main trap types are pictured in Figure 3 (A-C).

Figure 2. Shoreline types along the north central shoreline of Lummi Sea Pond (top) and the boulder dike wall (bottom); pictured on top are Elias Plaster and Delaney Adams (LNR), photo credit Bobbie Buzzell.

Table 1. Trap types, specifications, and modifications for invasive EGC trapping during the 2021 trapping season on Lummi Reservation tidelands.

Trap type	Brand	Trap size (in)	Mesh size (in)	Tunnel type	Modification
Fukui-style	American Maple Inc/Promar	24x18x8	1/2	2 x Mesh	Yes*
Shrimp	American Maple Inc/Promar	24x24x9	1	4 x Semi-rigid Mesh	Yes**
Minnow	Gee	9x17.5	1/4	2 x Rigid mesh	Yes***
Coonstripe shrimp trap	Ladner	30x30x18 (at bottom)	7/8	3 x Ring	No

*Zip-tied tunnel openings; **Zip-tied tunnel openings in September 2021; 2 pieces of 2' by 1/2" rebar added to weigh down trap; *** Tunnel openings expanded to ~2-3"

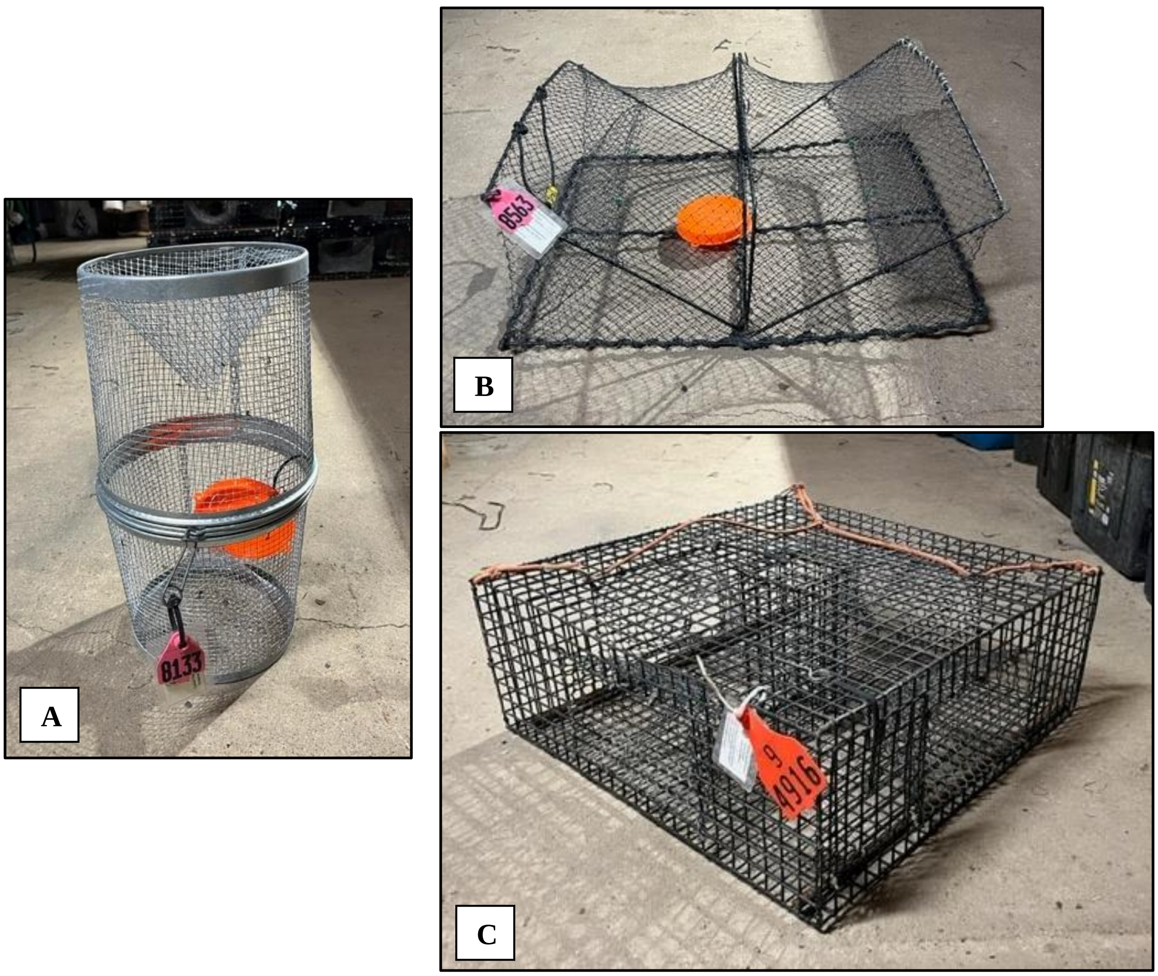

Figure 3. The three main trap types used during the 2021 European green crab trapping season in Lummi Sea Pond. (A) minnow, (B) fukui-style, and (C) shrimp. Orange lid of bait jars shown for minnow and fukui-style traps. Photo credits: Jonathan Hallenbeck.

Along the inside perimeter of LSP, minnow and fukui-style traps were alternately set 10-15 m apart in a single transect of 20 or more traps and each anchored with metal stake or weighted with rocks inside the trap when stakes could not penetrate the substrate. At the height of the season's trapping effort, transects of minnow and fukui-style traps were deployed in a parallel manner, but spaced at least 10 m away from one another. Shrimp traps were similarly deployed on the inside perimeter of LSP at 10-40 m apart. Starting in August, shrimp traps replaced the use of minnow and fukui-style traps along the dike road. Floating line and buoys were attached to each shrimp trap to facilitate visual locating. Shrimp traps were also deployed in transects in the middle of LSP when a watercraft was available. Figure 4 provides an example of 2 days of trapping effort and extent in LSP.

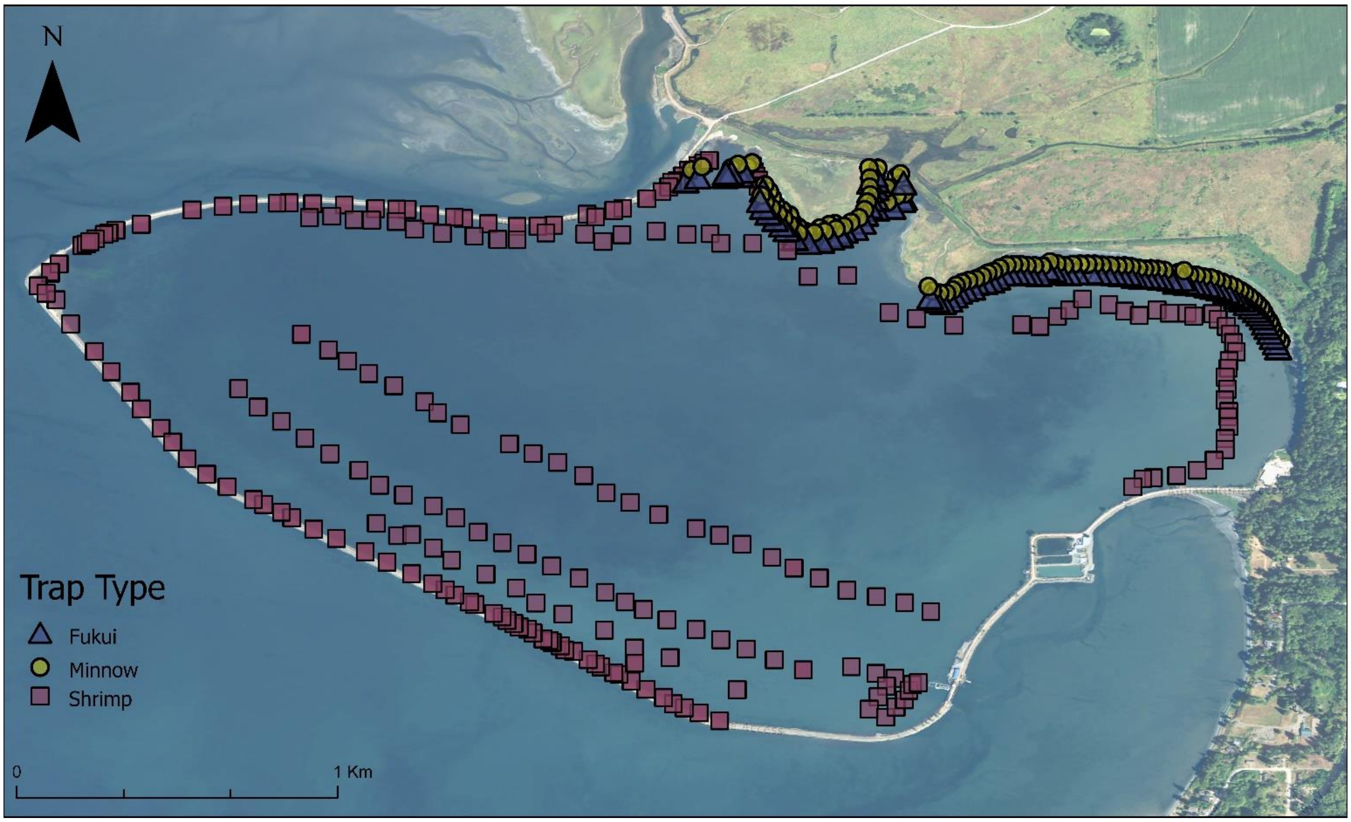

Figure 4. European green crab (*Carcinus* maenas) trapping effort (roughly 500 trap sets) and coverage in Lummi Sea Pond over 2 days in October 2021 involving multiple field staff from Lummi Natural Resources and Washington Department of Fish and Wildlife.

All traps included the following information when deployed and checked/retrieved: deployment and check/retrieval date and time, trap type, unique identifier (tag number), GPS coordinates, field staff initials, weather, bait type, count of female and male EGC, total EGC, and count of gravid female EGC. Clasping or mating EGC pairs and dysfunction traps (e.g. hole, open door, etc…) were also noted. We defined fishing time as number of soak nights where 1 soak night was equal to approximately 24 hours submerged underwater; soak night was calculated using the deployment and check dates during data entry and processing. EGC captured by hand were documented with the date/time and coordinates (exact or the nearest trap). Total carapace width was measured for either all captured EGC in a single day; or on a pre-determined subset day when trap processing time increased in September at the height of effort and catch rates. Similarly, trap processing time limited collection of other information, such as non-target species which were only recorded for minnow and fukui-style traps on trap check days April 16, and September 29.

Traps were baited with mackerel, sardines, herring, or salmon when available from the Lummi Nation hatcheries. Shrimp traps contained a central bait box and were baited with a single mackerel, sardine, or herring (estimated 0.25-0.50 lb) or piece of cut salmon (estimated >0.25 lb). Minnow and fukui-style traps contained bait jars that were baited with ½ of a single mackerel, sardine, or herring. EGC was also tested as bait (4 shrimp trap sets) or combined with other bait types (40 shrimp trap sets). Based on field observations of minimal EGC catch, EGC bait was deemed unfit for continued use. If minnow and fukui-style traps were deployed for more than 2 soak nights, traps were rebaited after the second soak night. Shrimp traps were rebaited as necessary or sometimes left unbaited over a weekend-long soak.

At the time of trap checking or retrieval, all catch was removed and EGC were retained, frozen, and disposed. Frozen EGC were either composted or delivered to Recycling & Disposal Services Inc. in Bellingham, Washington. Bycatch was immediately returned to the water when checking traps.

Summary Statistics

1) Document and summarize the 2021 trapping season by examining LSP green crab capture rates and quantify trapping effort,

Here, we described methods to standardize and compare trapping effort and catch rates in LSP. First, we provide an overall table summary of effort in 2021 which included; a total number of trap sets (n), total captured EGC, total gravid female EGC, and total mating pairs for each trap type. We defined trap set as a single trap deployed and checked, regardless of trap type, bait used, and trap functionality. Day-to-day effort was described by plotting total number of trap sets by the most frequently used trap types (shrimp, minnow, and fukui-style). To describe and visualize patterns in effort, a trendline was fitted using the locally weighted scatterplot smoothing (LOWESS) method.

We used catch per unit effort (CPUE) to describe relative abundance of EGC over time in LSP (Hubert and Fabrizio, 2007). CPUE was calculated for each trap set as:

$$CPUE=(N/t)\times 100$$

Where N=number of captured EGC,

and t=number of soak nights.

For standardization with previous EGC trapping data (Mueller and Jefferson, 2019), CPUE was expanded to 100 trap sets and only included shrimp, minnow, and fukui-style traps (coonstripe traps omitted, hand captures not applicable) that received 1 soak night prior to being checked. Traps that did not meet this criterion were omitted from the standardized CPUE, which included traps that were checked twice within the same day (<24 hours), checked after 2 or more soak nights (48+ hours), unbaited or baited with EGC, or dysfunctional (e.g., trap door open, damaged). Traps with "unknown" bait type in 2021 data were still included in CPUE (approximately 4,000 trap sets) but were removed for all further analyses.

2) Assess efficiency of various trap types used in LSP.

Daily mean CPUE for the trapping season was plotted by trap type and a trendline was fitted using the LOWESS method to describe and visualize patterns. Distribution of 2021 CPUE by trap type was displayed with a box-and-whisker plot; the box encloses the lower and upper quartiles of data points (i.e., 25% and 75%) and the median value is indicated by a line. Points indicate outliers.

CPUE of EGC for years (2019-2021), months (October and September), and trap type (minnow, fukui-style, and shrimp) was tested for differences among groups using a one-way non-parametric Kruskal-Wallis (K-W)

ANOVA rank sum test, which does not assume a normal distribution nor equal variances (H statistic; McKight and Najab, 2010). Significance testing was conservative with CPUE and limited to one variable at a time with the most robust sets of defined data, and the variables of most interest for increasing trapping efficiency. *Post-hoc* pairwise comparisons were completed using Dunn's test (Z statistic) where appropriate, to determine significance between more than three groups (Dinno, 2015; Ogle et al., 2022). To correct for multiple tests, the Sidak method was applied. Significance was determined at $a=0.05$. All analyses were completed in RStudio 1.4.1717 (R Core Team, 2022).

Due to a heavy effort/sample bias towards 2021 trapping effort and catch, not all trapping data could be compared across years. To gain power in statistical testing, fukui-style and minnow trapping data was summarized together and CPUE averaged for September and October in each trapping season. September was the peak month of catch rates in 2021, and October was the only common month trapped in all 3 trapping seasons. Prior to statistical testing, trap sets from each month and year grouping were randomly subset (R functions "set.seed()" for reproducibility and "sample()" without replacement), to n=48 to match the year of fewest trap sets prior to testing (September n=604, October n=48) and compensate for the disparity in number of trap sets. A violin chart overlaid with a box-and-whisker plot (see description for trap checks plot) was used to describe density and distribution of CPUE values for each group.

3) Examine catch rate discrepancies with increasing fishing time.

We assumed that fishing duration (i.e. soak night) influenced CPUE, and because many traps received 2 or more soak nights a large portion of data was rendered unusable for standardizing CPUE. However, LSP provided a unique situation to examine this assumption since movement of EGC into traps was not dependent on tidal exchange (Hunter and Naylor, 1993).

Here, we describe methods and controlled variables to determine influence of soak night on EGC captures in shrimp traps. Influence of bait type on shrimp trap CPUE has not been studied, but in fukui-style traps bait type has been shown to influence EGC catch rates (Favaro et al. 2020); we controlled for this possible variation by only examining trap data with salmon. Up to 5 soak nights were included in the analysis to reflect a week without checking traps. The number of trap sets was highly variable across soak nights with 5 soak nights containing the fewest trap sets (n=47). A random subset (see previous section for random method description) of trap sets that received 1, 2, or 4 soak nights was used to match the 5 soak nights sample size for statistical comparisons (n=47 for each group). No salmon-baited shrimp traps received 3 soak nights, and thus was omitted. The final subset consisted of shrimp traps checked along various sections of LSP's inside perimeter (Table 1). The K-W test was used to determine the influence of soak night on total captures, and Dunn's test was used for *post-hoc* pairwise comparisons where appropriate. A violin chart overlaid with a box-and-whisker plot was used to describe the density and distribution of total EGC captures in salmon-baited shrimp traps by soak night.

4) Describe EGC population dynamics, sex ratios and total carapace width distributions.

We found ridgeline density plots were appropriate for describing size trends in total carapace widths of EGC, which are increasingly being used to show size frequency densities over time (Waltham et al. 2020). Several plots were generated to describe patterns by sex, years, months, and trap type, including hand captures. No carapace widths from EGC captured in coonstripe traps were measured and so this trap style was excluded from the summary. Total number of EGC (n) measured is stated for each plot.

5) Provide temporal-spatial snapshots of increased trapping effort and catch rates in LSP.

To help readers fully grasp the extent of trapping effort, and the temporal and spatial change in CPUE, aerial snapshot maps of the LSP north central shoreline were used to display the increase in effort and catch rates over a

4-month period at 1-month intervals. Snapshots display all effort and catch rates (EGC per trap) over the course of 7 days for the most frequently used trap types (fukui-style, minnow, and shrimp). All maps were created in ArcGIS Pro 3.0.0 (ESRI 2022).

6) Summarize bycatch species.

As noted in trapping protocols, bycatch was not recorded for most of the trapping season; however, bycatch species count data from April 16 and September 29 was summarized with counts of EGC by trap type (fukui-style and minnow) using a stacked histogram to describe capture proportions of non-target species between the two dates. Trap transects from both trapping days were deployed in the same locations along the north central shoreline of LSP.

RESULTS and DISCUSSION

Effort and Catch Rates

At the end of 2021, a total of 85,803 EGC were removed from LSP and nearly 16,000 traps checked (Table 2). The majority of EGC were removed between September and November during the joint rapid-response effort by LNR, WDFW, NWSC, and WSG. Among the various trap types used, shrimp traps were the most used trap style and captured 70,129 EGC between July and December 2021. Shrimp traps also captured the most mating EGC pairs and gravid female EGC (Table 2). Minnow traps had the second most total captures of EGC, followed by fukui-style traps. Relatively few EGC were captured by hand, but this method was effective in removing mating pairs, likely because this behavior makes crabs slower, and more vulnerable to capture.

Table 2. Summary by trap type of 2021 total number of trap sets, European green crab (EGC) captures, and total gravid and mating pairs (clasping female and male crab pairs) in Lummi Sea Pond.

Trap Type	Trap sets	Total EGC	Total Gravid	Mating Pairs
Coonstripe	5	15	0	0
Fukui	5,054	6,069	5	3
Hand	-	308	0	14
Minnow	4,301	9,258	2	0
Shrimp*	6,621	70,153	43	33
Total	**15,981**	**85,803**	**50**	**50**

*Implemented in July 2021

Relative to trapping effort in LSP, very little trapping (15 trap sets) was conducted elsewhere on the tidelands in 2021 and so, sparse information is available for EGC distribution on the tidelands during that time. No EGC were trapped at the Sandy Point Heights tide gate (Fig.1) after a single night soak of minnow and fukui-style traps in April. Four EGC were captured in shrimp traps deployed in proximity to the two tide gate openings along the north dike. With limited trapping outside LSP in 2021, it was difficult to gauge the extent of EGC distribution on Lummi Nation tidelands.

Daily mean CPUE remained below 300 EGC per 100 trap sets for minnow and fukui-style traps from April to August (Fig. 5). Only 5 shrimp trap sets deployed for a single soak night in May resulted in a mean of 480 CPUE. Shrimp traps were not deployed again until the end of July, but daily catch rates similarly averaged 500 CPUE (n=30). Mean CPUE first increased with minnow and fukui-style traps in August and reached upwards of 800 CPUE at the beginning of September. Shrimp trap mean CPUE also increased in summer, but the peak was reached in late September and early October at a daily mean of 2000-4000 EGC per 100 trap sets. The largest catch for a single shrimp trap and soak night was 140 EGC.

Although increased effort and use of shrimp traps were major factors in record-breaking EGC captures in LSP (and Washington), the monthly trend in mean CPUE mirrored the increase in trapping effort (Fig. 5; Fig. 6). Increased effort was coupled with a sharp rise in daily mean CPUE in all three trap types, where CPUE more than tripled in less than a month.

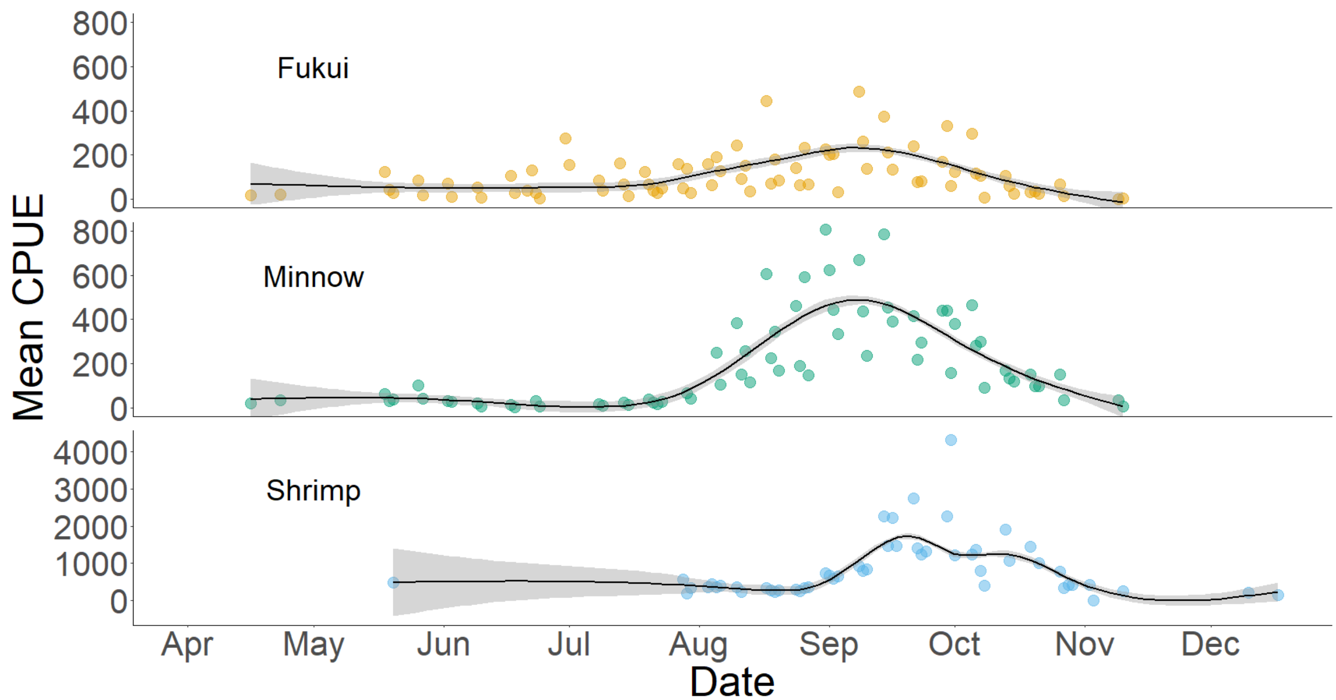

Figure 5. Mean CPUE (catch per unit effort, EGC per 100 trap sets) for each trapping day by trap type in Lummi Sea Pond for 2021 fitted with LOWESS trendline, gray represents standard error; trap counts for Fukui n=4910; minnow n=4245; shrimp n=3713 (note different y-axis scale limit for shrimp traps).

EGC captures in 2021 surpassed captures in prior trapping seasons, but there were some caveats when examining October and September monthly CPUE separately and across previous seasons (Table 3). Firstly, mean CPUE in September months significantly increased by more than 100 CPUE from 2020 to 2021 (H=18.70, df=1, *P<.01*; Table 3, Fig. 7). In October months, mean CPUE more than doubled from 2019 to 2020 (Z=-2.84, *P.adj<.01*). However, the decrease from 2020 to 2021 and the increase from 2019 to 2021 were not significant (Z=1.86, *P.adj=.18* and Z=-.98, *P.adj=.70*, respectively).

In summary, we statistically confirmed the rise in CPUE over the 3 trapping seasons even when controlling for number of trap sets (Fig. 7). Although a difference in October CPUE was not detected between 2021 and previous seasons, it is promising that CPUE was curbed in October 2021, and likely a result of heightened trapping effort in September– as was the goal of emergency-level trapping effort.

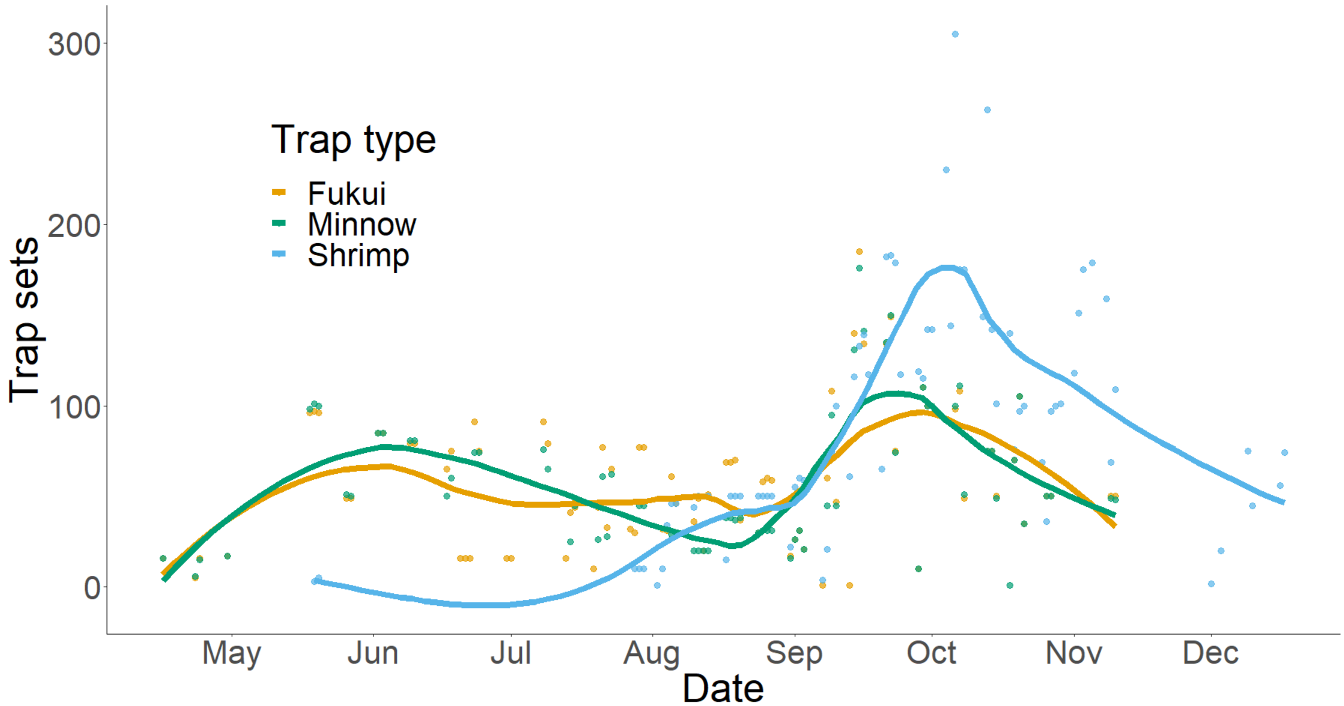

Figure 6. EGC daily trapping effort based on number of trap sets (regardless of soak nights, bait used, or trap functionality) by trap type for each day of effort from April to December 2021; LOWESS method used for fitting trendline.

Table 3. Lummi Natural Resources Department's 2019-2021 EGC monitoring and removal trapping summary for September 2020-2021 and October 2019-2021; only fukui-style and minnow trap data was used (CPUE=count of EGC per 100 trap sets). Mean CPUE adj. provides the adjusted mean CPUE after randomly subsetting trap sets for September (n=604) and October (n=48).

	September		**October**		
Year	*2020*	*2021*	*2019*	*2020*	*2021*
Mean CPUE	195.86	312.18	85.42	200.41	154.02
Mean CPUE adj.	-	305.96	-	185.42	168.75
Total trap sets	604	2,611	48	491	1,916
Total EGC	1,183	8,151	41	984	2,951

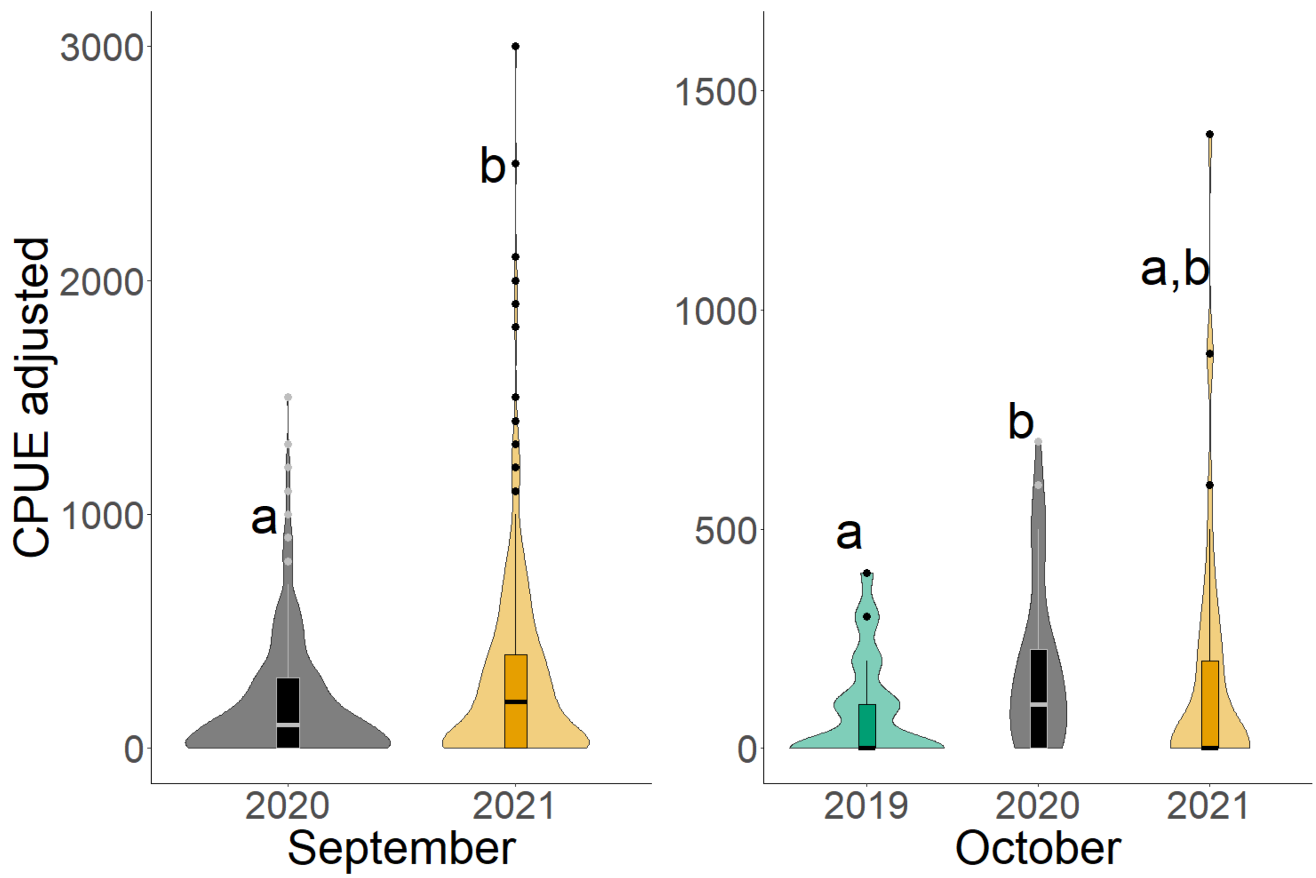

Figure 7. Violin and box-and-whisker plots of adjusted minnow and fukui-style trap CPUE (count of EGC per 100 traps sets) from September 2020-2021 (left) and October 2019-2021 (right) in Lummi Sea Pond. Traps were randomly subset from September 2021 (n=604) and October 2019-2021(n=48) to create even sample sizes between years; different letters indicate statistical difference (*P<.01*).

Pairwise comparisons of CPUE by trap type confirmed shrimp traps were the most effective trap style. Mean catch rate of shrimp traps was 1024 EGC per 100 trap sets, or nearly 5 times the mean capture rate of minnow traps (217.6 EGC per 100 trap sets) and 8.5 times the mean capture rate of fukui-style traps (120.2 EGC per 100 trap sets; *P.adj<.01* for all comparisons; Fig. 8). During peak effort at the start of October, daily mean capture rates frequently exceeded 1000 EGC per 100 trap sets, while mean capture rates of minnow and fukui-style traps remained below 500 EGC per 100 trap sets (Fig. 4). Although this trend was not tested on a temporal scale, shrimp trap CPUE consistently exceeded catch rates of the other trap styles throughout the season.

Ranson (2022) noted similar findings examining September 2021 trapping data and found that shrimp traps had a higher EGC detection probability than minnow and fukui-style traps regardless of trap placement inside LSP. One of the most obvious differences between the shrimp trap and other styles, is its larger volume, likely increasing capture capacity. Along with other notable differences of each trap style (e.g., number of tunnel entries, mesh size), it has been shown that the degree of bait exposure can influence CPUE (Miller 1979). Bait jars limit residual feeding activity of both target and incidental catch in minnow and fukui-style traps; however, bait jars likely reduce the smell of bait in the water compared to the more accessible bait box style in shrimp traps (Fig. 3).

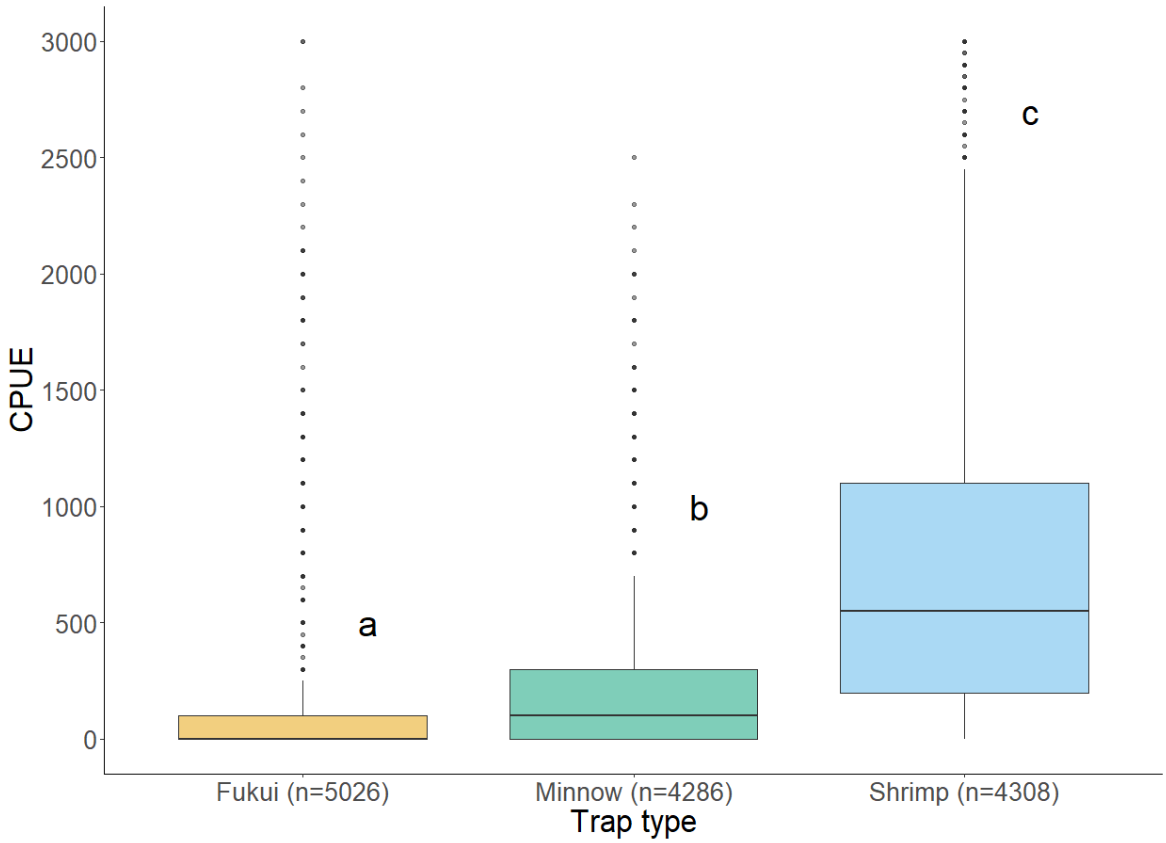

Figure 8. Box-and-whisker plot of EGC CPUE (EGC per 100 trap sets) for the three most used trap styles during the 2021 trapping season in Lummi Sea Pond; different letters indicate statistical differences between trap styles.

As previously assumed, statistical testing indicated soak night length influenced the total captures of EGC in salmon-baited shrimp traps (K-W test, H=70.578, df=3, $P<0.01$). *Post hoc* analysis suggested there was a significant increase in total captures after 2 soak nights; but no differences in total captures were found between 1 and 2 soak nights, and between 4 and 5 soak nights (Table 4; Fig. 9). Despite confining variables within certain parameters (shrimp traps, salmon bait, October trap sets), catch data was highly dispersed, especially for 1 and 2 soak nights where SD > mean total EGC captures (Table 5). Future exploration of soak length would benefit from larger sample sizes and provide more confident results. Nevertheless, from our results we might assume that trap sets with 1 or 2 soak nights could be pooled for summarizing CPUE (i.e. trap sets with 2 soak nights counted as 1 soak night) and utilize more trapping data, but encourage caution due to the high variability common in EGC catch data as was observed with LSP.

Increasing soak time increased total EGC captures; however, doubling the soak time did not result in doubling EGC captures (Table 5; Fig. 9). For example, mean captures from 2 to 4 soak nights increased by roughly 70% and mean captures from 4 to 5 soak nights only increased by 15%. Although mean EGC captures nearly doubled from 1 to 2 soak nights, this increase was not statistically significant. As such, there was a decrease in catch efficiency as soak time increased. Thus, rebaiting traps after 1 or 2 soak nights would result in more EGC captures than checking and rebaiting traps at 4 or 5 soak nights.

Table 4. *Post hoc* pairwise comparison test results (Dunn's test) of soak night influence on total EGC captures (n=47); *P.adj* provides adjusted *p-value* using the "Sidak" method, *a=0.05*

Soak Night Comparison	Z	*P.unadj*	*P.adj*
1-2	-1.95	*0.05*	*0.27*
1-4	-6.03	*<0.01*	*<0.01*
2-4	-4.08	*<0.01*	*<0.01*
1-5	-7.02	*<0.01*	*<0.01*
2-5	-5.07	*<0.01*	*<0.01*
4-5	-0.99	*0.32*	*0.90*

Table 5. Calculated mean, standard deviation (SD), and standard error (SE) of EGC captures in Lummi Sea Pond in salmon-bait shrimp trap sets in October 2021 (n=47).

Soak Night	Mean EGC Captures	SD	SE
1	9.00	9.42	1.37
2	17.60	21.61	3.15
4	29.70	18.00	2.63
5	34.19	17.40	2.54

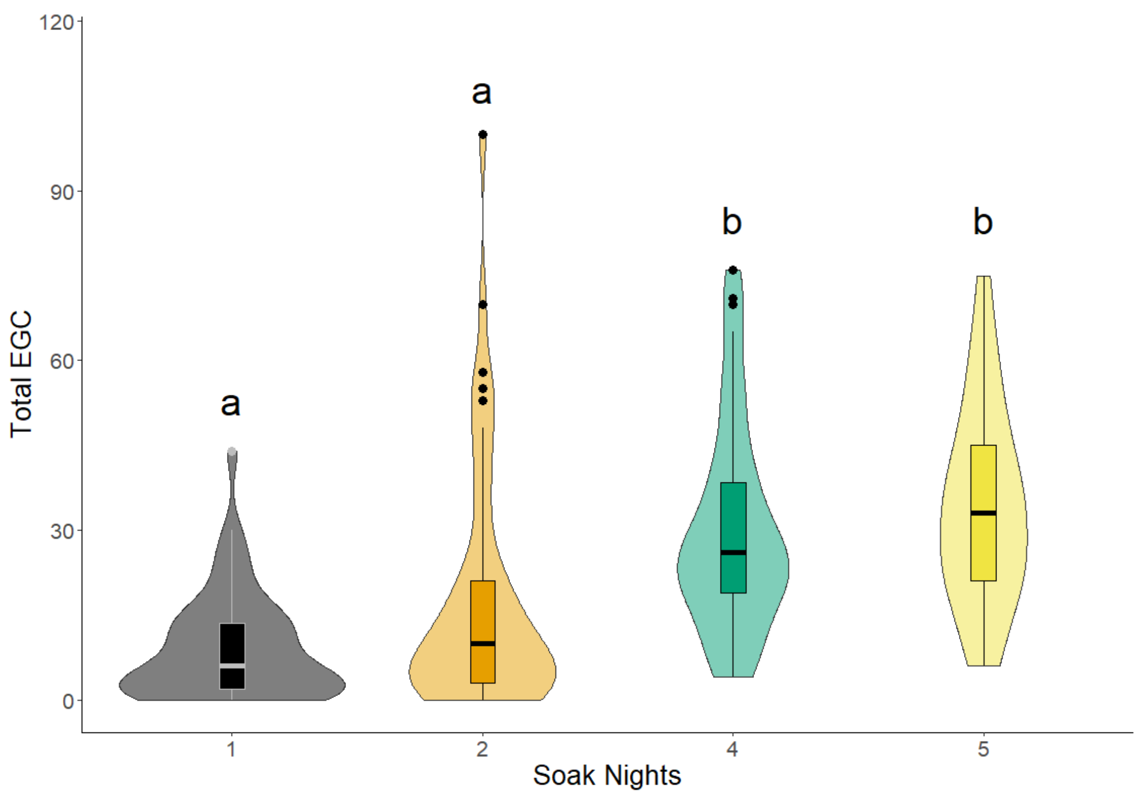

Figure 9. Total EGC captures in salmon-baited shrimp traps by number of soak nights (1, 2, 4, or 5) during the 2021 trapping season in Lummi Sea Pond (each group randomly subset to n=47).

Even though trapping efficiency decreased as soak length increased, we postulated reasons for why EGC continually entered shrimp traps as soak nights increased. From field observations, salmon bait could be used more generously and likely lasted longer in shrimp traps compared to sardines or other bait fishes. Another possible explanation for increased captures at 4 and 5 soak nights, is EGC might be attracted to the sound of other crab having a feeding frenzy, as has been observed by commercial crabbers (e.g. Livingston Lures[3]).

A multitude of variables, including crab behavior, bait age, crab escapement rates, and soak length, cumulatively influence rate of capture, and have been examined for other crab fisheries to better predict population abundances based on capture rates (Smith and Jamieson, 1989; Taggart et al. 2005; Sturdivant and Clark, 2011). In our exploration, EGC catch rate trends follow those of other crab fisheries, where catch rates increase over the first days of fishing and then reach a threshold. While we were able to examine soak length as one of the influences on EGC capture rates, examining other variables (bait age, crab escapement, etc…) would improve catch efficiency and remove biases associated with population density estimates derived from catch rates.

Size Structure and Population Dynamics

Ridgeline density plots suggested approximately even sex ratios (males: females) each trapping season in LSP and that the distribution of EGC carapace widths have expanded in the last couple trapping seasons (Fig. 10). However, caution is warranted for comparing 2019 with 2020-2021 distributions since 2019 EGC data is confined to only 42 individuals collected between October and November. Nonetheless, 2019 EGC size distribution suggested the presence of two cohorts— the larger cohort was distributed around the YOY-adult estimated threshold (based on the smallest gravid female captured in 2021), and a smaller cohort with only a few EGC (<40mm; Mueller and Jefferson, 2019). Mean carapace widths of both sexes were near the YOY-adult threshold in 2019.

The range of EGC size distribution was smaller in 2019 than in 2020 and 2021, and likely reflects the longer trapping seasons in the latter years (Fig. 10). EGC captured in 2020 were largely dominated by a YOY cohort; like 2019, the mean carapace width for males and females was below the YOY-adult threshold. The subset of EGC captured in 2021 had a wider and uneven distribution of sizes and sex compared to previous years. Female mean carapace width size was below the YOY-adult threshold but mean EGC size of males was above the threshold. Although male and female EGC size distributions did not strongly mirror each other, where females had a smaller maximum carapace width than males, the overall sex ratio for 2021 was still closely 1:1.

EGC carapace width distribution by month in 2021 highlights evidence of 3 EGC cohorts present in LSP (Fig. 11). EGC size distribution expanded over the first few months of the trapping season (April-June), where the minimum and maximum carapace widths were 38 mm and 66 mm in April, respectively, and 11 mm and 88 mm in July, respectively. In April, mean size of males was below the YOY-adult threshold and females were on average larger than males; however, the smaller sample size in April (n=21) might not be representative of EGC distribution during this period. Mean size of males increased in May through July above both the average female size and YOY-adult threshold. In July, a new YOY cohort emerged (~25 mm) and was the dominant size class by September. Mean size of both sexes gradually increased between September and December.

Although the sex ratio remained nearly 1:1 for most of the trapping season, a couple of trapping months indicated slight skews towards one sex or the other (Fig. 11). Sex ratios skewed towards males in April and August (2:1), and then towards females in November and December (roughly 2:3). Interestingly, 38 out of 50 gravid EGC captured in LSP were in shrimp traps checked in November and December (Table 2). Traps containing the majority of gravid EGC had been left unchecked for 2-4 weeks, so it is unlikely EGC were lured by bait but rather were seeking shelter and protection from predators.

[3] Example crab call lures available at https://www.livingstonlures.com/products/blue-crab-caller.

Distribution of EGC carapace widths in 2021 varied based on trap style (Fig. 12). Shrimp traps primarily captured EGC slightly above the YOY-adult threshold, between 40 and 60 mm in carapace width. Minnow traps captured almost exclusively YOY where the mean size of both sexes occurred around 40 mm. Fukui-style traps had a wide distribution range of size for both sexes and likely represents all three EGC cohorts captured in LSP during the 2021 trapping season. Hand captures were the minority of measured EGC (n=34) since these crabs were captured opportunistically. Most hand captures were female EGC less than 35 mm in carapace width and were collected in the shallow zone along the north marshy shoreline in LSP (Fig. 4). In contrast, the mean size of male EGC captured by hand was above the YOY-adult threshold.

Although shrimp traps were not fully introduced to LSP until July 2021, there did not appear to be a change in the EGC size distribution trend observed month-to-month (Fig. 11). Given the different size ranges of EGC observed with each trap style (Fig. 12), the larger size range observed in July and August was due to the consistent use of minnow and fukui-style traps rather than the introduced use of shrimp traps. The introduction of shrimp traps might have similarly been thought to be the reason for the size range increase from 2020 to 2021 (Fig. 10), but instead likely represents the size range increase from an aging population where each consecutive year of reproduction increases the complexity of EGC size range in LSP.

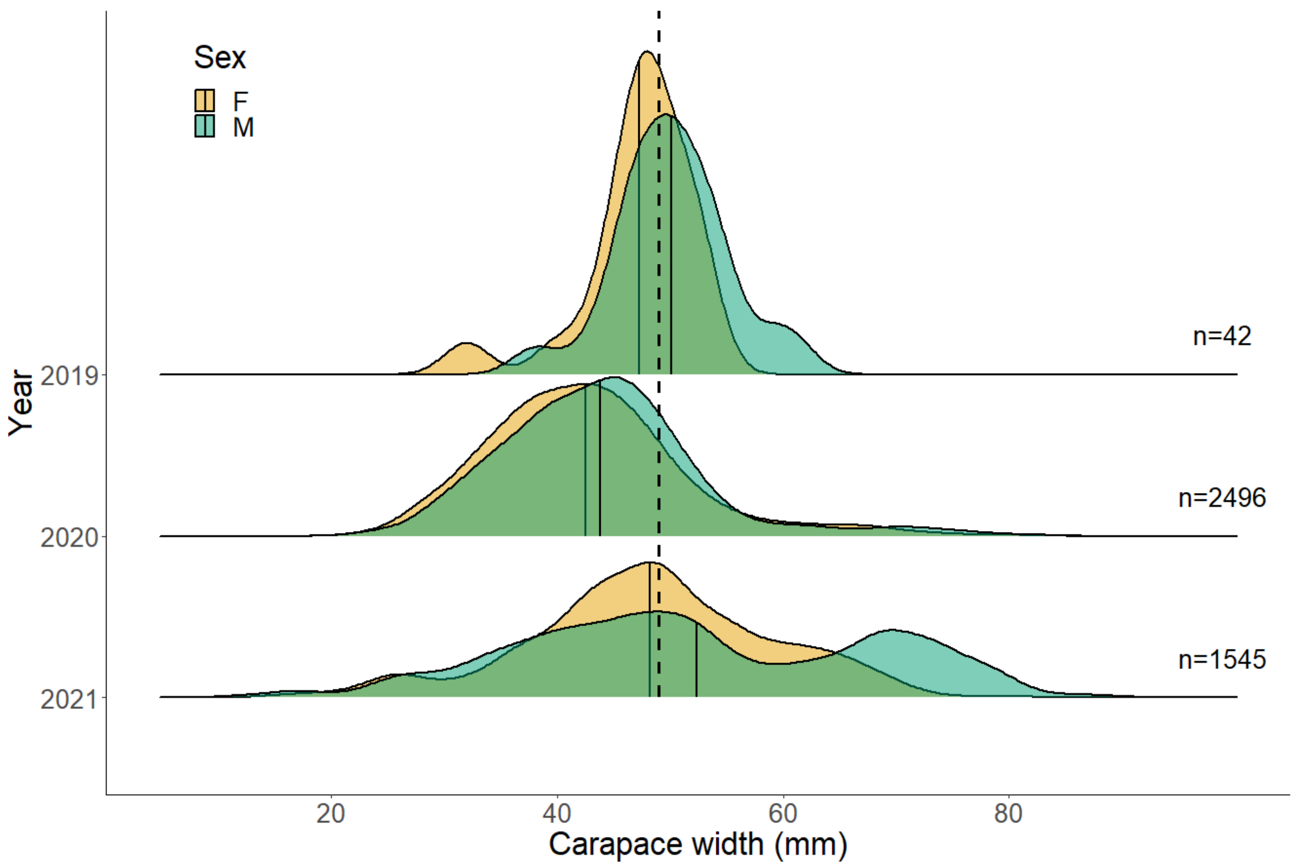

Figure 10. Ridgeline plot showing size (carapace width in mm) density distribution of EGC by sex sampled from Lummi Sea Pond during the 2019 (October-December), 2020 (April-November), and 2021 (April-December) trapping periods. Solid lines are means for each sex by year, and dashed line indicates delineation between young of year (≤49mm) and 1+ year cohorts (≥50mm); n=total EGC count.

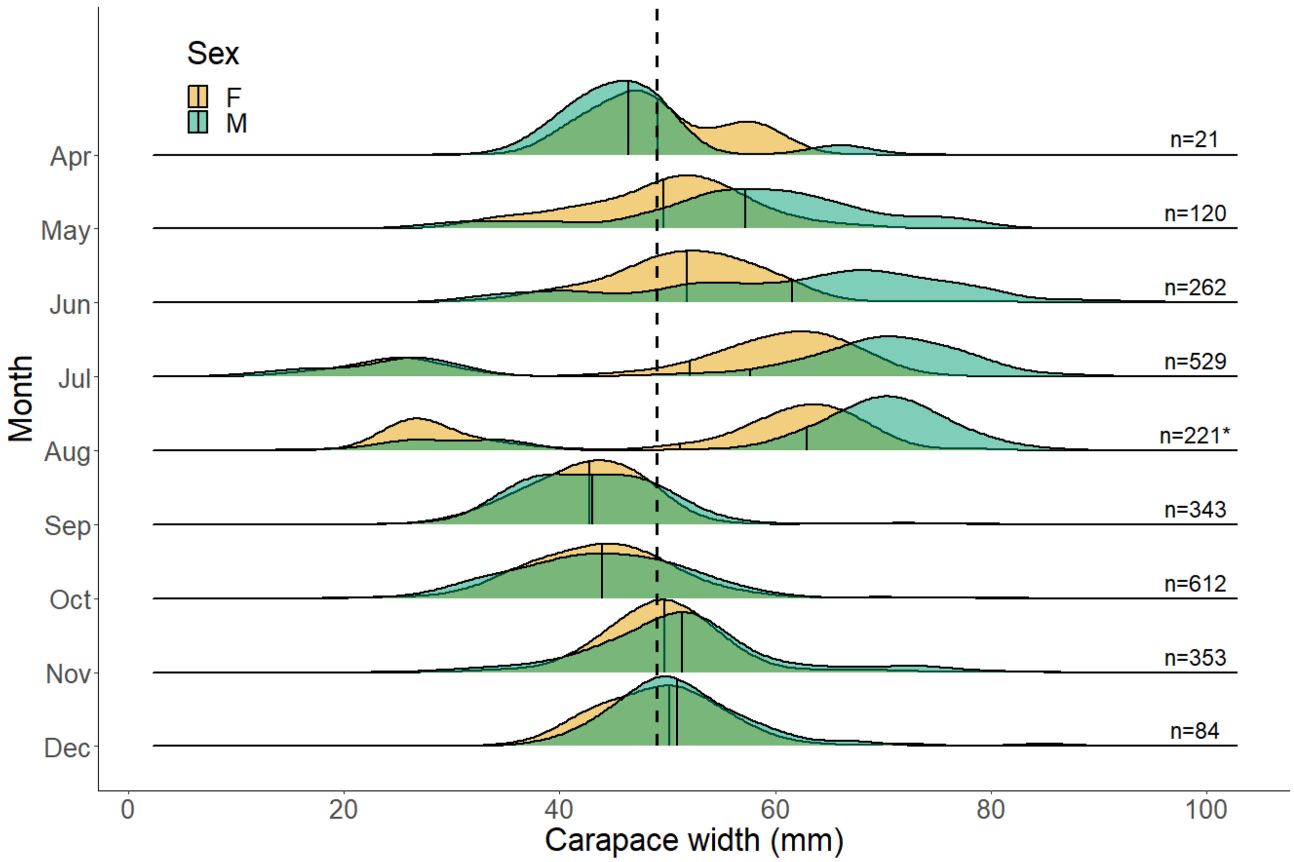

Figure 11. Ridgeline plot showing monthly size (carapace width in mm) density distribution of EGC by sex sampled in Lummi Sea Pond. Solid lines are means for each sex by month, and dashed line indicates delineation between young of year (≤49mm) and 1+ year cohorts (≥50mm); n=total EGC count (* indicates the month when carapace width subsets began).

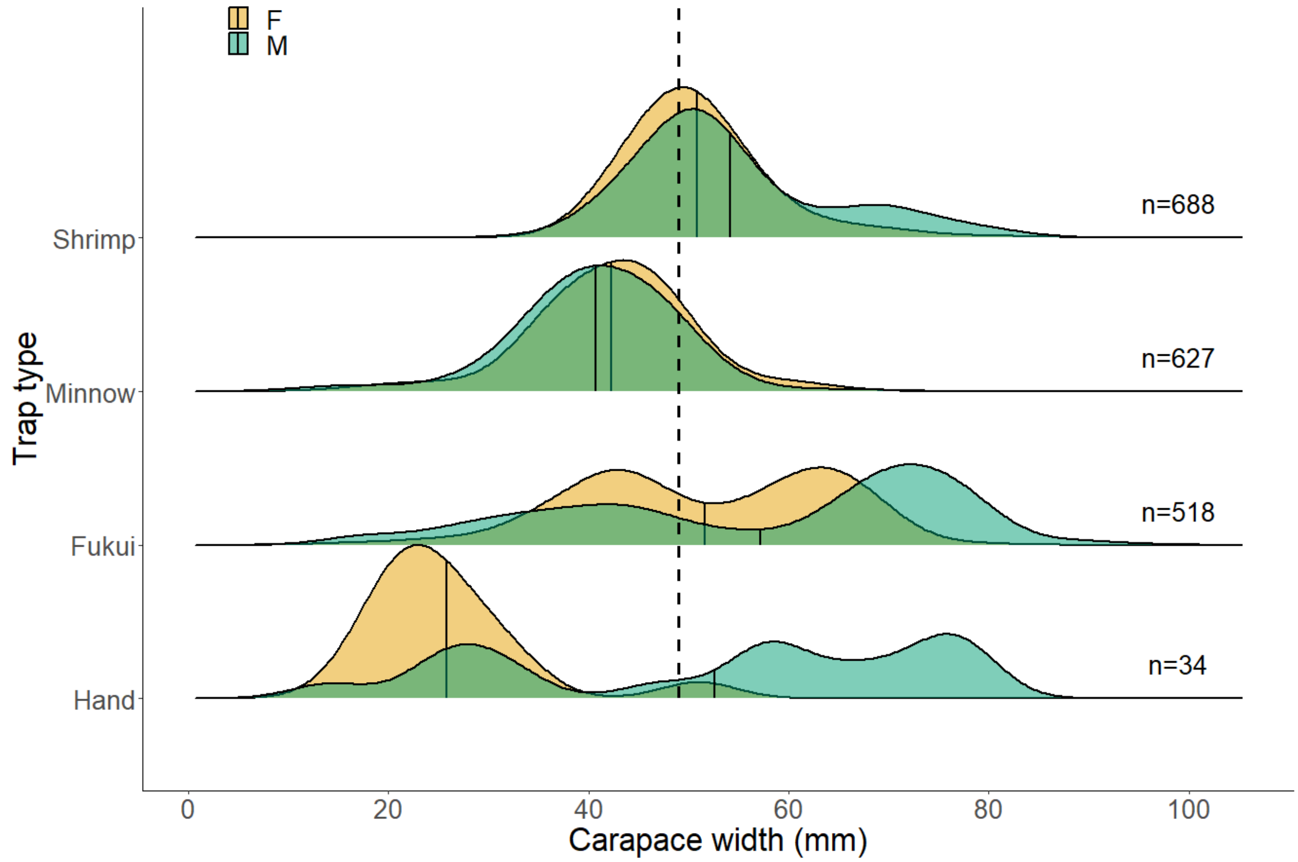

Figure 12. Ridgeline plot showing size (carapace width in mm) density distribution of EGC sampled in Lummi Sea Pond by trap type and sex (April-December). Solid lines are means for each sex by trap type, and dashed line indicates delineation between young of year (≤49mm) and 1+ year cohorts (≥50mm); n=total EGC count.

Spatial and Temporal Snapshots: North central shoreline of Lummi Sea Pond

Although we did not test spatial variation of CPUE for this report, field observations provided some evidence of EGC movement within LSP. One of the clearest observations was the arrival of YOY in August along the marshy northern shoreline of LSP, which is the shallowest (<1m) area of LSP and resembles typical habitat most settled by EGC in the Pacific Northwest (Fig. 13-14; Grosholz and Ruiz, 1996). Consistent trapping with minnow and fukui-style traps showed the rapid increase in crabs per trap from July to September, and then a decrease in October, which might indicate the timeframe when YOY were beginning to forage in deeper water (Fig 13).

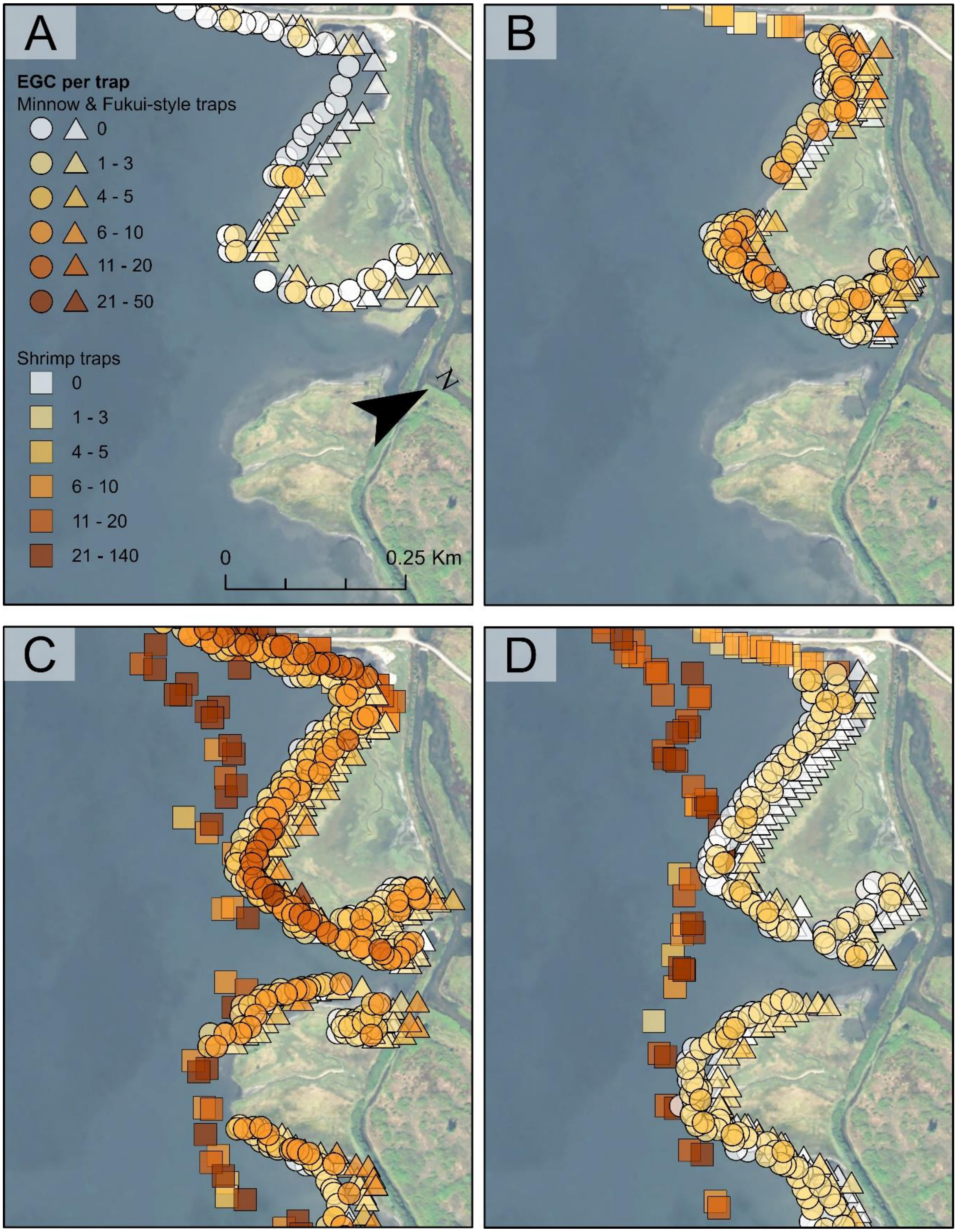

Figure 13. One-month interval snapshots[4] of 2021 European green crab trapping effort and catch rates (EGC per trap) by trap type along the north central shoreline of Lummi Sea Pond; A=week of July 16, B=week of August 18, C=week of September 10, D=week of October 12.

[4] Aerial map sourced from the National Agriculture Imagery Program (NAIP) Compressed County Mosaic (CCM) 2017

Figure 14. A bag of young of year EGC in a 5-gallon bucket captured in Lummi Sea Pond in 2021; photo credit Bobbie Buzzell.

Bycatch Sampling

A total of 4 bycatch groups (3 to species level and 1 to family level) were documented in trap sets from both April and September during the 2021 trapping season (Fig. 15). Bycatch included hairy shore crabs (*Hemigrapsus oregonensis*), Pacific staghorn sculpin (*Leptocottus armatus*), and hairy helmet crab (*Telmessus cheiragonus*), as well as hermit crabs which were grouped at the family level (Paguridae). Only two species of hermit crabs have been previously documented in the greater Lummi Bay, including the grainy hermit crab (*Pagurus granosimanus*) and the hairy hermit crab (*Pagurus hirsutiusculus*; Dolphin et al. 2010). Traps checked on April 16 included all 4 bycatch groups alongside EGC. Trap sets checked on September 29 captured a larger number of hermit crabs relative to April trap sets, but no hairy helmet crabs were encountered. In September, EGC outnumbered all other bycatch (arrival of YOY). Bycatch captured in September 2021 is the same as the assemblage documented in Lummi Sea Pond in 2019 (Mueller and Jefferson 2019).

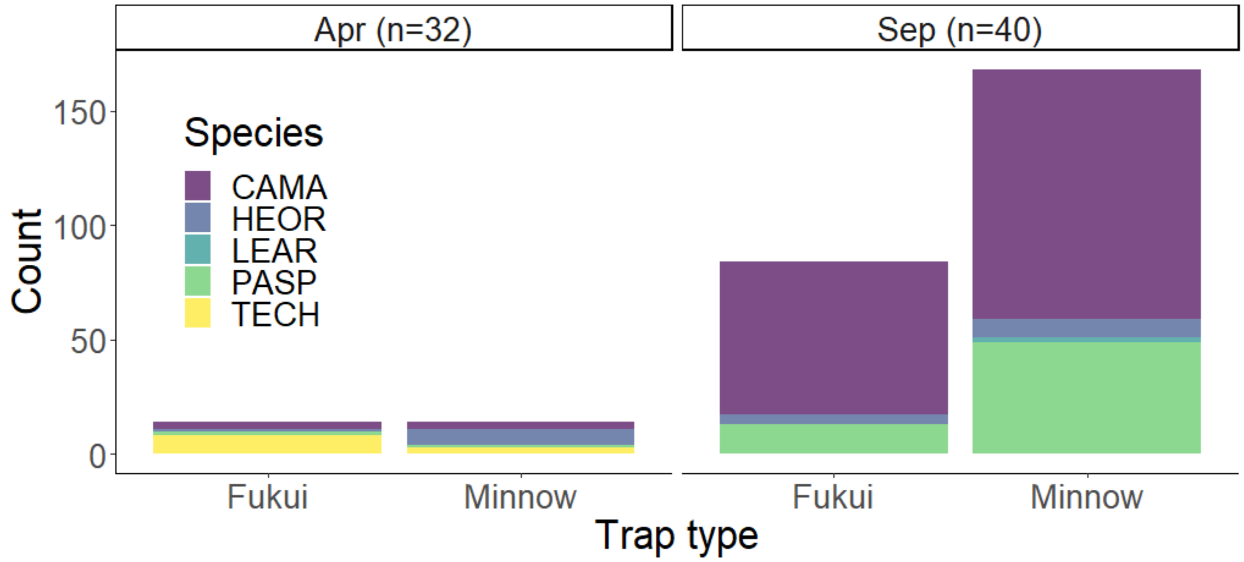

Figure 15. Counts of European green crab (CAMA) and bycatch species captured in fukui-style and minnow traps deployed for a single soak night on April 16 and September 29, 2021; HEOR, *Hemigrapsus oregonensis*; LEAR, *Leptocottus armatus*; PASP, family Paguridae (hermit crabs); TECH, *Telmessus cheiragonus*.

MANAGEMENT IMPLICATIONS

European green crab densities in LSP pose a serious risk to Lummi Nation's natural resources, particularly shellfish harvesters, and is well-recognized by Lummi Indian Business Council (LIBC Resolutions # 2020-032 and 2021-158). Mueller and Jefferson (2019) highlighted that the LSP population of EGC could serve as a source population for neighboring shores, potentially expanding the population range of EGC further into Puget Sound. Given the risks associated with the LSP population, management reduction of EGC across Lummi Nation tidelands is of the utmost priority to LNR.

LSP trapping in 2021 revealed the complexities of adaptive strategies when responding to heightened levels of EGC densities. This approach led to a lack of consistency in some of the collected data, including bait type, retrieval time, and trap modification type, which limited analyses in the data set that might have informed trapping efficiency. Despite challenges associated with adaptive strategies, LNR, WDFW, and local agencies collaborated to pull off one of the largest trapping efforts in Washington State. The staggering level of effort provided a robust data set for exploring methods and has since guided future EGC trapping in LSP.

As previously discussed, shrimp traps resulted in the highest catch rates in 2021 (Fig. 5) and were an important tool for increasing EGC captures. However, shrimp traps are larger, and more cumbersome to transport long distances compared to minnow and fukui-style traps (Table 1). Shrimp traps are also less suited for deploying in narrow estuarine channels cut through salt marsh habitat, which YOY EGC frequently inhabit along the west coast United States (Grosholz and Ruiz, 1996).

Even though minnow and fukui-style traps did not result in the highest catch rates, they serve a purpose in identifying areas of EGC presence and absence, thus informing where EGC trapping should be concentrated. Due to the small mesh size and smaller tunnel opening, minnow traps were the most effective in capturing smaller YOY (Table 1; Fig. 11), an adaptive trapping strategy could involve increasing minnow trap sets in mid- to late-summer, when YOY first begin to enter traps (Fig. 10). In areas where shrimp traps are difficult to deploy, the use of fukui-style traps could be increased and placed closer together (e.g., 5 m instead of 10 m) alongside minnow traps.

Based on results examining soak night influence on catch rates and depending on priorities, implications might follow on how frequently to check and rebait traps. To better utilize staff and other resources, traps could be checked after every 2 days to minimize hours spent in the field and conserve bait use. Certain considerations will dictate the feasibility of this increased soak time, such as minimizing bycatch mortalities, wear and tear of traps, and tide conditions (minimal concern for LSP) which are at the discretion of individual trapping programs and available resources.

Salmon was an economically viable bait source during the height of the trapping season but was not consistently available. Future trapping will need a consistent bait type which will also allow for more reliable comparisons of catch data in other EGC monitoring programs. In addition, it is unknown if salmon is a greater attractant than the other commonly used bait types (Favaro et al. 2020) but its increased use in other programs[5] warrants a follow-up study to better inform managers of its effectiveness.

Mueller and Jefferson (2019) previously reported that Lummi Bay EGC catch rates were on par with the 1998 EGC densities of Willapa Bay, Washington State; however, it has taken 20-30 years for EGC in Willapa Bay to reach concerning densities in LSP where it has taken less than 3 years to observe exponential density increases since the estimated settlement period (2018-2019). Located to the immediate north, Drayton Harbor's EGC population has a similar timeline to LSP of EGC discovery and establishment. Like LSP in Lummi Bay, Drayton Harbor resides within Semiahmoo Bay, a semi-enclosed, shallow body of water; however, tides move more freely in and out of the harbor and EGC are more subjected to natural environmental conditions. After a year of consistent trapping, estimated 2021 catch rates were below 10 CPUE in Drayton Harbor[6] -- a stark contrast against the exponential rise in EGC catch rates in LSP.

Rapid increase in EGC densities within LSP since 2019 speaks to the "incubator effect" (coined by Mueller and Jefferson, 2019). As predicted, the sea pond has proven to be an ideal habitat for EGC—limited tide influence, shallow, protected, ample food and shelter, and limited predators. LSP conditions and resources coupled with the successful adaptability of EGC has led to the second largest known density of EGC in the Salish Sea; only surpassed by the densities recently trapped in Sooke Basin, Vancouver Island, where EGC have been established since 2012 or earlier[7].

While the EGC density in LSP is of high concern, EGC are captured at significantly greater densities on the U.S. east coast (>200 EGC per trap set; Favaro et al. 2020) where they are known to negatively impact nearshore habitats and local species (Lovell et al. 2007; Matheson et al. 2016). Currently there are no documented impacts of EGC on Lummi Nation tidelands; however, if EGC become established at similar densities as the U.S. east coast, EGC may outcompete juvenile Dungeness crab, over-predate on juvenile clams, and reduce eelgrass habitat essential to native crab and juvenile salmonid species (Colnar and Landis, 2007).

Suggestions for future research echo those of Mueller and Jefferson 2019 and include conducting: Before-After Impact-Control style assessments for culturally and economically important natural resources, an economic impact survey to determine costs to Lummi shellfish hatchery production, and a success/benefit analysis for potential LNR response to EGC population increase. To inform these study designs, we consider ways to establish

[5] Personal communication with Metlakatla Tribe, AK.
[6] Grason, E. & Buzzell, B. (2021). What Does the Invasion at Lummi Mean for the Salish Sea? *Washington Sea Grant Crab Team Blog.* Access at https://wsg.washington.edu/21-lummi-update/
[7] Ryan, J. (2022). Think 85,000 invasive crabs is a lot? Wait 'til you see Vancouver Island. KUOW, NPR. Access at https://www.kuow.org/stories/80-000-invasive-crabs-is-a-lot-wait-til-you-see-vancouver-island

clear benchmarks for existing species' presence for future comparisons. Documenting the presence and relative abundance of bycatch through monitoring efforts can provide a metric for these comparisons.

Trapping has had mixed success in reducing EGC densities along the west coast United States[8] (Grosholz et al. 2021). In the short-term, trapping will mitigate the predicted harm on ecosystems caused by EGC, but it is recognized that trapping is a "band aid" solution for controlling EGC in LSP. However, if future resources allow, "functional eradication", or maintaining EGC densities below a certain threshold to prevent ecological damage, may provide a longer-term maintenance solution (Green and Grosholz, 2021).

An additional longer-term approach is to develop a maintenance schedule for LSP, where the pond can be partially drained during specific times of year to reduce settlement of EGC, especially during cold weather when EGC are most vulnerable. This strategy will be more costly upfront because it will require repairing the current non-functioning tide gates to reduce the water level more effectively throughout the sea pond. Recent work understanding life history of EGC in its larval stages along the eastern Pacific, indicates larval success is the number one predictor of strong settlement (Yamada et al. 2022). As a first step to strategically manage and effectively mitigate EGC at the larval phase in LSP, the development and seasonal timings of planktonic stages of EGC in LSP will need to be documented.

Trapping was highly limited outside of LSP in 2021, and besides some exploratory trapping conducted in 2019 (Mueller and Jefferson) and 2020[1], little is known about the distribution and abundance of EGC throughout the rest of Lummi Reservation tidelands. To an extent, the wall of LSP limits movement of EGC into the surrounding Lummi Bay but based on the trapping that could be explored in 2021 it was evident that EGC are potentially establishing further into the bay. Increased trapping effort across the tidelands, especially in sensitive shellfish harvest areas like Portage Bay, will allow for a thorough assessment of EGC presence and help determine high priority areas for EGC control and management.

EGC are a serious threat to Lummi resources not the first aquatic invasive species to establish on Lummi Tidelands (Dolphin et al. 2010). While some bivalve species have been purposely established for commercial harvest in Lummi Bay (e.g., Manila clams, *Venerupus phillipinarum* and Pacific oysters, *Crassostrea gigas*), several other aquatic species were introduced unintentionally, including, but not limited to, varnish clams (*Nuttallia obscurata*), bubble snail (*Haminoea japonica*), Japanese mud snail (*Battiliaria attramentaria*), and Japanese eelgrass (*Zostera japonica*). Although some of these previously established invasive species have known impacts in other geographical ranges (e.g., Chan and Bendell, 2013; Patten, 2014) specific impacts on reservation tidelands are largely unknown and highlights the need for further documentation of invasive species on Lummi Reservation tidelands. EGC trapping response has been largely reactive rather than preventative and further stresses the need for proactive invasive species monitoring across the tidelands.

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[8] Grason, E. (2020). 2020 Salish Sea Green Crab Update. *Washington Sea Grant Crab Team Blog*. Access at https://wsg.washington.edu/2020-salish-sea-green-crab-update/

ACKNOWLEDGMENTS

Funding and support for EGC trapping in 2021 was provided by LIBC, WDFW, WSG, and the Bureau of Indian Affairs Invasive Species Program. EGC trapping in 2021 could not have been done if not for the cross-collaboration between LNR, Washington State, and local agencies. Staff from LNR, WDFW, WSG, and the NWSC were fundamental in heightened trapping effort in September and October. Trapping staff from LNR included Bobbie Buzzell, Lisa Balton, Delaney Adams, Elias Plaster (Employment and Training Center), Daniel Washington, Nicholas Jefferson, Rachel Dalthorp, and Karl Mueller. Trapping staff from WDFW included Lindsey Parker, Nathan Goldshmidt, Ronald Coleman, Kyle Selstead, Lennah Mohar, Chelsey Buffington, and Allen Pleus. Staff from WSG, Emily Grason and Abigail Keller; and from NWSC, Leah Robison and Alexandra Simpson. Delaney Adams entered the 2021 trapping data and completed the QA/QC for data used in this report. We thank LNR Directory's Office staff and Lummi Council members for supporting an emergency declaration in November 2021, which has paved the way for acquiring additional trapping resources and expanding trapping effort on Lummi Nation tidelands. WDFW also provided bait, additional traps, and vessels. Salmon bait was provided and delivered by LNR Salmon Enhancement staff. We thank the LNR Shellfish Hatchery staff for accommodating an emergency response on Lummi Sea Pond and LNR Stock Assessment for lending a boat to EGC trapping staff. The LNR Director's office and Benjamin Starkhouse from Harvest Management provided guidance on planning, implementation, and communications with outside agencies. Randall Finkbonner provided coonstripe shrimp traps for test trapping in LSP. Guidance and reviews for this report were provided by Karl Mueller, Shawn Evenson, Lisa Balton, Delaney Adams, Nicholas Jefferson, Benjamin Starkhouse, and Devin Flawd.

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