SWINOMISH LARVAL AND JUVENILE DUNGENESS CRAB MONITORING REPORT FOR 2019

Sarah K. Grossman*, Claire E. Cook, and Julie S. Barber
Swinomish Indian Tribal Community, Fisheries Department. 11426 Moorage Way. La Conner, WA 98257.
* Corresponding author: sgrossman@swinomish.nsn.us

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Table of Contents

Front cover photo: Claire E. Cook

List of Tables

List of Figures

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ABSTRACT

The Dungeness crab (*Metacarcinus magister*) is one of the most highly-valued marine species in the Pacific Northwest. Throughout the region, the species forms the basis for many local fishing economies and is prized for its cultural and recreational significance. Although the biology and ecology of *M. magister* is relatively well-understood compared to other marine invertebrates, fundamental gaps still exist, notably in crab populations within the inland waters of the Salish Sea. In 2018, Swinomish began monitoring the larval flux, juvenile settlement and growth, and ecology of Dungeness crab at sites in northern Whidbey and southern San Juan Basins. In 2019, we embarked on our second year of monitoring. Over the course of the 2019 monitoring season, both larval and juvenile Dungeness crab were observed at larval flux and intertidal sites from April to August, with peak larval delivery and juvenile densities observed from late-April to late-May. Relative to other crab species observed, Dungeness crab had the longest larval contribution period with near constant presence from April to early August. Over this protracted larval delivery period, post larval and early instar Dungeness crab sizes were found to vary by month, with early arriving megalopae and J1 instars having significantly larger carapace dimensions than later arriving cohorts. Our second year of monitoring results demonstrates how larval and juvenile Dungeness crab dynamics can vary annually. Most notably, between 2018 and 2019 differences were observed in the timing of the delivery of peak pulses of megalopae and sizes of megalopae delivered varied between years. In 2019 megalopae were caught in the light traps starting in April and peak delivery was in the early-season, whereas in 2018 megalopae were not captured until early May and peaked in mid-June. Developing a better understanding of larval and juvenile dynamics across San Juan and Whidbey Basins could have far-reaching implications for continued successful management of this essential fishery and provide valuable baseline data to inform future management practices as environmental conditions change.

Keywords Dungeness crab, *Metacarcinus magister*, larvae, larval flux, recruitment, juvenile, Puget Sound

INTRODUCTION

This report summarizes the annual dynamics of early life-history phases of Dungeness crab [*Metacarcinus* (*Cancer*) *magister*] in northern Whidbey and southern San Juan Basins during 2019. Included in this report are data summaries from the larval flux and intertidal density and growth surveys conducted by the Swinomish Fisheries Department. These monitoring activities are the basis of a long-term monitoring effort developed with the aim of resolving extensive gaps in our knowledge of early life history phases of *M. magister* in northern Puget Sound and the southern Strait of Georgia. In addition, we aim to develop a baseline of biological and physical metrics in the region in order to determine potential limitations to adult populations and assess the need for more adaptable management plans.

METHODS

Dungeness crab larval flux surveys

During the 2019 monitoring season, light traps were deployed from April to September/October at five locations to monitor the relative abundance of larval Dungeness crab in San Juan and Whidbey Basins (Figure 1). The Cornet Bay (COR) and Rosario Head (ROS) sites monitored in 2018 were also sampled in 2019. We discontinued the Skyline Marina site in order to expand the geographic range of our monitoring sites with the addition of three new sites: Seafarers Memorial Park in Anacortes (ANA), the Naval Air Station Whidbey Base in Oak Harbor (OAK), and the Coupeville Wharf in Penn Cove (PEN) - Coupeville, Washington (Figure 1, Table 1). In 2018 low numbers of Dungeness crab megalopae were caught on the first day traps were deployed in early May, missing the start of the larval delivery period. In 2019 we deployed the larval crab traps a month earlier in an attempt to ensure we captured the start of the larval delivery season. Light traps were deployed on 9 April at COR, ROS, and PEN, 10 April at OAK, and 18 April at ANA. The traps were pulled from the water, ending the monitoring period after roughly two weeks (one full tidal cycle) of zero catch, on 13 August at PEN, 3 September at COR and OAK, 11 September at ANA. We continued monitoring at ROS until 16 October for investigative purposes to determine if another later arriving cohort of megalopae arrived significantly later than expected.

Larval crab catch (inclusive of megalopae and instars that molted in the trap between site visits) was standardized by catch per hour (megalopae/hr). In addition, carapace dimensions including carapace width (CW), carapace height (CH), and total height (TH), of 30 megalopae and instars (if present from megalopae that molted in the trap) were measured per week, per site. A more detailed explanation of methods can be found in Cook et al. (2018).

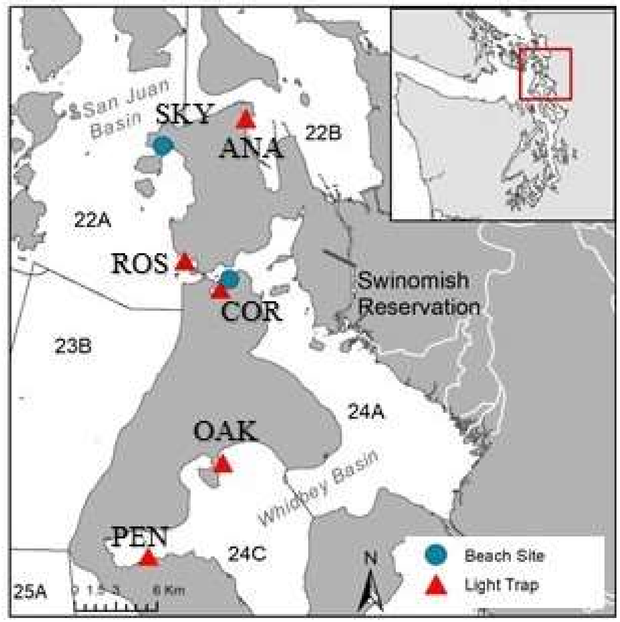

Figure 1. Location of larval flux and intertidal monitoring locations in San Juan and Whidbey Basins. Numbers depict crab management subregions.

Table 1. Location metadata of larval flux sites in 2019.

Site Code	Location	Basin	Shellfish Management Area	Subregion
ROS	Rosario Head, Oak Harbor, WA	San Juan	1	22A
ANA	Seafarers Memorial Park, Anacortes, WA	San Juan	1	22B
COR	Cornet Bay, Oak Harbor, WA	Whidbey	2E	24A
OAK	NAS Whidbey, Oak Harbor, WA	Whidbey	2E	24C
PEN	Coupeville Wharf, Coupeville, WA	Whidbey	2E	24C

Juvenile Dungeness crab intertidal surveys

Intertidal surveys were conducted on a bi-weekly basis from 23 April to 27 August 2019 during low tides. Intertidal sites were sampled two additional times on 18 January and 16 March 2019 before the settlement season, to survey Dungeness crab densities prior to the arrival of the 2019 cohorts. Surveys were conducted using a randomized sampling scheme with 10 0.25 m^2 quadrat samples per beach per low tide series through the juvenile settlement period. At each sample site, quadrats were excavated to a depth of 3 cm and all materials were collected in a 4 mm sieve and rinsed with local seawater to remove material < 4 mm from the bulk sample. The

Table 2. Location metadata for intertidal sampling beaches.

Site Code	Location	Basin	Shellfish Management Area	Subregion
SKY	Cabana Park, Anacortes, WA	San Juan	1	22A
COR	Cornet Bay, Oak Harbor, WA	Whidbey	2E	24A

remaining materials were sorted through and all Dungeness crab instars and megalopae were enumerated and CW and CH were recorded. Intertidal areas of two beaches were monitored: Cabana Park near Skyline Marina (SKY) in San Juan Basin and Cornet Bay (COR) in Whidbey Basin (Table 2, Figure 1). In 2018 we had monitored at six locations but due to staff restraints we opted to continue monitoring at two intertidal sites, one from each oceanographic basin, in favor of adding additional larval flux sites. Detailed methods on how to conduct our intertidal surveys can be found in Grossman et al. (2021a).

Ecological context

In addition to monitoring for Dungeness crab larval and juvenile abundance, we quantified sample bycatch in both our light trap and intertidal excavated quadrat samples. When possible, all decapod species captured were identified to the lowest taxonomic group possible and enumerated. A summary of the total catches over time is presented for crab species found during larval flux monitoring.

Surface water temperature was monitored at COR and OAK larval flux sites from 11 April to 3 September 2019 using HOBO U24-002-C loggers programmed to collect readings at 15-minute intervals. Daily mean temperature °C was calculated and plotted by site.

Analysis

Summary statistics were used to characterize Dungeness crab larval abundance at sites through time. The 2019 larval crab monitoring season was broken up into three time periods, each summarizing catch rates over periods of six weeks: early-season (ES) 15 April to 14 June, mid-season (MS) 15 June to 25 July, and late-season (LS) 26 July to 17 September.

Intertidal densities were qualitatively assessed and described with summary statistics. To examine the relationship between Dungeness crab settlement [defined here as megalopae and/or juvenile stage 1 (J1) instars] and recruitment (J2+ instars), and their relative contributions to total crab intertidal density, the densities of settlers and recruits were plotted by sampling date.

Carapace widths of Dungeness crab megalopae collected in larval flux sites were compared both between sites and by month. Using a non-parametric Kruskal-Wallis (KW) test, we first tested if mean CW, regardless of month, differed among sites and used a follow-up Conover-Inman test (Bonferroni p-adjusted with an initial alpha set to 0.05) to determine where differences existed. Because there were differences in megalopae CW between some sites, we followed up with individual KW tests on megalopae CW by month for each site independently. Subsequent temporal analyses were performed using the post-hoc Conover-Inman test (Bonferroni p-adjusted with alpha set to 0.05) (Sokal & Rohlf 2012).

We also examined the differences in J1 instar CW found in the intertidal surveys by site regardless of month using a KW test. Because no differences were found between the two sites, we pooled site data together and tested for differences in CW by month using the KW test and the post-hoc Conover-Inman test (Bonferroni p-adjusted with alpha set to 0.05).

Interannual comparisons of CW of Dungeness crab megalopae for the monitoring season at COR and ROS (the two sites monitored in both 2018 and 2019) were compared using descriptive statistics only, due to the disparity in sample sizes between years. The CW of intertidal J1 instars collected at COR and SKY for the whole monitoring season were also examined between years (2018 and 2019) using a KW test.

RESULTS AND DISCUSSION

2019 Dungeness crab larval catch

Dungeness crab megalopae were first observed on 15 April at ROS, nearly a week after traps were deployed. Megalopae were first captured at COR and ANA on 18 April and 26 April respectively. Located south of the

Table 3. Dungeness crab CPUE (catch/hr), minimum, maximum, mean, standard error (se), sum of *M. magister* larvae captured, and days sampled by period. Statistics tallied by early-season (9 April to 14 June), mid-season (15 June to 25 July), late-season (26 July to 17 September), and total season from 9 April to 11 September 2019.

	9 Apr to 14 Jun	ANA	COR	OAK	PEN	ROS
Early-season	min CPUE	0.0	0.0	0.0	0.0	0.0
	max CPUE	11.6	290.5	0.1	0.0	198.7
	mean CPUE ± se	1.2 ± 0.3	29.4 ± 7.1	0.0 ± 0.0	0.0 ± 0.0	24.0 ± 6.2
	Total catch	584	15,515	2	0	14,516
	Days sampled	58	58	51	43	67
	15 Jun to 25 Jul	ANA	COR	OAK	PEN	ROS
Mid-season	min CPUE	0.3	0.0	0.0	0.0	0.1
	max CPUE	142.8	98.5	0.3	0.1	23.6
	mean CPUE ± se	12.7 ± 5.0	12.7 ± 3.2	0.0 ± 0.0	0.0 ± 0.0	6.3 ± 1.0
	Total catch	4,207	4,221	10	1	2,061
	Days sampled	40	40	32	33	40
	26 Jul to 11 Sep	ANA	COR	OAK	PEN	ROS
Late-season	min CPUE	0.0	0.0	0.0	0.0	0.0
	max CPUE	17.2	0.2	0.0	0.0	0.6
	mean CPUE ± se	0.8 ± 0.4	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Total catch	333	8	0	0	12
	Days sampled	47	37	39	13	80
	2 May to 11 Sep	ANA	COR	OAK	PEN	ROS
2019 Total	min CPUE	0.0	0.0	0.0	0.0	0.0
	max CPUE	142.8	290.5	0.3	0.1	198.7
	mean CPUE ± se	4.2 ± 1.4	16.2 ± 3.3	0.0 ± 0.0	0.0 ± 0.0	9.8 ± 2.3
	Total catch	5,124	19,744	12	1	16,589
	Days sampled	147	137	124	91	189

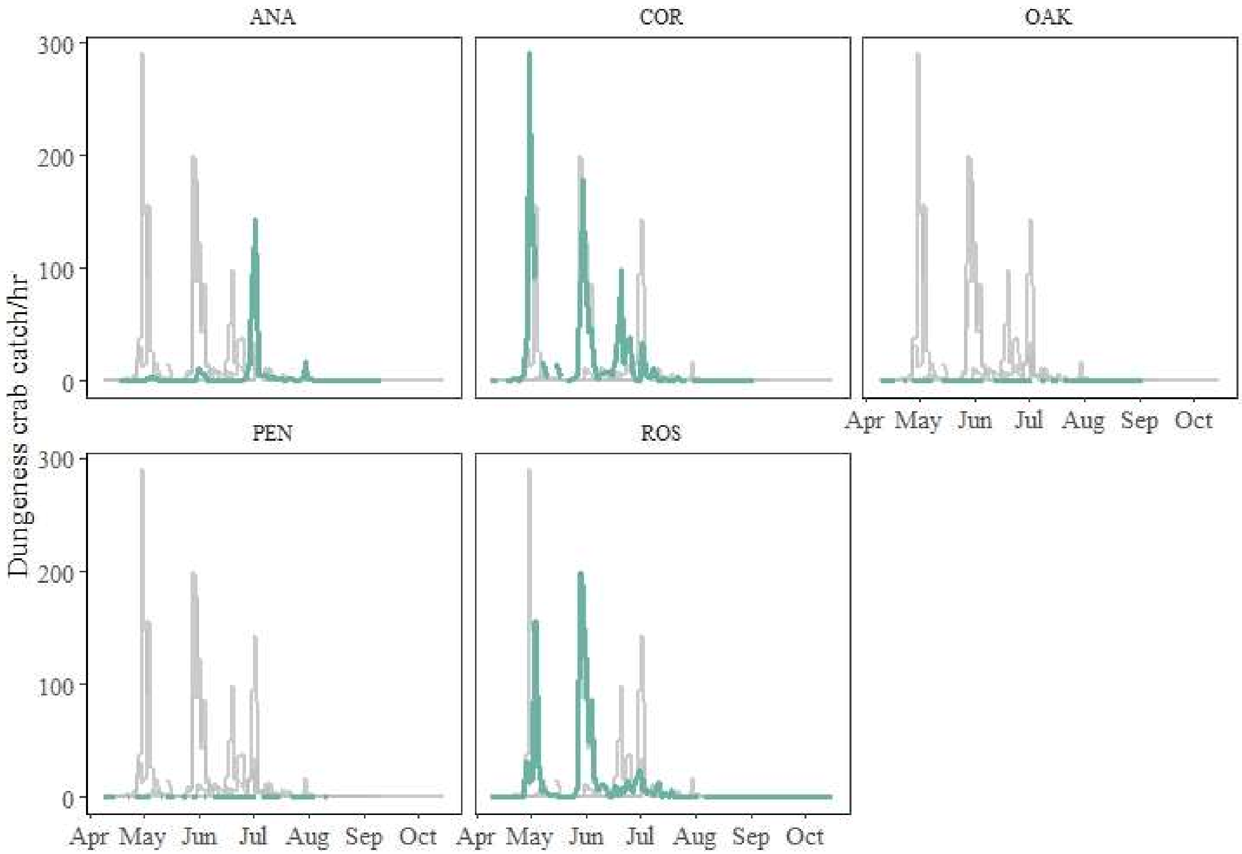

Figure 2. Dungeness crab catch per hour at Anacortes (ANA), Cornet Bay (COR), Oak Harbor (OAK), Coupeville (PEN), and Rosario (ROS) from April to October 2019. Gray lines represent the catch from all three sites overlaid with green lines representing the catch from the individual site.

Skagit River delta in central Whidbey Basin, OAK and PEN did not have any larval Dungeness crab catch until 13 June at OAK and a total of one megalopa was caught on 24 July at PEN, representing the entire annual catch at PEN (Figure 2).

Total Dungeness crab larval abundance through the April to September monitoring period was highest at the sites located nearest Deception Pass (COR and ROS) and negligible in central Whidbey Basin. The COR site captured the most larvae (n = 19,744), closely followed by ROS (n = 16,590), while ANA had roughly a quarter of those catches (n = 5,124), and OAK (n = 12) and PEN (n = 1) had extremely low catches. The highest daily catch across all sites was recorded at COR (290.5 catch/hr) on 30 April 2019 (Figure 2, Table 3). The COR site also had two other distinct delivery peaks on 30 May (178.9 catch/hr) and 20 Jun 2019 (98.5 catch/hr) before tapering off in July (Figure 2). The first high peak delivery pulse for ROS was observed on 3 May (155.4 catch/hr), followed by a second larger peak on 28 May (198.7 catch/hr), and finally a third smaller delivery pulse on 30 June 2019 (23.6 catch/hr). The ANA site, like COR and ROS, had a pulse of megalopae delivered in early May and early June, though the total catches were lower with a maximum catch rate of 11.6 catch/hr. On 2 July, ANA had the highest daily peak of megalopae (142.8 catch/hr) for that site and also among all traps at that time of year (Figure 2). Up to this point the minor pulses at ANA were likely residual megalopae from the pulses sourced from the western side of Fidalgo and Whidbey Islands or further west. However, the third and largest pulse at ANA delivered roughly 70 % of the megalopae captured in 2019 over a one-week period. In the late-season period, the ANA site was the only site to receive a pulse of megalopae (maximum flux of 17.2 catch/hr). All of the megalopae captured at the OAK site were found between 13 June and 3 July 2019. However, the maximum catch was two megalopae in an eight-hour fishing period (0.3 catch/hr). The one megalopa captured at PEN was found on 24 July 2019. Across all five sites, catches did not exceed one megalopa per sampling event after 8 August 2019. The last megalopae were caught on 5 September 2019 at ROS, a full month later than the last megalopae captured at COR (located just east across Deception Pass, Washington).

We found that the vast majority of the total catch at COR and ROS (the two sites with the highest catches) occurred

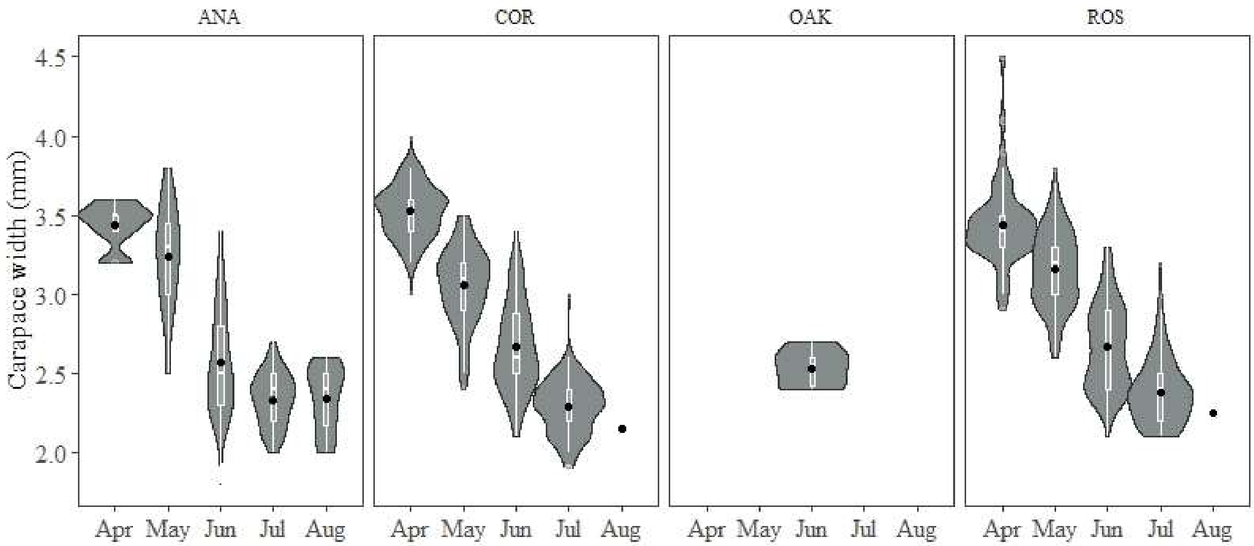

Figure 3. Violin plots depicting the relative distribution, proportion, and mean (dot) of carapace width (mm) of Dungeness crab megalopae caught in light traps [Anacortes (ANA), Cornet Bay (COR), Oak Harbor (OAK), and Rosario Head (ROS)] from May to August 2019. Results from PEN not shown due to the small catch (n = 1).

during the early-season. In fact, the early-season catches at COR and ROS accounted for 78% and 88% of the total season catch in 2019, respectively. While catch rates tapered off during the mid-season at COR and ROS, ANA experienced a 10-fold increase in the mean catch rate (1.2 ± 0.3 to 12.7 ± 5.0 SE catch/hr) from the early-season. Interestingly, the mid-season total catch and catch rates at ANA (n = 4,207; 12.7 ± 5.0 SE catch/hr) and COR (n = 4,221; 12.7 ± 3.2 SE catch/hr) were very similar, while ROS received roughly half the number of larval Dungeness crab (n = 2,061; 6.3 ± 1.0 SE catch/hr) during this period. It is our hypothesis that the ANA and COR mid-season catches originated from the southern Strait of Georgia and Whidbey Basins, respectively, whereas the early-season catches originated from Pacific coast populations and were delivered into the Salish Sea through the Strait of Juan de Fuca. During the late-season, catches at ANA (n = 333; 0.8 ± 0.4 SE catch/hr) were comparable to the early-season totals and rates. Compared to the ANA trap, all other sites received only a handful of megalopae during the late-season (Table 3).

Dungeness crab megalopae carapace width

During the 2019 monitoring season, the sizes of Dungeness crab megalopae were not the same across the sites or through time. From April to August, a significant difference was observed between mean CW by site (ANA, COR, and ROS) in 2019 (X^2 = 82.45, df = 2, p <0.001, Table 4). Follow-up tests revealed that throughout the whole larval delivery period, CWs were significantly smaller at ANA (2.5 ± 0.02 SE mm) compared to both COR (2.8 ± 0.02 SE mm) and ROS (2.8 ± 0.02 SE mm), while no difference in CW was detected between COR and ROS (Table 4). The OAK CWs were excluded from this analysis because of the small sample size (n = 6) and because measurements at this site were only taken in June, however, the mean CW (2.5 ± 0.03 SE mm) was similar to ANA (Table 5).

A steady decline in the mean carapace width (CW) of Dungeness crab megalopae was observed over the 2019 monitoring period by site (Figure 3). For each site (ANA, COR, and ROS) significant differences were detected between months (Table 6). Follow-up tests showed that the decreases in CWs were significant between all months except for between July and August at ANA (April was excluded from the analysis for ANA and August was excluded for COR and ROS because of the small sample sizes) (Table 6). Mean CW of megalopae captured in April was 3.5 ± 0.02 SE at COR and 3.4 ± 0.04 SE at ROS. By May, megalopae CW means by site decreased 13 % at COR (3.1 mm ± 0.02 SE) and 8 % at ROS (3.2 mm ± 0.02 SE). The mean CW for May at ANA was 3.2 mm ± 0.05 SE). The largest month over month decrease in CW occurred between May and June, with mean CWs decreasing an additional 13 % at COR (2.7 mm ± 0.02 SE) and 21 % at ANA (2.6 mm ± 0.03 SE). The CW decreases were more modest in July, ranging from 9 % at ANA (2.3

Table 4. Kruskal-Wallis (X^2) and Conover-Iman (t-statistic) follow-up test results of carapace width by site [Anacortes (ANA), Cornet Bay (COR), Rosario (ROS)].

Kruskal-Wallis X^2 = 82.45, df = 2, p-value = < 0.001*

	ANA		COR	
	t	p	t	p
COR	-7.80	< 0.000*		
ROS	-8.77	< 0.000*	-1.32	0.279

Table 5. Count (n), mean, and standard error (se) of megalopae carapace width by month at Anacortes (ANA), Cornet Bay (COR), Rosario (ROS), and Oak Harbor (OAK) sites in 2019.

	ANA		COR		ROS		OAK	
	n	mean ± se	n	mean ± se	n	mean ± se	n	mean ± se
All 2019	303	2.5 ± 0.02	416	2.8 ± 0.02	358	2.8 ± 0.02	6	2.5 ± 0.05
Apr	5	3.4 ± 0.07	73	3.5 ± 0.02	50	3.4 ± 0.04		
May	35	3.2 ± 0.05	103	3.1 ± 0.02	98	3.2 ± 0.02		
Jun	101	2.6 ± 0.03	118	2.7 ± 0.03	118	2.7 ± 0.02	6	2.5 ± 0.05
Jul	146	2.3 ± 0.01	120	2.3 ± 0.02	90	2.4 ± 0.02		
Aug	16	2.3 ± 0.05	2	2.2 ± 0.05	2	2.3 ± 0.05		

Table 6. Kruskal-Wallis (X2) and Conover-Iman (t-statistic) follow-up test results of megalopae carapace width by month, across sites [Anacortes (ANA), Cornet Bay (COR), Rosario (ROS)].

	ANA		COR		ROS	
X^2	108.67		322.64		251.12	
p	<0.000*		<0.000*		<0.000*	
	t	p	t	p	t	p
Apr vs. May	-	-	11.44	< 0.001*	5.44	< 0.001*
Apr vs. Jun	-	-	22.88	< 0.001*	17.84	< 0.001*
Apr vs Jul	-	-	35.62	< 0.001*	24.17	< 0.001*
May vs. Jun	7.63	< 0.001*	12.30	< 0.001*	15.12	< 0.001*
May vs. Jul	12.48	< 0.001*	26.34	< 0.001*	22.74	< 0.001*
May vs. Aug	7.40	< 0.001*	-	-	-	-
Jun vs. Jul	6.59	< 0.001*	14.50	< 0.001*	8.95	< 0.001*
Jun vs. Aug	2.74	0.019*	-	-	-	-
Jul vs Aug	-0.44	1.000	-	-	-	-

± 0.01 SE) to 14 % at COR (2.3 ± 0.02 SE), before leveling off in August. The observation of larger megalopae being delivered earlier in the season followed by smaller megalopae later in the larval delivery season is consistent with our 2018 results and those of megalopae collected in central Oregon (Shanks et al. 2010, Grossman et al. 2021b).

The megalopae delivered to COR and ROS throughout the April to September monitoring season were primarily made up of the larger size classes of megalopae arriving prior to 15 June (Figures 2 & 3). It is our hypothesis that the high abundance of larger megalopae caught in the light traps prior to 15 June were primarily sourced from populations originating from the Pacific coast (Grossman et al. 2021b, Dinnel et al. 1993). The ANA and OAK sites primarily received the smaller size classes of megalopae caught after 15 June. These megalopae were likely sourced from phenotypically-distinct populations within the Salish Sea (Dinnel et al. 1993). One of the near-term goals of our research is to evaluate genetic diversity of population inputs in order to assess population connectivity across sites. If indeed the phenotypically distinct cohorts represent genetically distinct source populations, the megalopae morphometric measurements from the 2018 and 2019 monitoring seasons will eventually be used to evaluate the relative annual contribution of each larval input delivered to sites within our study area.

Juvenile Dungeness crab intertidal surveys

Dungeness crab juvenile settlement density

Over the winter of 2019, we added two intertidal survey dates (January and March) to examine how many young-of-the-year crab overwintered in the intertidal at COR and SKY. Due to the fact that we missed the start of the larval delivery and settlement period in 2018, we began our in-season bi-weekly monitoring on 23 April 2019, sampling two sites from the 2018 monitoring season. Despite our best efforts, no Dungeness crab instars were found at COR during the early winter sampling events. However, at SKY we found a mean density of 0.8 ± 0.8 SE m^{-2} in January and 0.8 ± 0.5 SE m^{-2} in March. On the first in-season sampling date on 23 April, no crab were found during the survey at SKY or COR. It is likely that all of the juvenile instars found in March (which settled during summer 2018) migrated from the intertidal to the subtidal habitat by the late-April sampling date, ahead of the next wave of larval settlement (also observed in McMillian et al., 1995).

Starting 8 May, early stage instars were present in the intertidal plots at both sites. Dungeness crab intertidal densities peaked at SKY 22.4 ± 9.1 SE m^{-2} on 8 May and at COR 15.6 ± 10.1 SE m^{-2} on 4 June 2019 (Figure 4), corresponding with the largest pulses of larvae found during the early-season larval delivery period (Figures 2 and 4). Intertidal Dungeness crab abundances decreased during the mid- and late-season periods from the early-season levels. During the mid-season, there were nearly twice as many juvenile instars found at SKY (10.0 ± 2.4 SE m^{-2}) than at COR (5.2 ± 2.8 SE m^{-2}). The SKY densities remained higher than COR during the late-season. On the last sampling date, 27 August 2019, the mean intertidal density at SKY was nearly half the mid-season (5.2 ± 1.3 SE m^{-2}), while the COR intertidal density was roughly a quarter of the mid-season peak (1.2 ± 0.9 SE m^{-2}).

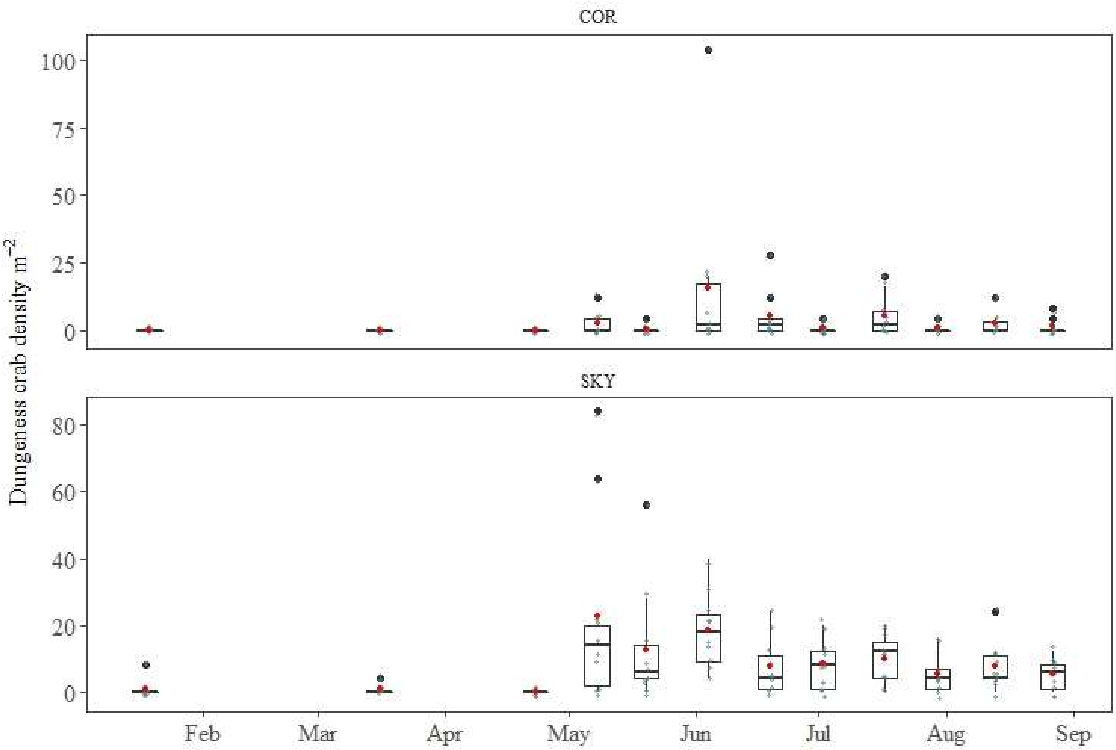

Figure 4. Median, mean density (red dot) and distribution (grey jitter) of intertidal Dungeness crab m^{-2} at Cornet Bay (COR) and Skyline (SKY) during the January, March, and April to August 2019.

Despite the large early-season pulses of megalopae found at the COR larval flux site, the expected corresponding high densities of J1 instars at the COR intertidal site did not manifest in the same way as the SKY intertidal site (Figure 5). The dynamics between juvenile settlers (first stage instars, J1) and recruits (J2+ instars) played out as we expected at SKY. A large number of J1 instars were found during the times of high larval flux, followed by a slow steady increase in the numbers of recruits, plateauing by August (Figure 5). The COR intertidal site did not exhibit the same settlement/recruitment patterns as SKY, despite the largely similar patterns of megalopae abundance and timing observed between the COR and ROS larval flux sites. Appreciable numbers of J1 instars were not observed at COR until early June (a month after peak SKY settlement), corresponding with the second larval peak at COR (Figures 2 & 5). It remains unclear why the first and largest larval pulse at COR failed to result in a correspondingly large peak in settlers. It also remains unclear what beach-level factors contributed to the lower recruitment numbers at COR relative to SKY, given the comparable larval abundances delivered to the nearby larval flux monitoring sites. The relationship between larval delivery and settlement is obviously complicated by a multitude of factors (e.g., hydrodynamic processes, larval patchiness, settlement preferences, competition, habitat suitability) which we aim to further evaluate over time.

Dungeness crab size and instar stage composition

In addition to tracking larval flux and intertidal densities over time, we were interested in tracking growth and development of 0+ juvenile crab (up to ~25 to 40 mm CW; Gunderson et al. 1990, Armstrong et al. 1989) while they occupy intertidal nursery habitats. As with the megalopae captured in the light traps (see discussion above), the CW of J1 instars found during surveys gradually decreased from May to August at our intertidal sites (Tables 7 & 8, Figures 6 & 7). No significant difference was detected between CW sizes between COR and SKY (X^2 = 0.40, df = 1, p-value = 0.528) but varied significantly by month (X^2 = 117.25, df = 3, p-value = <0.001; Table 8). Follow-up tests revealed that the sizes of J1 instars over time varied significantly across all months, except July and August (Table 8). Across both intertidal sites, mean CW of J1 instars was greatest in May (COR: 7.1 ± 0.08 SE mm, SKY: 6.9 ± 0.05 SE mm) and lowest in August (COR: 5.2 ± 0.05 SE mm, SKY: 5.2 ± 0.10 SE mm) (Table 7). The period between June and July sampling dates experienced the most dramatic decrease in mean CW at both sites, with CWs in July a full millimeter smaller than those in June (Table 7), likely representing delivery from phenotypically-distinct cohorts.

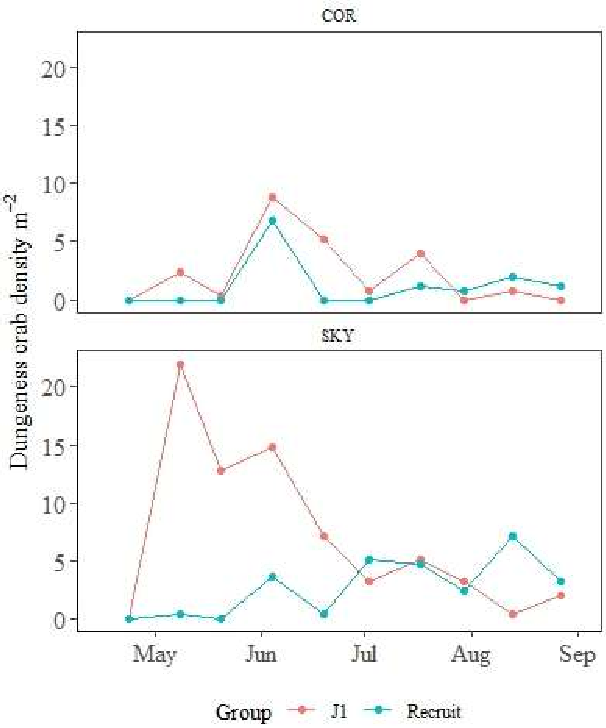

Figure 5. Mean density of intertidal Dungeness crab juvenile stage 1 (J1) instars (red, recent settlers) and recruits (blue, J2 and larger instars) at Cornet Bay (COR) and Skyline (SKY) from April to August 2019.

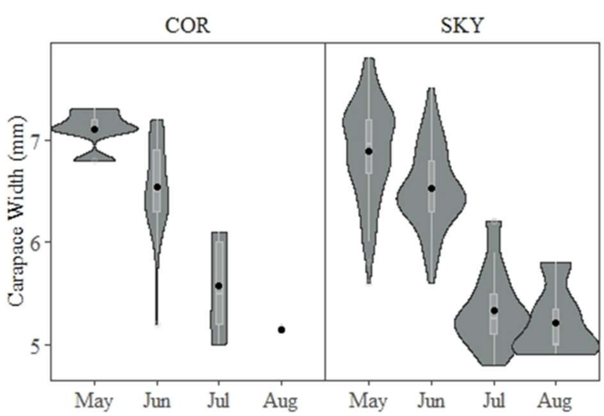

Figure 6. Violin plot depicting the relative distribution and proportion and mean (dot) of carapace width (mm) of Dungeness crab juvenile stage 1 instars from Cornet Bay (COR) and Skyline (SKY) intertidal monitoring sites from April to August 2019.

In May, juvenile Dungeness crab found in the intertidal plots were almost exclusively megalopae or J1 instars (maximum CW 7.8 mm at SKY and 7.3 at COR) (Figure 7). One older instar was found at SKY (CW 34.0 mm) which likely settled in summer 2018. By June there were no longer any instars from the previous settlement season

Table 7. Count of observations and mean carapace width (± standard error) of intertidal juvenile stage 1 instars collected from intertidal habitats by site and month.

	COR		SKY	
	n	mean ± se	n	mean ± se
2019	42	6.4 ± 0.10	166	6.4 ± 0.06
May	5	7.1 ± 0.08	80	6.9 ± 0.05
Jun	28	6.6 ± 0.08	49	6.5 ± 0.06
Jul	7	5.6 ± 0.18	26	5.3 ± 0.07
Aug	2	5.2 ± 0.05	11	5.2 ± 0.10

Table 8. Kruskal-Wallis (X^2) and post-hoc Conover-Iman (t-statistic) results on differences in carapace widths of intertidal juvenile stage 1 instars by month.

Kruskal-Wallis $X^2 = 117.25$, df = 3, p-value = < 0.001*

		Aug	Jul	Jun
Jul	t	-0.68		
	p	1.000		
Jun	t	-7.30	-9.45	
	p	< 0.001*	< 0.001*	
May	t	-10.55	-14.24	-6.06
	p	< 0.001*	< 0.001*	< 0.001*

(2018) on the beach and up to J2 instars were present (maximum CW 11.3 mm at both sites). Maximum CW of instars in July reached 17.5 mm at COR and 19.5 mm at SKY. During our final sampling date in August, the maximum CW of instars were 27.1 mm at COR and 27.5 mm at SKY (Figure 7).

In May and June, the majority of Dungeness crab found in the intertidal habitats were recent settlers (megalopae and J1 instars). By August a clear divergence in growth of the settlement cohorts was observed, roughly four modes (most prominently observed in the San Juan Basin data) of CW representing May, June, July, and August settlement time frames (Figure 7). Growth patterns between the two sites in San Juan and Whidbey Basins were similar in 2019, with the largest of the end of season CWs approaching 30 mm. The instars with CW ~30 mm in August may molt two more times to reach 40 mm by fall (roughly the size that instars immigrate from intertidal habitats, McMillan et al. 1995) when temperatures drop and slow growth and development of *M. magister* (Hartnoll 1982, Orensanz & Gallucci 1988). Even with the larger cohort (likely May settlers) approaching 30 mm in August, the vast majority of *M. magister* instars found at our monitoring sites were < 20.0 mm. It is evident from the January and March sampling events that smaller instars will likely overwinter in intertidal habitats before migrating to subtidal areas in the spring. In the future, we

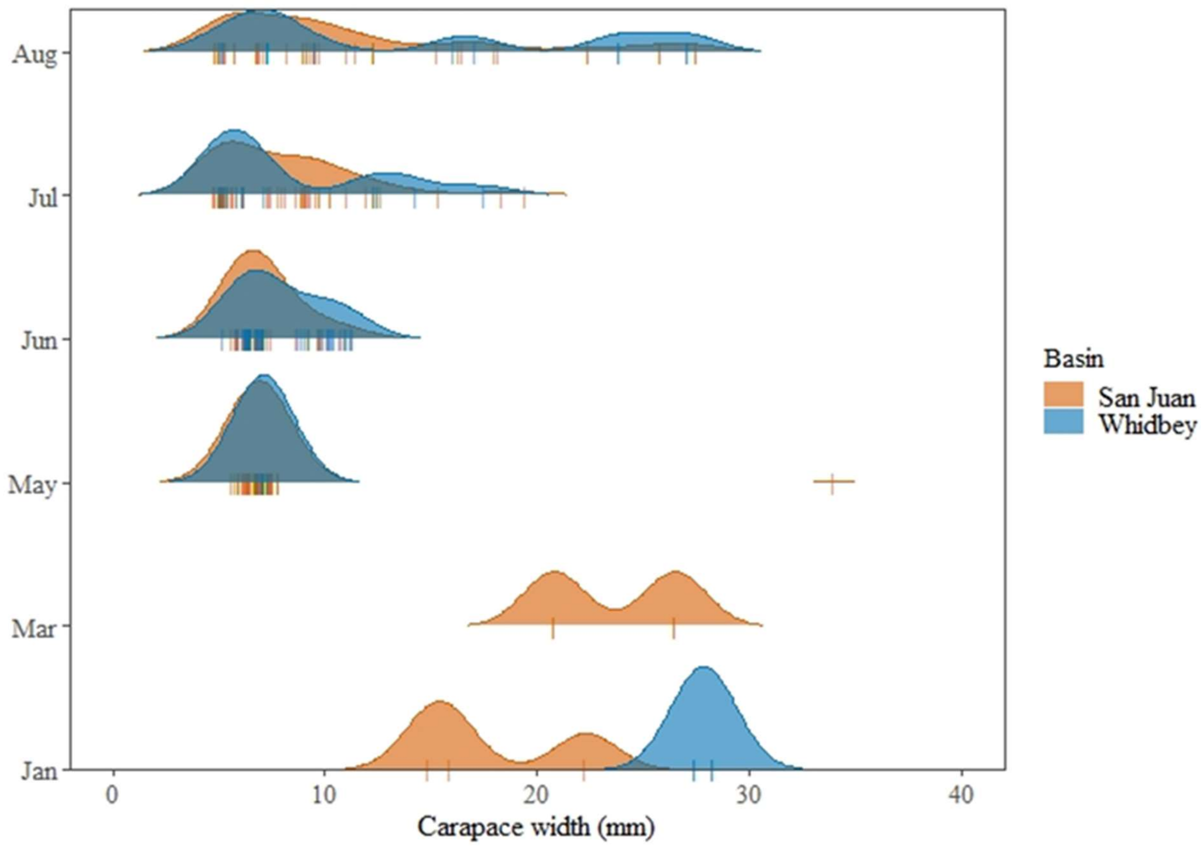

Figure 7. Relative frequency distribution of carapace widths (mm) of intertidal Dungeness crab instars caught from San Juan Basin (orange) and Whidbey Basin (blue) in January, March, and May to August 2019

will continue to monitor COR and SKY on a monthly basis to capture winter growth and survival of young-of-the-year *M. magister*.

Interannual variability of Dungeness crab larval abundance and sizes

In comparing 2018 and 2019 larval catch data (overall and month by month) at COR and ROS (the two sites monitored both years) interesting similarities and differences were observed in the spatial and temporal patterns of larval Dungeness crab delivery to these sites. Total annual catch abundances at COR were relatively similar between the two years, while ROS had nearly 4.5 times more megalopae delivered in 2019 than the previous year (Table 9). The most notable difference between 2018 and 2019 was the timing of larval delivery. In 2018, catches at both sites were relatively low until mid-June when a series of large pulses came through the system, ending in mid-July. In contrast, 2019 experienced two large pulses of megalopae that arrived at both sites in the early-season time period followed by a third, slightly smaller, pulse corresponding with the 2018 peaks in the mid-season (Figure 8). The majority of 2019 larvae were delivered to the sites in the early-season, whereas in 2018 the majority were delivered in the mid-season. As noted above (see *Dungeness crab size and instar stage composition*), overall size and timing of delivery to the juvenile nursery habitats are important factors that could drive differences in growth rates and the relative time it takes for each cohort to reach important developmental milestones (Orensanz and Gallucci, 1988).

In both 2018 and 2019, Dungeness crab megalopae captured at larval flux sites were significantly larger at the start of the delivery season and the CW decreased progressively over the summer months (Grossman et al., 2021b and *Dungeness crab megalopae carapace width* section above). Because of this, we would assume that annual mean CW would be larger for 2019 relative to 2018

Table 9. Total annual abundance of larval Dungeness crab caught in light traps by site and year.

	COR	ROS
2018	20,592	3,716
2019	19,744	16,589

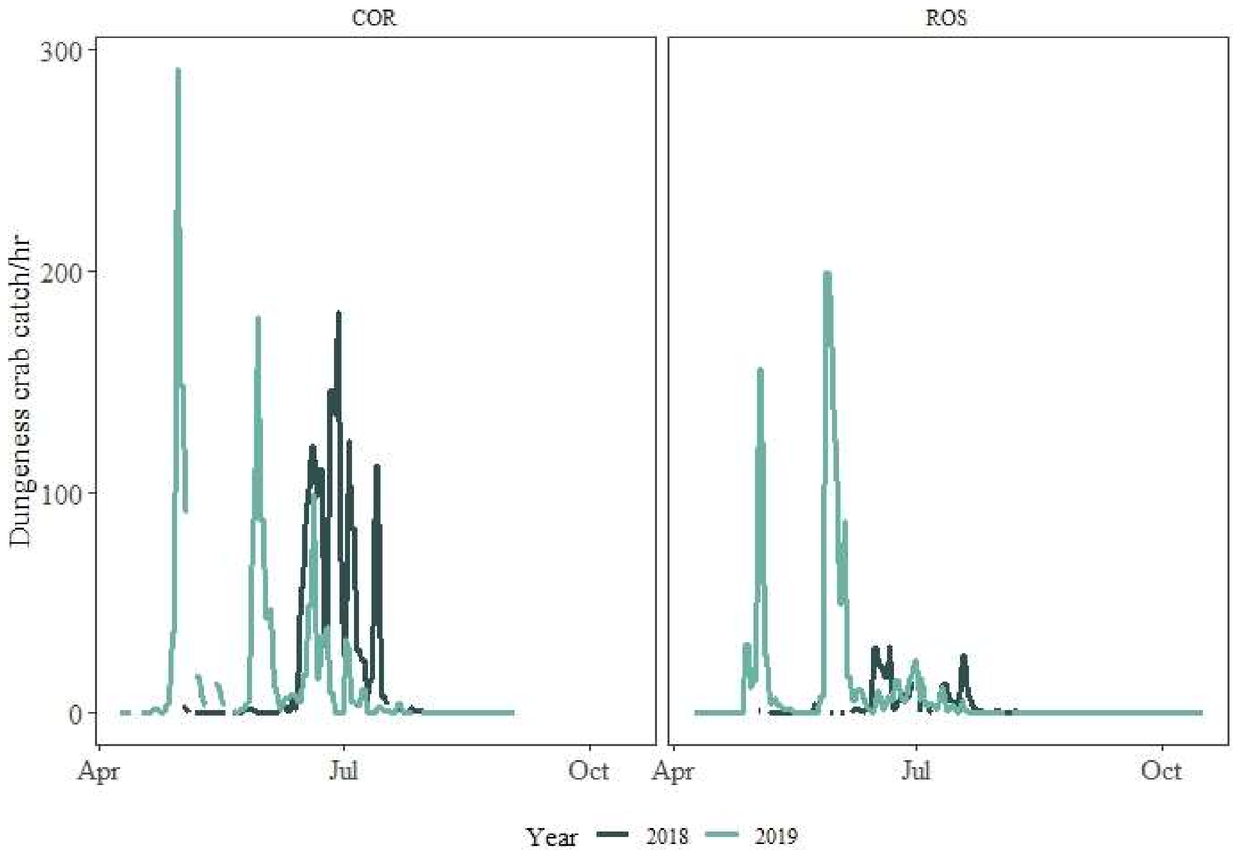

Figure 8. Dungeness crab catch per hour at Cornet Bay (COR) and Rosario (ROS) from April to October. Black lines represent the catch from 2018 and green lines represent the catch from 2019.

due to the majority of larval delivery occurring in the early-season when megalopae were larger. However, we qualitatively found that the mean CW by site for the 2018 season (COR 3.2 ± 0.04 SE mm (n = 116); ROS 3.2 ± 0.04 SE mm (n = 135), Grossman et al. 2021b) was greater than the 2019 season mean CW [COR 2.8 ± 0.02 SE mm (n = 416); ROS 2.8 ± 0.02 SE mm (n = 358); Figure 9]. While a methods change between 2018 and 2019 (we measured 10 megalopae per week in 2018 and increased the sample size to 30 per week in 2019) may explain some of the difference between the annual means, it is still clear that month by month larger megalopae were captured in 2018 compared to 2019 (Table 10). It is too early in our research to speculate on the physical and/or biological factors influencing carapace dimensions given that we are currently unable to determine the origins of larvae delivered to our monitoring sites. Within the central Salish Sea, larvae have the potential to be sourced from any of three genetically differentiated adult populations (Jackson & O'Malley 2017). At this point in our research, we are unsure if the *M. magister* larvae delivered to our sites in the early-season are larger than in the late-season because of genetic predisposition, or because they were reared in waters more conducive to larval growth, or some combination of these two hypotheses. We hope to address these hypotheses further through additional years of monitoring carapace dimensions of larvae delivered to our research sites and through a regional temporal genetic analysis of the larvae.

Because megalopae captured at sites in 2018 were larger than in 2019, we expected to see a similar relationship with the J1 instars found in the intertidal habitats. However, we instead found that J1 instars at both COR (X^2 = 32.9, df = 1, p <0.001) and SKY (X^2 = 41.2, df = 1, p <0.001) were larger in 2019 (mean CW 6.4 ± 0.10 SE mm and 6.4 ± 0.06 SE mm, respectively) relative to 2018 (mean CW 5.5 ± 0.04 SE mm and 5.8 ± 0.06 SE mm, respectively). As with megalopae CW, the CW of J1 instars steadily decreased over the course of the season in both years (Figure 6; Grossman et al. 2021b). We hypothesize that while J1 instar CWs (combined from May to August) were larger in 2019 compared to 2018, the size difference was primarily driven by the number of large instars observed during the early-season.

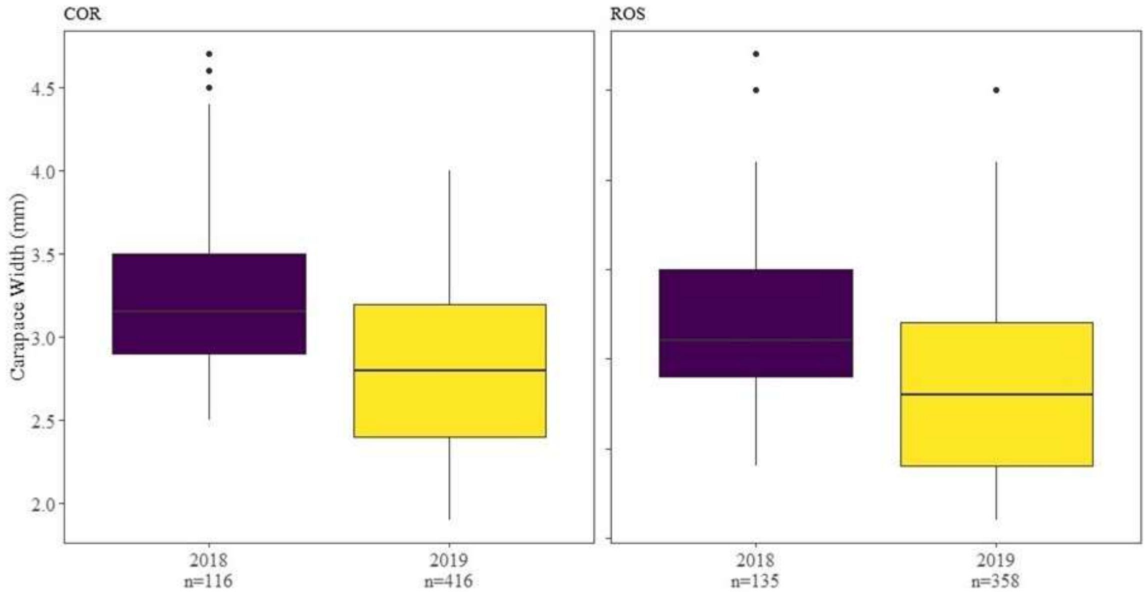

Figure 9. Box plots depicting the relative distribution of carapace width (mm) of Dungeness crab megalopae caught in light traps by year (data from April to August combined for 2018 and 2019) at Cornet Bay (COR) and Rosario (ROS).

Tracking annual and inter-annual sizes of Dungeness crab megalopae and J1 instars, in conjunction with associated environmental and biological metrics, could have important implications for refining growth models for this species in Puget Sound. Tracking Dungeness crab sizes is particularly important because we believe that larvae delivered across the larval season are sourced from a wide range of geographic locations, spanning environmental gradients. Indeed, Dungeness crab megalopae (and subsequent instars) reared in lower temperatures have been shown to be larger by the second juvenile stage, relative to those reared at higher temperatures (Sulkin et al. 1996). Thus, it appears that megalopae arriving earlier in colder waters may grow to larger sizes. There are, however, potential tradeoffs for these early arriving crab, most notably longer intermolt periods (the time between growth phases) (Sulkin et al. 1996). Food availability may counteract the delaying effect of cold rearing conditions on intermolt periods. In a laboratory experiment, high food and low temperature conditions resulted in larger crab by the fifth or sixth instar stage, relative to low food and high temperature treatments (Terwilliger & Dumler 2001). These authors also demonstrated that high food availability can counteract the negative impacts of warm water temperatures on growth, with growth from treatments receiving high food-higher water temperature significantly outpacing low food availability in either temperature treatment. Thus, physical conditions such as temperature and food availability can contribute to the growth rates of cohorts within a year class. These variables, in addition to others not fully discussed here (e.g., habitat quality, seasonality, and source population conditions), will likely need to be accounted for when modeling growth in Puget Sound crab.

As described above, megalopae delivered to sites in 2018 were overall larger than those delivered within the same time frames in 2019. Also, larval delivery during the 2018

Table 10. Mean (and standard error) and count of megalopae carapace width measurements (millimeters) from Cornet Bay (COR) and Rosario (ROS) by month for 2018 and 2019.

	COR				ROS			
	2018		2019		2018		2019	
	n	mean ± se	n	mean ± se	n	mean ± se	n	mean ± se
All Months	116	3.2 ± 0.04	416	2.8 ± 0.02	135	3.2 ± 0.04	358	2.8 ± 0.02
April	-	-	73	3.5 ± 0.02	-	-	50	3.4 ± 0.04
May	21	3.8 ± 0.11	103	3.1 ± 0.02	28	3.8 ± 0.06	98	3.2 ± 0.02
June	44	3.3 ± 0.05	118	2.7 ± 0.03	40	3.3 ± 0.05	118	2.7 ± 0.02
July	50	2.9 ± 0.03	120	2.3 ± 0.02	50	2.9 ± 0.02	90	2.4 ± 0.02
August	1	2.8	2	2.2 ± 0.05	17	2.8 ± 0.04	2	2.3 ± 0.05

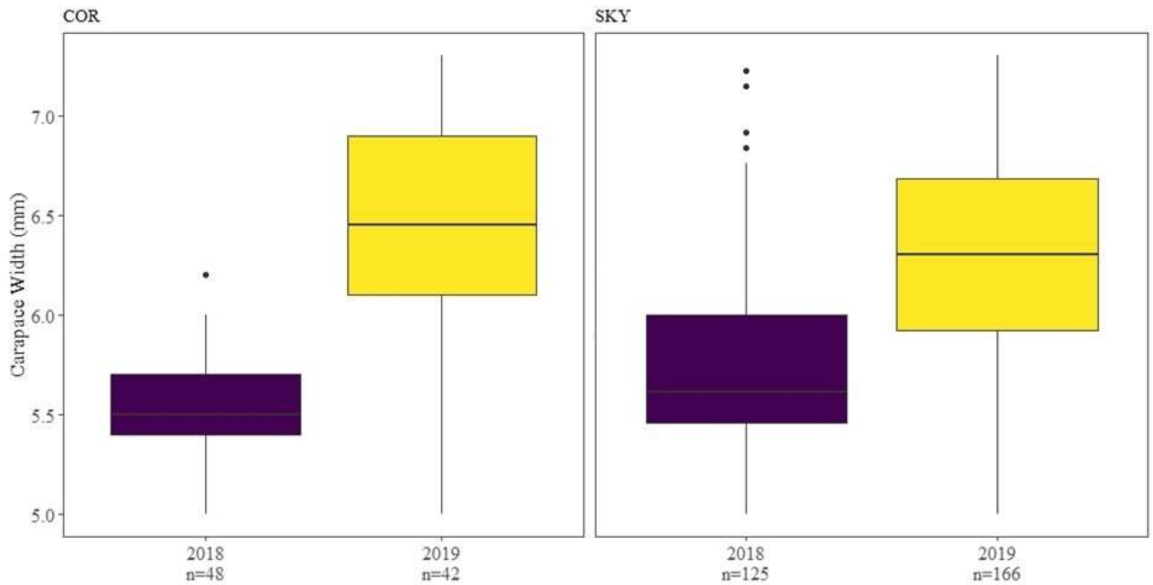

Figure 10. Box plots depicting the relative distribution of carapace width (mm) of intertidal Dungeness crab juvenile stage 1 instars by year (data from May to August combined for 2018 and 2019).

season was predominantly composed of later-arriving cohorts (peaks mid-June), whereas in 2019 a majority of the larvae delivered to sites was composed of the early-arriving cohort (peak in May). Given these patterns, we would expect that the recently settled intertidal J1 instars would exhibit peak densities that corresponded with peak larval flux. Accordingly, at both sites in 2018, peak densities of intertidal J1 instars were observed in July, following the large larval pulses observed in mid-June to mid-July. Also matching this expected pattern, we found that in 2019 at SKY the peak intertidal J1 density occurred in late May following the early-May larval pulse. However, the large larval pulses in May did not result in a strong settlement signal at COR in 2019. It remains unclear why the most pronounced larval pulse we recorded across sites failed to result in a peak of intertidal settlers at COR, as it did at SKY in 2019. We hypothesize that our COR site is not as optimal for Dungeness crab settlement and/or survival as the SKY habitat.

Ecological context

Other species - larval flux

While Dungeness crab were the focus of this study, we also observed megalopae of several other crab species, including the most abundant species: *Cancrid* spp. (*Cancer productus* and *Glebocarcinus oregonensis,* combined because of the logistical limitations to differentiating the magnitudes of these species on a daily basis*)*, *Lophopanopeus bellus*, *Hemigrapsus* spp. *Oregonia gracilis*, and *Pugettia* spp. Like Dungeness crab, larvae of these other species were not evenly observed between the three larval flux sites that caught the most megalopae (ANA, COR, ROS). However, unlike Dungeness crab larvae, each of these species were captured in the light traps during more discrete time periods. In early April 2019, a large pulse of *L. bellus* was observed at ANA, COR, and ROS and were most abundant at COR (Figures 11 and 12). As was the case in 2018, *L. bellus* megalopae were observed on the first sampling date in 2019 and were likely in the system a few days to a week prior to trap deployment. Catches of *L. bellus* peaked between 15 and 25 April 2019, with the highest catch rate (34.8 catch/hr) at COR. Megalopae of *Cancrid* spp. were first observed on 16 May 2019 and were found at sites until 1 August 2019, with an extremely large pulse captured at COR (2,611 catch/hr) on 25 June 2019. The *Cancrid* spp. group made up a majority of the catch at COR, whereas the delivery to other sites was relatively minor compared to the *M. magister* delivery (Figure 12). The largest peak *Cancrid* spp. delivery, excluding COR, was 26.6 catch/hr at ANA. Arriving concurrently with the *Cancrid* spp., *O. gracilis* were observed in low numbers from 15 May to 17 July 2019, with the highest catch (n = 61) occurring at ROS on 1 July 2019. The latest arriving megalopae were the *Hemigrapsus* spp. and *Pugettia* spp. (due to logistical limitations, we opted not to attempt to differentiate between *H. oregonensis* and *H. nudus* or between the several *Pugettia* spp. likely to be observed across the study region). *Hemigrapus* spp. were first observed on 6 July at PEN and last observed on 30 September at ROS. On 17 June 2019 two *Pugettia* spp. were observed at ANA, however no additional *Pugettia* spp. megalopae were observed at any site until 30 June 2019. From 30 June to 29 August 2019 *Pugettia* spp. were consistently observed in low numbers across all sites.

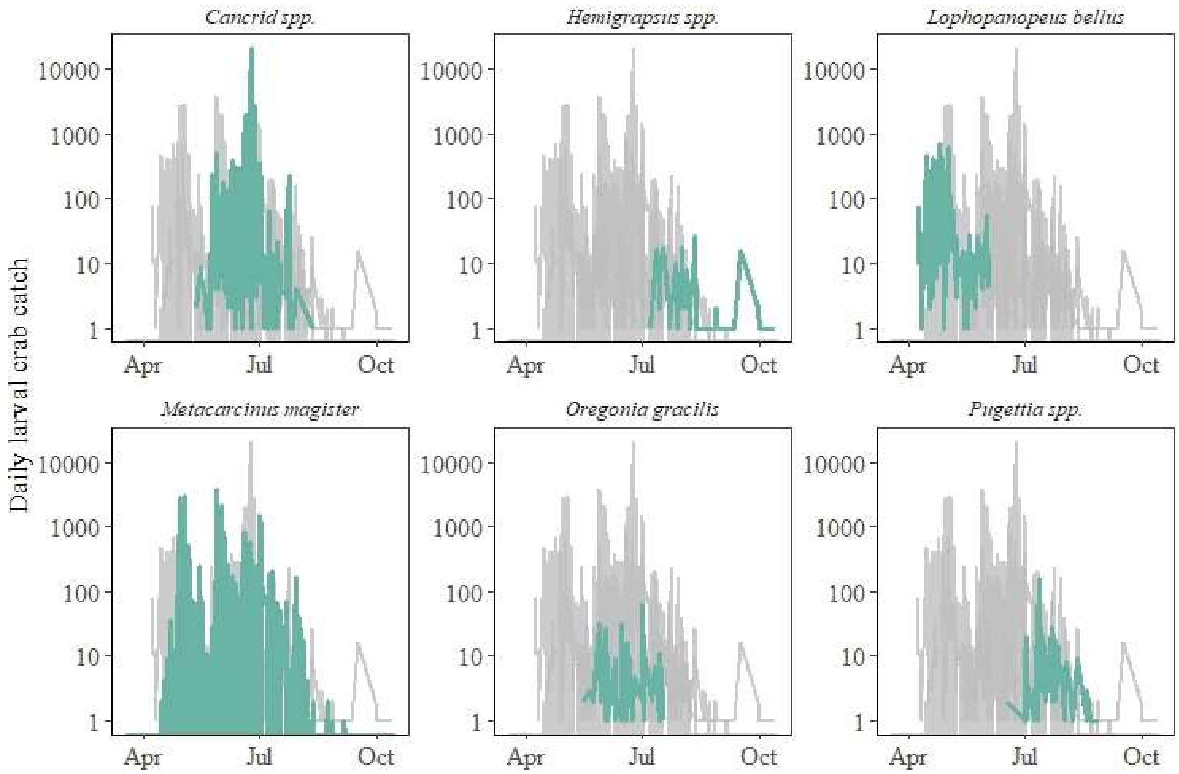

Figure 11. Daily larval crab catches (all sites combined) of *Cancrid* spp. (*Cancer productus* and *Glebocarcinus oregonensis*), *Hemigrapsus* spp., *Lophopanopeus bellus*, *Metacarcinus magister*, *Oregonia gracilis*, and *Pugettia* spp. (April to October 2019). Gray lines represent the daily catch of all species and the overlaid green line represents the catch of the target species.

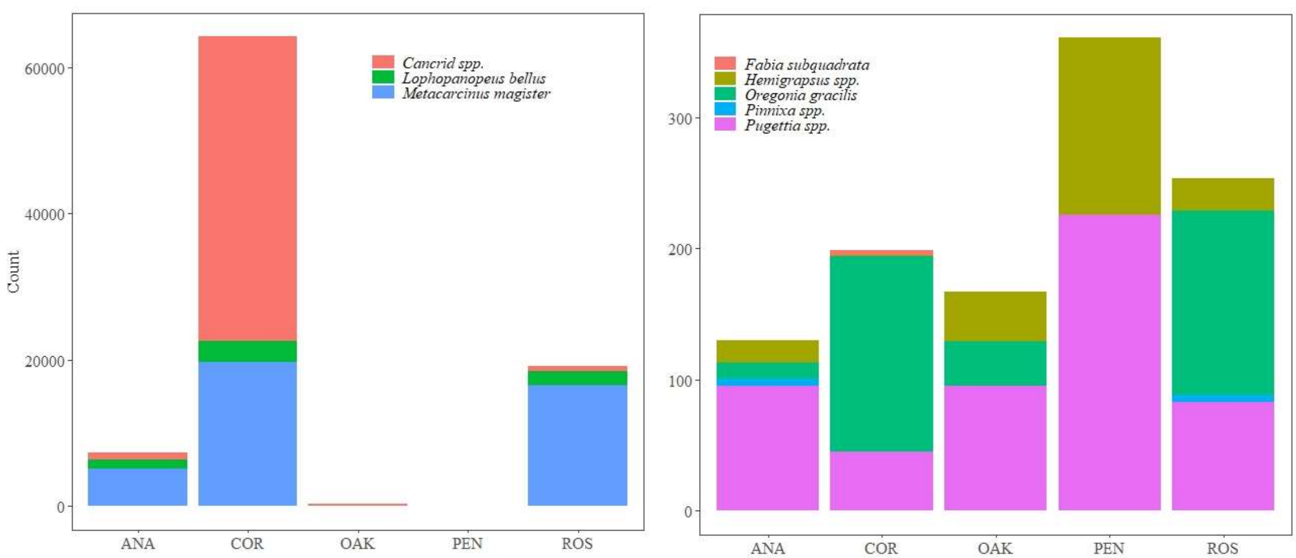

Figure 12. Total megalopal abundance of the most abundant species [left; *Cancrid* spp. (*Cancer productus* and *Glebocarcinus oregonensis*), *Lophopanopeus bellus*, *Metacarcinus magister] and less abundant species (*right*; Fabia subuatrata, Hemigrapsus* spp., *Oregonia gracilis*, *Pinnixia* spp., and *Pugettia* spp.) at Anacortes (ANA), Cornet Bay (COR), Oak Harbor (OAK), Coupeville (PEN) and Rosario Head (ROS) larval flux sites in 2019.

Over the course of the 2019 monitoring season *M. magister* were the predominant species captured at both ANA and ROS, while the COR trap caught more *Cancrid* spp. than *M. magister* (Figure 12). Dungeness crab megalopae catches were minimal at OAK and PEN (Figure 12). We believe that the OAK and PEN catches were heavily influenced by low salinity surface water conditions at the sites (SITC Fisheries Department, unpublished

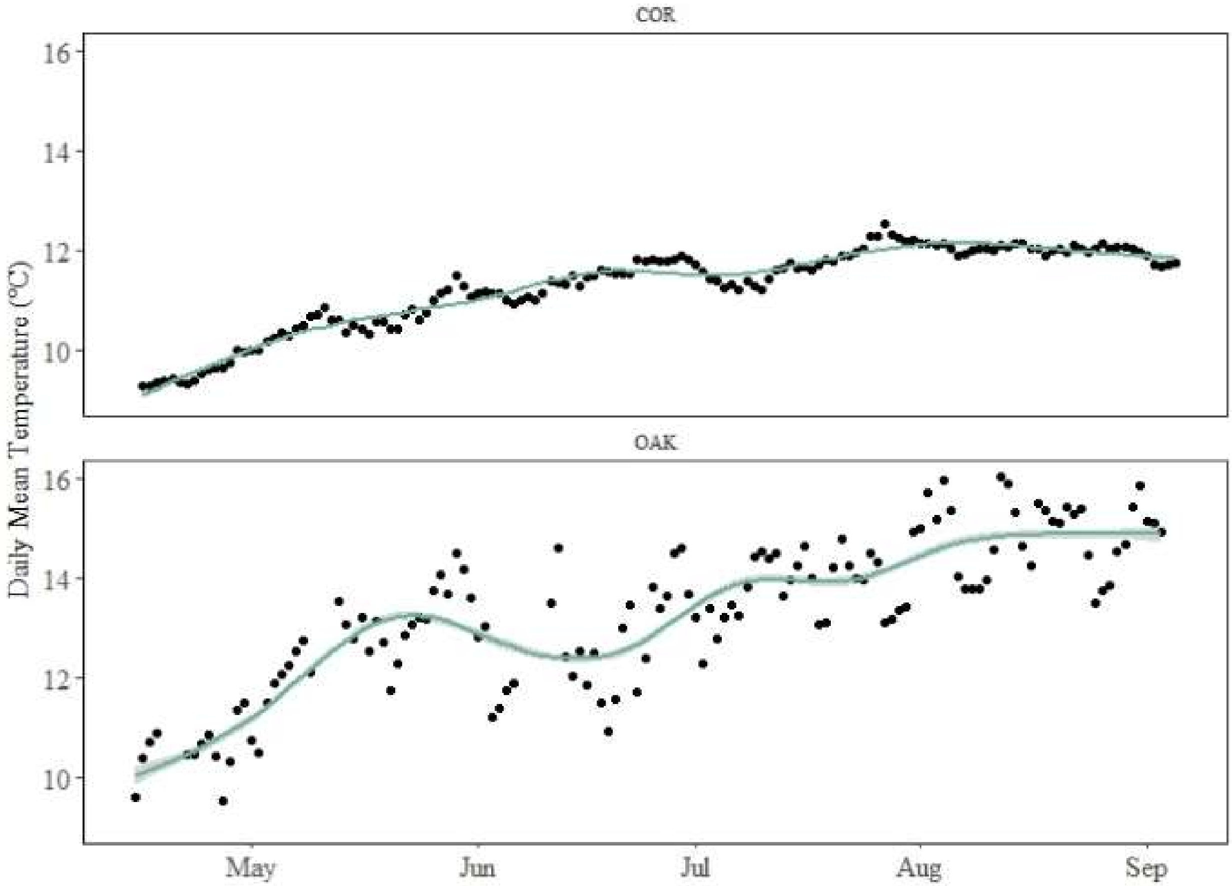

Figure 13. Mean daily surface water temperature (degrees Celsius) with a smooth function trend line from April to September 2019 at Cornet Bay (COR) and Oak Harbor (OAK).

data). Our hypothesis is that the freshwater lens at these sites precluded megalopae (of all species) from migrating to the surface waters where the larval traps were located. It is plausible that megalopal abundance results could change at these sites if we used traps submerged below the stratification boundary in future studies.

Environmental conditions

Surface water temperatures were monitored at COR and OAK from 11 April to 3 September 2019, corresponding with the larval flux monitoring. Surface water temperatures were generally warmer and more variable across the season at OAK than COR, with April to September means of 13.3 ºC ± 0.02 SE and 11.3 ºC ± 0.01 SE, respectively. At COR, surface water temperatures were relatively moderate (Figure 13), with the lowest temperatures recorded in April (monthly mean 9.5 ºC ± 0.01 SE, minimum 9.0 ºC) and peak temperatures in August (monthly mean 12.1 ºC ± 0.01 SE, maximum 14.2 ºC). Surface water temperatures at OAK exhibited a broader range in monthly means (April 10.4 ºC ± 0.02 SE, August 14.8 ºC ± 0.03 SE) and daily maximums (April 12.8 ºC and August 18.1 ºC) over the course of the monitoring season, relative to COR (Figure 13). Differences observed in the variability of water temperature between COR and OAK are likely due to COR's proximity to Deception Pass and the increased water column mixing from the shallow sill and funneling of tidal flow. In contrast, OAK is located in a broad waterbody where water residence time is likely higher and the surface water is more influenced by ambient air temperatures. While the surface water temperatures were more moderate at COR relative to OAK, it is unlikely that temperature alone can explain the difference in megalopal abundance between the sites. Over time we hope to incorporate additional water property parameters and depth profile measurements to gain a better understanding of site-specific characteristics and, eventually, evaluate how water properties influence presence, growth, and survival of Dungeness crab across Swinomish management regions.

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