SWINOMISH LARVAL AND JUVENILE DUNGENESS CRAB MONITORING REPORT FOR 2020

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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. Over the course of the 2020 monitoring season, both larval and juvenile Dungeness crab were observed at larval flux and intertidal sites from May to August, with peak larval delivery and juvenile densities observed from late-May to mid-July. Relative to other crab species observed, Dungeness crab had the longest larval contribution period with near constant presence from May to early August. However, *Cancrid* spp. (*Cancer productus* and *Glebocarcinus* oregonensis) were captured in the highest abundance. Over this protracted Dungeness crab larval delivery period, postlarval 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. Across these three years of monitoring, we have documented differences in the annual variability for the timing of the peak delivery of megalopae where in 2018 and 2020 delivery peaked in mid-June to late-July, however in 2019 the peak was in late-April to late-May. Patterns in total annual delivery were not consistent across sites or between years. Cornet Bay which had observed the highest annual total in 2018 and 2019, saw a 60 and 57% decline in returning megalopae in 2020, respectively, while 2020 Rosario annual totals were 5.4 times greater than in 2018. The Anacortes site also experienced a sharp decline in returning megalopae with an annual total of 729 in 2020 compared to 5,124 in 2019. In terms of size, in 2018, megalopae caught in the light traps were significantly larger than those caught in 2019 and 2020. Continuing to develop a baseline 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 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 2020. Included in this report are data summaries from the larval flux and intertidal density and growth surveys conducted by the Swinomish Fisheries Department. These 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

Over the course of the 2020 monitoring season, light traps were deployed from April to September at four locations to monitor the relative abundance of larval Dungeness crab in San Juan and Whidbey Basins (Figure 1). The Cornet Bay (COR), Rosario Head (ROS), Seafarers Memorial Park in Anacortes (ANA), and Naval Air Station Whidbey Base in Oak Harbor (OAK) sites were monitored in 2020, while the Coupeville Wharf in Penn Cove (PEN) site was discontinued due to the similarity in catch with OAK (Figure 1, Table 1, Grossman et al. 2022). The COR, ROS, and ANA traps were deployed on 7 April 2020. Due to logistical constraints, the OAK trap was not deployed until 10 June 2020. The traps were pulled from the water, ending the monitoring period after roughly two weeks (one full tidal cycle) of zero catch, on 14 September 2020 for COR, ROS, and ANA. The OAK site monitoring did not catch any larval Dungeness crab and the trap was pulled on 4 August 2020.

Larval crab catch (inclusive of megalopae and juvenile stage one "J1" 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).

Juvenile Dungeness crab intertidal surveys

Intertidal surveys were conducted on a bi-weekly basis from 11 April to 31 August 2020 at Cornet Bay (COR) and Skyline (SKY) and monthly at Joseph Whidbey State Park (JOE) during low tides. Additionally, pre- (21 January and 5 March) and post-settlement season (COR and SKY only; 19 October and 15 November) surveys were also conducted to monitor survival and growth of Dungeness crab at sites. Surveys were conducted using a randomized sampling scheme with 10 0.25 m^2 quadrat samples per beach monitoring event. 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 remaining materials were sorted through and all Dungeness crab instars and megalopae were enumerated and CW and CH were recorded. Intertidal areas of three beaches were monitored: Cabana Park near Skyline Marina (SKY) in San Juan Basin, Cornet Bay (COR) in Whidbey Basin, and Joseph Whidbey State Park (JOE) in

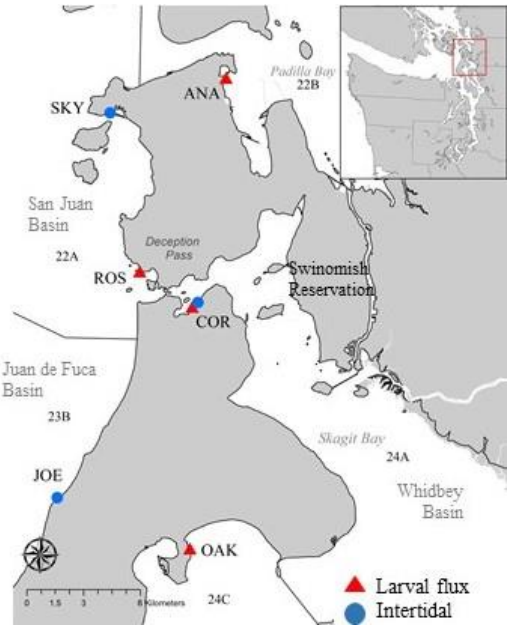

Figure 1. Location of larval flux and intertidal monitoring locations in San Juan and Whidbey Basins. Numbers depict management subregions.

Table 1. Location metadata of larval flux sites in 2020.

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

* Naval Air Station

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
JOE	Joseph Whidbey, Oak Harbor, WA	Juan de Fuca	3	23B

the eastern region of the Strait of Juan de Fuca Basin (Table 2, Figure 1). 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. 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, ROS and ANA larval flux sites from 6 April to 14 September 2020 and from OAK 15 June to 9 September, 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 2020 larval crab monitoring season was broken up into three time periods, each summarizing catch rates over periods of six weeks: early-season (ES) 7 April to 14 June, mid-season (MS) 15 June to 25 July, and late-season (LS) 26 July to 14 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 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 at SKY by month using a KW test. There were not enough J1 instars captured at COR to perform a statistical analysis. Because the KW test determined differences in CWs by month, we followed up with the post-hoc Conover-Inman test (Bonferroni p-adjusted with alpha set to 0.05).

Interannual comparisons (2018-2020) of mean CW of Dungeness crab megalopae at ANA (2019 and 2020), COR, and ROS were compared using a KW test. Differences in annual mean CW were detected at COR and ROS and we followed up with the post-hoc Conover-Inman test (Bonferroni p-adjusted with alpha set to 0.05).

RESULTS AND DISCUSSION

2020 Dungeness crab larval catch

Dungeness crab megalopae were first observed on 12 May at ROS and COR and 22 May at ANA. No megalopae were caught at OAK throughout the entire season (Figure 2). The dates megalopae were first observed at sites in 2020 were just under a month later than in 2019.

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 (7 April to 14 June), mid-season (15 June to 25 July), late-season (26 July to 14 September), and total season from 7 April to 14 September 2020.

	7 Apr to 14 Jun	ANA	COR	ROS
Early-season	min CPUE	0.0	0.0	0.0
	max CPUE	4.6	16.1	81.6
	mean CPUE ± se	0.2 ± 0.1	2.4 ± 0.5	7.6 ± 2.1
	Total catch	125	1,400	4,678
	Days sampled	69	69	67
	15 Jun to 25 Jul	**ANA**	**COR**	**ROS**
Mid-season	min CPUE	0.1	0.2	0.0
	max CPUE	7.1	90.7	262.0
	mean CPUE ± se	1.6 ± 0.3	20.7 ± 4.2	47.5 ± 12.0
	Total catch	564	6,947	15,432
	Days sampled	41	41	41
	26 Jul to 14 Sep	**ANA**	**COR**	**ROS**
Late-season	min CPUE	0.0	0.0	0.0
	max CPUE	0.4	0.0	0.0
	mean CPUE ± se	0.0 ± 0.0	0.2 ± 0.1	0.0 ± 0.0
	Total catch	23	80	0
	Days sampled	51	51	53
	7 Apr to 14 Sep	**ANA**	**COR**	**ROS**
2020 Total	min CPUE	0.0	0.0	0.0
	max CPUE	7.1	90.7	262.0
	mean CPUE ± se	0.5 ± 0.1	6.6 ± 1.3	15.0 ± 3.4
	Total catch	729	8,427	20,110
	Days sampled	161	161	161

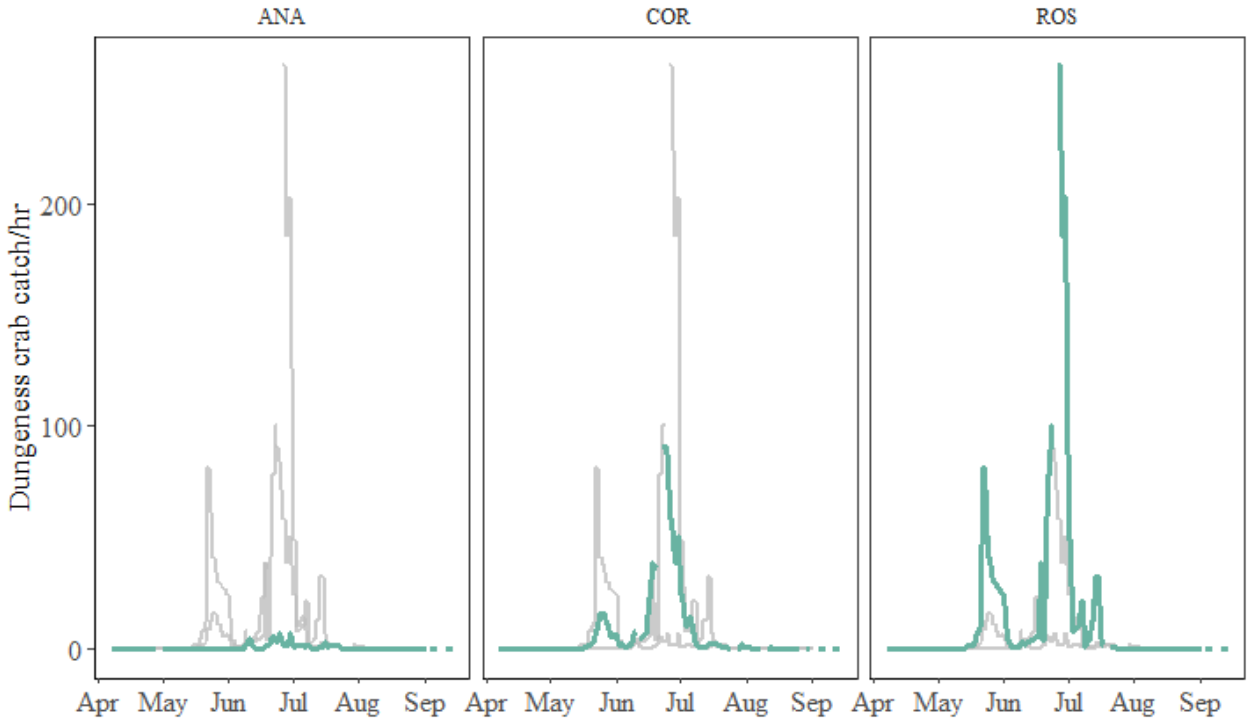

Figure 2. Dungeness crab catch per hour at Anacortes (ANA), Cornet Bay (COR), and Rosario (ROS) from April to September 2020. Gray lines represent the catch from all three sites overlaid with green lines representing the catch from the individual site.

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 lowest at ANA. The ROS site captured the most larvae total (n = 20,110), followed by COR (n = 8,427), while ANA had roughly a quarter of those catches (n = 729), and no Dungeness larvae were captured at OAK (n = 0). The highest daily catch across all sites was recorded at ROS (261.7 catch/hr) on 26 June 2020 (Figure 2, Table 3). The ROS site exhibited a smaller peak (81.6 catch/hr) a month earlier on 23 May (Figure 2). The COR site had two distinct delivery pulses, the largest of which peaked on 23 June (90.7 catch/hr) before the daily catch tapered off in early July (Figure 2). The ANA site's peak catch was 7.1 catch/hr and was observed on 30 June 2020. Relative to COR and ROS, the peaks at ANA could be considered minor. However, the ANA site does exhibit two slightly elevated pulses on 11 June (4.6 catch/hr) and 21 June (5.2 catch/hr). We hypothesize that the low-level catches at ANA were residual megalopae sourced from the pulses on the western side of Fidalgo and Whidbey Islands or further west. Across all sites, after 17 July catches did not exceed 2.4 catch/hr between sampling events. The last megalopae were caught on 23 July at ROS and 20 August 2020 at COR, nearly a full month later than the last megalopae captured at ROS (located just west across Deception Pass, Washington).

We found that the highest larval abundances were observed in the mid-season at all three sites where larvae were found. While the larvae arrived later in 2020 relative to 2018 and 2019, the early season catch accounted for between 17 % (at ANA and COR) and 23 % (ROS) of the total season catch. In the mid-season, catch rates increased at all three sites with seasonal abundances representing 77 % at ANA and ROS and 82 % of the total catch at COR. In the late-season, no Dungeness crab larvae were captured at ROS while COR and ANA had total counts of 80 (< 1 % of total catch) and 23 (3 % of total catch), respectively.

Dungeness crab megalopae carapace width

Over the course of the 2020 monitoring season, the carapace widths of megalopae delivered varied spatially and decreased over time. From May to August 2020, a significant difference was observed between mean CW by site (X^2 = 70.53, df = 2, p <0.001, Table 4). Follow-up tests

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 = 70.53, df = 2, p-value = < 0.001*

	ANA		COR	
	t	p	t	p
COR	-5.95	< 0.000*		
ROS	-8.74	< 0.000*	-3.19	0.002*

Table 5. Count (n), mean, and standard error (se) of megalopae carapace width by month at Anacortes (ANA), Cornet Bay (COR), and Rosario (ROS) sites in 2020.

	ANA		COR		ROS	
	n	mean ± se	n	mean ± se	n	mean ± se
May	14	3.1 ± 0.07	90	3.3 ± 0.03	113	3.3 ± 0.02
Jun	129	2.5 ± 0.02	147	2.7 ± 0.03	145	2.8 ± 0.03
Jul	51	2.3 ± 0.03	68	2.3 ± 0.03	66	2.3 ± 0.03
Aug	4	2.3 ± 0.03	17	2.3 ± 0.06	0	-
All 2020	198	2.5 ± 0.02	322	2.8 ± 0.03	324	2.9 ± 0.03

revealed that throughout the entire delivery period, CWs were significantly smaller at ANA (2.5 ± 0.02 SE mm) compared to both COR (2.8 ± 0.03 SE mm) and ROS (2.9 ± 0.03 SE mm), while CW at COR was significantly smaller than at ROS (Tables 4 & 5).

The CWs of megalopae showed a steady and significant decline by month at all three sites (Figure 3 & Table 6). Follow-up tests showed that the decreases in CWs were significant between all months except for between July and August at COR and ANA (Table 6). No megalopae were caught at ROS in August. Mean CW of megalopae captured in May was 3.1 ± 0.07 SE at ANA, 3.3 ± 0.03 SE at COR, and 3.3 ± 0.02 SE at ROS. By June, megalopae CW means by site decreased 19 % at ANA (2.5 mm ± 0.02 SE), 18 % at COR (2.7 mm ± 0.03 SE), and 15 % at ROS (2.8 mm ± 0.03 SE). The decreases in CW leveled off by July; CWs decreased an additional 8 % at ANA (2.3 ± 0.03 SE), 15 % at COR (2.3 ± 0.03 SE), and 18 % at ROS (2.3 ± 0.03 SE) before leveling off in August (Table 5). The observation of larger megalopae being delivered earlier in the season followed by smaller megalopae later in the

Table 6. Kruskal-Wallis (X^2) 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		195.56	
p	<0.000*		<0.000*		<0.000*	
	t	p	t	p	t	p
May vs. Jun	-5.85	< 0.001*	-12.72	< 0.001*	-15.27	< 0.001*
May vs. Jul	-10.25	< 0.001*	-18.78	< 0.001*	-21.29	< 0.001*
May vs. Aug	-6.20	< 0.001*	-11.69	< 0.001*	-	-
Jun vs. Jul	-8.75	< 0.001*	-8.97	< 0.001*	-9.31	< 0.001*
Jun vs. Aug	-3.68	0.009*	-5.42	< 0.001*	-	-
Jul vs Aug	-0.82	1.000	-0.27	1.000	-	-

larval delivery season is consistent with our 2018 and 2019 results and those of megalopae collected in central Oregon (Shanks et al. 2010, Grossman et al. 2021b, 2022).

The megalopae delivered to all three sites throughout the May to August larval period were primarily comprised of the smaller size classes of megalopae, arriving during the mid-season. It is our hypothesis that the low levels of larger megalopae caught in the traps prior to 15 June were primarily sourced from populations originating from the Pacific coast (Grossman et al. 2021b, Dinnel et al. 1993). The smaller, later arriving megalopae that dominated catches in 2020 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 morphometric

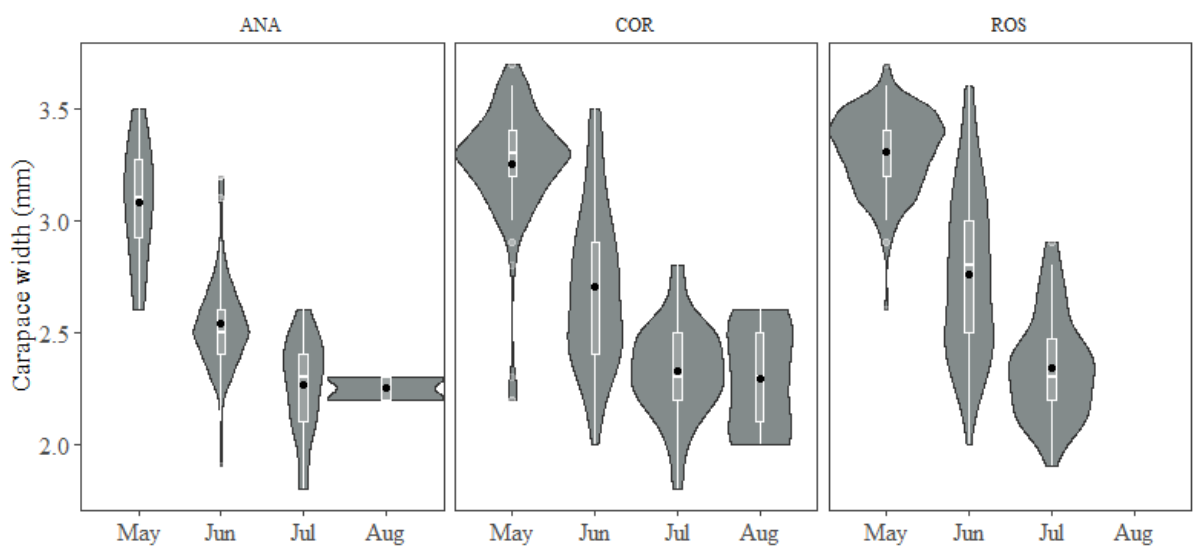

Figure 3. Violin plots depicting the relative distribution, proportion, and mean (dot) of carapace width (mm) of Dungeness crab megalopae caught in light traps [Anacortes (ANA), Cornet Bay (COR), and Rosario Head (ROS)] from May to August 2020.

measurements from the 2018 to 2020 monitoring seasons will eventually be used to evaluate the relative annual contribution of larval inputs from the different source populations delivered to sites within our study area.

Juvenile Dungeness crab intertidal surveys

Dungeness crab juvenile settlement density

In 2020 we monitored intertidal sites during the pre-settlement season, the settlement period (i.e., while megalopae were observed in larval traps), and the post-settlement season. This monitoring schedule allowed us to observe the densities and sizes of Dungeness crab that overwintered in the intertidal habitats prior to the arrival of the next year class, in addition to tracking the current year's cohorts.

During the pre-settlement season surveys, which were conducted in January and March, no crab were caught at COR. At JOE, no crab were found during the January survey but in March we found 0.8 ± 0.5 SE crab/m^2. In both January and March, SKY mean densities were 1.6 ± 0.9 SE m^{-2} (Figure 4). On the first three in-season sampling dates from 9 April to 9 May 2020, no crab were found during the surveys at COR, JOE, or SKY. It is likely that all of the juvenile instars found in March (which settled during summer 2019) migrated from the intertidal to the subtidal habitat by the April sampling dates, ahead of the next wave of larval settlement (also observed in McMillian et al. 1995). Starting 26 May, early stage instars were present in the intertidal plots at all three sites (Figure 4). Dungeness crab intertidal densities peaked at JOE on 27 May at 2.0 ± 1.6 SE m^{-2} and no crab were observed at this site until the 4 August survey where the mean density had returned to the pre-season level (0.8 ± 0.5 SE m^{-2}). We hypothesize that the JOE results are due to one or a combination of the following factors: very few Dungeness crab settled at JOE, our monthly monitoring schedule missed the 'true' peak settlement period and survival of the peak delivery pulse was low, or the habitat was too dynamic during the 2020 season and was not hospitable for juvenile Dungeness crab. Peak mean densities at SKY occurred on 7 July at 24.4 ± 7.3 SE m^{-2} roughly corresponding with the peak larval catch/hr observed at the ROS site. At COR, peak intertidal densities were observed on 3 August at 3.6 ± 2.3 SE m^{-2}. The mean densities of Dungeness crab instars were lower at COR relative to SKY across sampling dates (Figure 4). This pattern is consistent

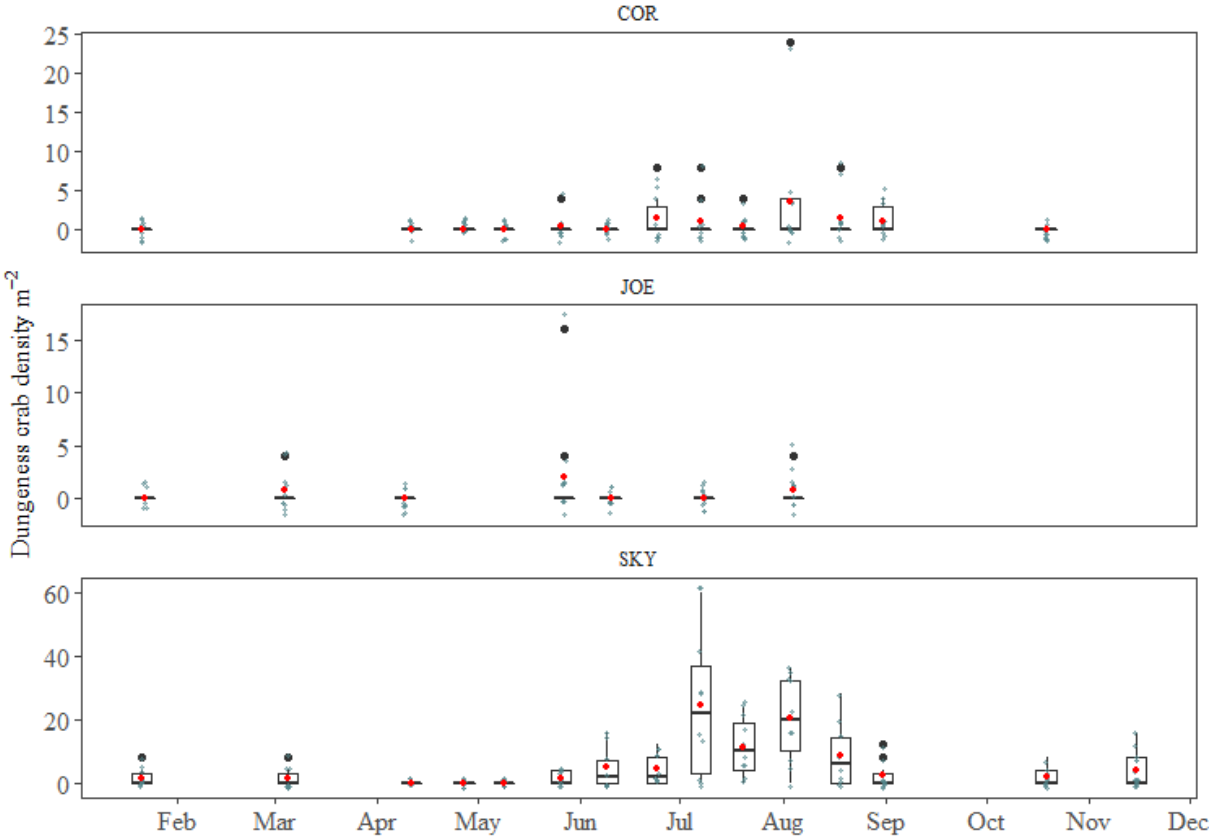

Figure 4. Median, mean density (red dot) and distribution (grey jitter) of intertidal Dungeness crab m^{-2} at Cornet Bay (COR), Joseph Whidbey (JOE), and Skyline (SKY) in 2020. Note differences in scale.

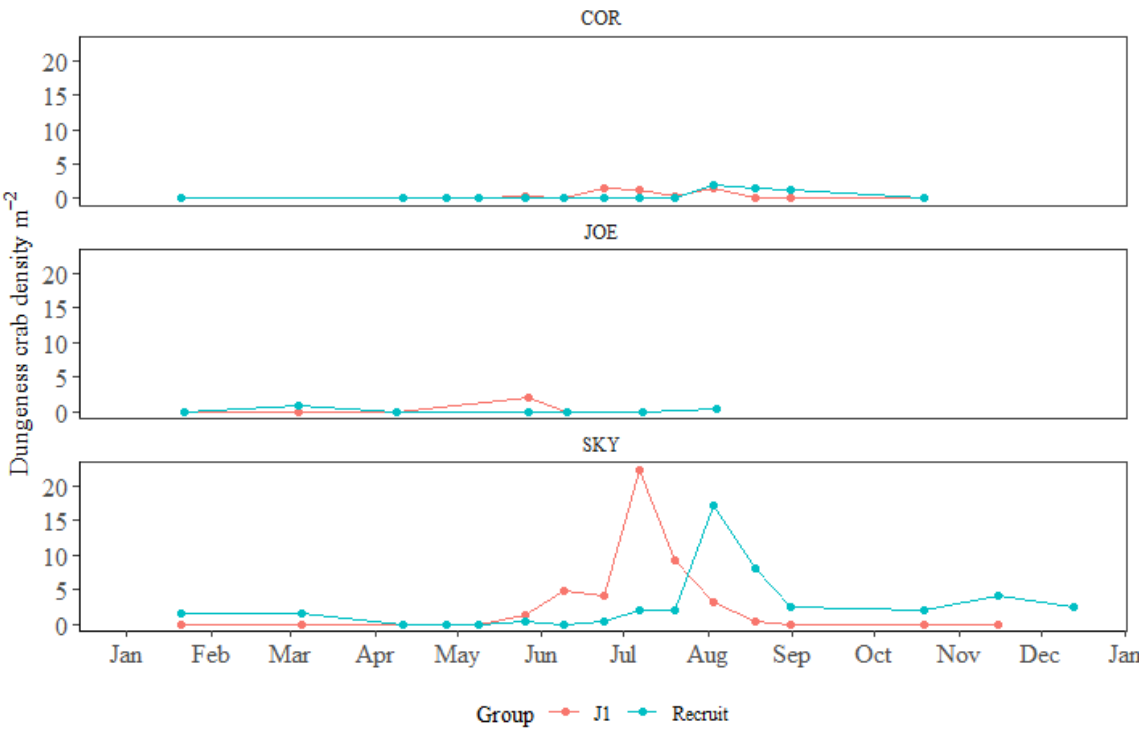

Figure 5. Mean density of intertidal Dungeness crab juvenile stage 1 (J1) instars (red, recent settlers) and recruits (blue, J2 and larger instars) at Cornet Bay (COR), Joseph Whidbey (JOE) and Skyline (SKY) from January to December 2020.

with the patterns in the magnitude of delivery between ROS and COR larval monitoring sites (see 2020 Dungeness crab larval catch section above).

Qualitatively, intertidal Dungeness crab abundances decreased during post-settlement season period from the peak levels observed in July and August. In fall 2020, the highest intertidal density at SKY was 4.0 ± 1.4 SE m^{-2}, while no crab were found at COR (Figure 4). Given the ROS captured over twice as many Dungeness crab megalopae compared to COR over the larval delivery season, it is not surprising that SKY had higher densities of juvenile Dungeness crab compared to COR.

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 in late-June/July, followed by a slow steady increase in the numbers of recruits, and finally plateauing by September and into the fall months (Figure 5). The low numbers of J1 instars found at JOE in early June were not found as recruits in later months (Figure 5). Interestingly, in June at JOE, we noticed a large influx of sand covering the cobble/mixed algae habitat where juvenile Dungeness crab were most abundant. We hypothesize that as the recent settlers grew at JOE, they may have moved to more stable habitat offshore or elsewhere along the beach where the complex habitats are more stable.

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; Armstrong et al. 1989, Gunderson et al. 1990) 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 June to August at our intertidal sites (Table 7, Figures 6 & 7). Due to the low numbers of J1 instars observed at COR, statistics were only performed for SKY where a

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
May	-	-	1	6.9
Jun	3	7.0 ± 0.20	17	7.3 ± 0.12
Jul	3	6.1 ± 0.65	79	6.1 ± 0.09
Aug	2	5.1 ± 0.06	9	5.1 ± 0.20
2020	8	6.0 ± 0.36	106	6.2 ± 0.09

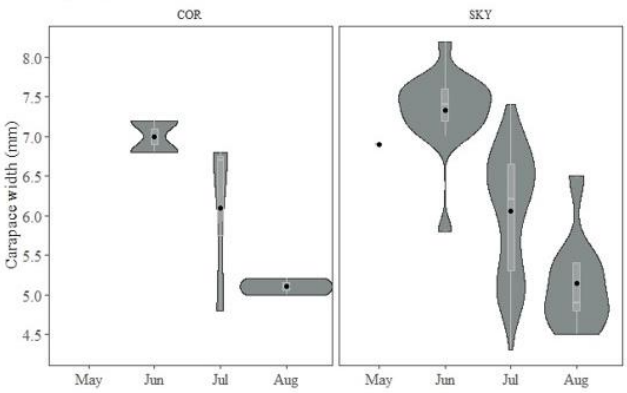

Figure 6. Violin plot depicting the relative distribution, proportion, and mean (dot) of carapace width (mm) of Dungeness crab juvenile stage 1 instars from Cornet Bay (COR) and Skyline (SKY) intertidal monitoring sites from April to August 2020.

significant difference was detected between CW sizes by month (excluding May where only one J1 instar was found: X^2 = 41.78, df = 2, p-value = <0.001). Follow-up tests revealed that the sizes of J1 instars varied significantly across all months, with CW progressively getting smaller through time at SKY (Table 8). Across both intertidal sites, mean CW of J1 instars was greatest in June (COR: 7.0 ± 0.20 SE mm, SKY: 7.3 ± 0.12 SE mm) and lowest in August (COR: 5.1 ± 0.06 SE mm, SKY: 5.1 ± 0.20 SE mm). From June to August, COR and SKY J1 instar CW means decreased by 1.9 and 2.1 mm, respectively (Table 7). We hypothesize that this indicates that the beaches in San Juan and Whidbey Basins experience Dungeness crab delivery from phenotypically-distinct cohorts. To date, it remains unclear if these observed phenotypic differences are a result of genetically-distinct populations or if the rearing conditions experienced across months is driving the relative size differences.

From May to early June, juvenile Dungeness crab found in the intertidal plots were almost exclusively J1 instars (Figure 7). By late June, the maximum CW of instars from the 2020 year class reached 11.5 mm at SKY and 7.2 mm at COR. In July, the maximum CW of instars remained flat at both sites, with 11.1 mm at SKY and 6.8 mm at COR. By the end of the settlement season in August, the largest instars had a CW of 14.2 mm at COR and 14.1 mm at SKY. During our final sampling date in December 2020, no instars were found at COR and the maximum CW at SKY was 25.5 mm, minimum CW 10.4 mm, and the mean CW was 15.5 mm ± 1.7 SE (Figure 7). We presume that the majority of crab that settled in 2020 will overwinter in these intertidal habitats. Given the relatively small mean December CW, we hypothesize that a majority of the crab remaining in the intertidal at SKY likely settled later in the larval delivery period (~July/August) and will have to go through three to four additional molts before reaching the ~40 mm CW threshold for emigration to deeper waters (McMillian 1995).

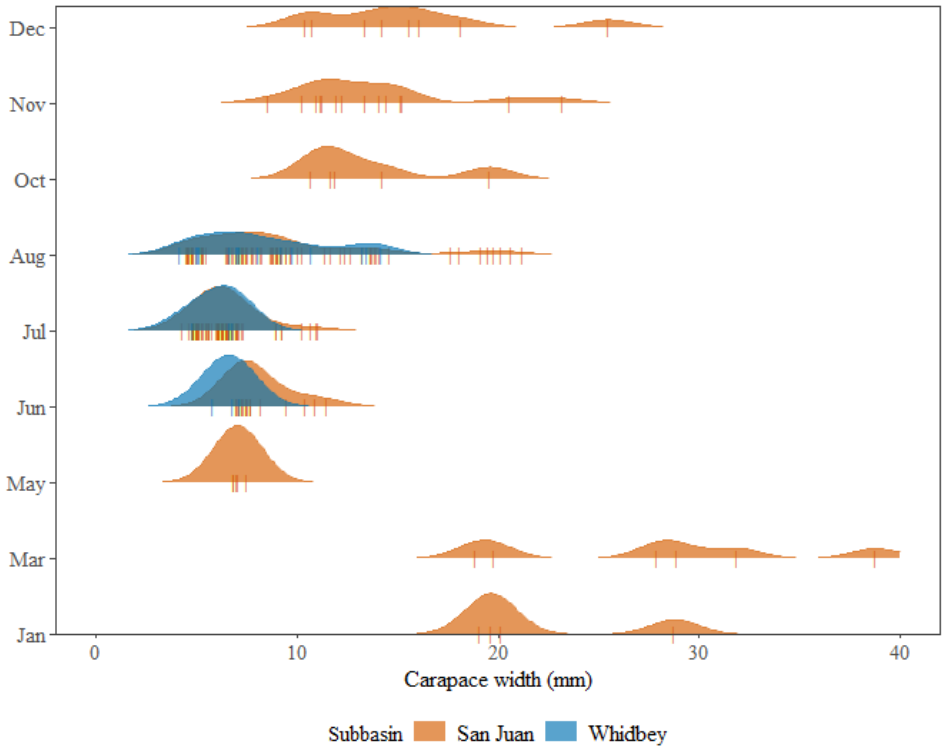

Figure 7. Relative frequency distribution of carapace widths (mm) of intertidal Dungeness crab instars caught from San Juan Basin (orange) and Whidbey Basin (blue) in January, March, and May to August 2020

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 at Skyline.

Kruskal-Wallis $X^2 = 47.462$, df = 2, p-value = < 0.001*

		Jun	Jul
Jul	t	6.99	
	p	< 0.001*	
Aug	t	7.48	3.46
	p	< 0.001*	0.001*

Interannual variability of Dungeness crab larval abundance and sizes

From 2018 to 2020, larval Dungeness crab catch data across our monitoring sites varied greatly between sites and years (Table 9). Total annual catch abundances at COR were similar in 2018 and 2019 (n = 20,592 and 19,744, respectively) but total catch was roughly 57% lower in 2020 (n = 8,427). Interestingly, ROS observed the lowest catches in 2018 (n = 3,716) and in 2019 there was a 446% increase in the larval delivery (n = 16,589) and the highest total catch was observed in 2020 (n = 20,110). ANA, which was not monitored in 2018, exhibited an annual pattern similar to COR, though at a lower magnitude. Specifically, the total catch in 2019 at ANA was n = 5,124 and the 2020 catch was 729 megalopae, reduced by 86% from 2019.

The timing of larval pulses also varied across years, with each year between 2018 and 2020 exhibiting unique delivery patterns. In 2018, catches at COR and ROS were relatively low (< 100 megalopae/day) until mid-June when much larger catches were observed until tapering off again in mid-July. The mid-season delivery represented 94 to 98 % of the yearly catch at ROS and COR, respectively. In 2019, a majority of the larvae were delivered prior to mid-June at COR (79 % of total) and ROS (88 % of total), whereas at ANA the most significant pulse occurred in late June (Figure 8). Larval delivery patterns observed in 2020 were a mix of the previous two year's patterns. The early-season represented 17 to 23 % of the total catches at COR and ROS, followed by larger pulses in the mid-season at COR (82 % of total) and ROS (77 % of total). Across all three monitoring years, the late-season catches were < 1 % of the total catch.

In previous reports we have hypothesized that the larval pulses delivered to our study sites in April and May likely originate from Dungeness crab populations from the outer Pacific coast. This hypothesis continues to be supported by the consistent phenotypic differences observed (size and timing of larval delivery) between the start and end of the larval delivery season. Carapace dimensions of megalopae from outer coast populations have been shown to be larger

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

	COR	ROS	ANA
2018	20,592	3,716	-
2019	19,744	16,589	5,124
2020	8,427	20,110	729

than conspecifics from the inland waters of the Salish Sea (DeBrosse et al. 1990). In addition to differences in overall sizes of the megalopae, Dungeness crab from outer coast populations are present as post-larvae in the water column and have been shown to settle earlier in the spring and summer compared to populations from the Salish Sea (MacKay & Weymouth 1935, Gunderson et al. 1990, Jamieson & Phillips 1993, Sulkin et al. 1996). 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 & Gallucci 1988).

Dungeness crab megalopae captured at larval flux sites from 2018 to 2020 were significantly larger at the start of

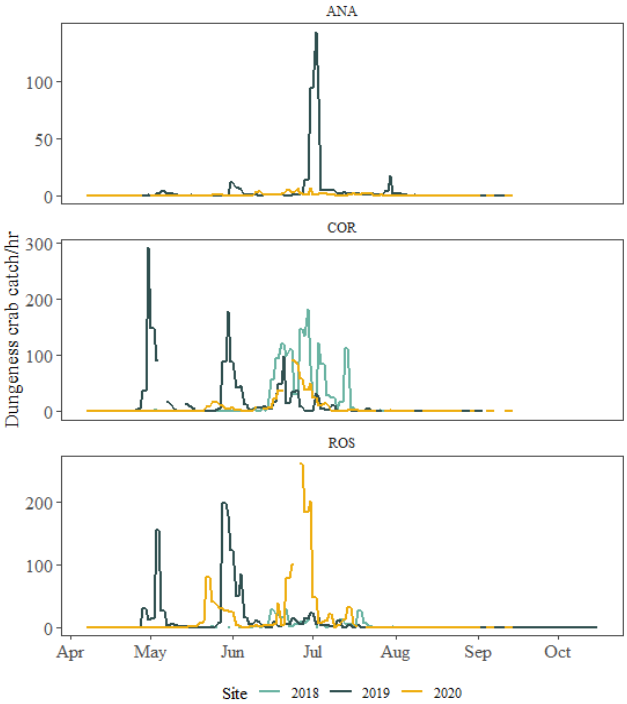

Figure 8. Dungeness crab catch per hour at Anacortes (ANA), Cornet Bay (COR) and Rosario (ROS) from April to October. Green lines represent the catch from 2018, black lines represent the catch from 2019, and yellow represent 2020.

the delivery season and the CW decreased progressively over the summer months (Table 6 and Grossman et al. 2021b, Grossman et al. 2022). Because of this, we would assume that annual mean CW would be larger for 2019 relative to 2018 and 2020 because the majority (79 to 88 % of total) of the 2019 larval delivery occurred in the early-season when megalopae were larger. While we found no difference in annual mean CW between years at the ANA site (only monitored in 2019 and 2020), there was a difference by year in mean CW at COR and at ROS (Table 10). Specifically, we found that the mean CW at COR and ROS 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 significantly 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)] and the 2020 season mean CW (see Table 5 for 2020 CW means, Figure 9). Similarly, we did not expect seasonal mean CWs at COR and ROS in 2019 and 2020 to be similar given the seasonal differences in delivery patterns but there was no significant difference in annual mean CW between these two years (Table 10).

We believe it is too early in our research to speculate on the physical and/or biological factors influencing carapace dimensions given 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

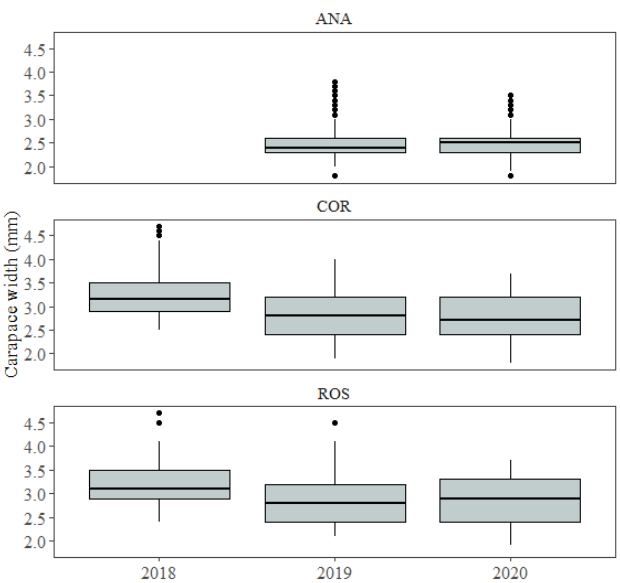

Figure 9. Box plots depicting the relative distribution of carapace width (mm) of Dungeness crab megalopae caught in light traps by year (data from April to August combined for 2018 to 2020) at Anacortes (ANA), Cornet Bay (COR) and Rosario (ROS).

Table 10. Kruskal-Wallis (X^2) and post-hoc Conover-Iman (t-statistic) results on differences in carapace widths of megalopae for Anacortes, Cornet Bay (COR) and Rosario (ROS) by years 2018, 2019, and 2020.

	ANA		COR		ROS	
X^2	1.21		70.23		53.91	
p	0.27		<0.000*		<0.000*	
	t	p	t	p	t	p
2018 vs 2019	-	-	7.87	< 0.001*	7.43	< 0.001*
2018 vs 2020	-	-	8.44	< 0.001*	6.40	< 0.001*
2019 vs 2020	-	-	1.18	0.355	-1.24	0.323

delivered to our sites in the early-season are larger than the late-season larvae because of a genetic predisposition or because they were reared in waters more conducive to greater larval growth, or some combination of these two hypotheses. We hope to investigate these hypotheses further through additional years of monitoring larval dynamics and ocean conditions at our research sites and by analyzing regional and temporal genetic variability paired with circulation modeling.

Ecological context

Other species - larval flux

While Dungeness crab were the focus of this study, we also observed 12 other larval crab species/species groups, including the following most abundant species: *Cancrid* spp. (*Cancer productus* and *Glebocarcinus oregonensis*, combined because of the logistical limitations of differentiating the magnitudes of these species on a daily basis), *Lophopanopeus bellus*, *Hemigrapsus* spp. (*H. oregonensis* and *H. nudus*), *Oregonia gracilis*, and *Pugettia* spp (Table 11; *Pagurus* spp. were also found at all sites, though only daily presence was recorded). Like Dungeness crab, larvae of these other species were not evenly observed among the three larval flux sites (ANA, COR, and ROS).

Table 11. Abundances of crab families, genus, or species observed at Anacortes (ANA), Cornet Bay (COR), and Rosario (ROS) larval crab monitoring sites in 2020.

	ANA	COR	ROS
Acantholithodes hispidus	1	-	-
Cancrid spp.	1,556	216,649	128,024
Fabia subquadrata	1	7	3
Hemigrapsus spp.	66	18	16
Lophopanopeus bellus	2,794	8,546	22,938
Metacarcinus magister	734	8,422	20,110
Oregonia gracilis	61	239	462
Pinnixa spp.	187	194	118
Placetron wosnessenskii	6	-	8
Porcellanidae	-	-	1
Pugettia spp.	128	85	81
Telmessus cheiragonus	4	4	3

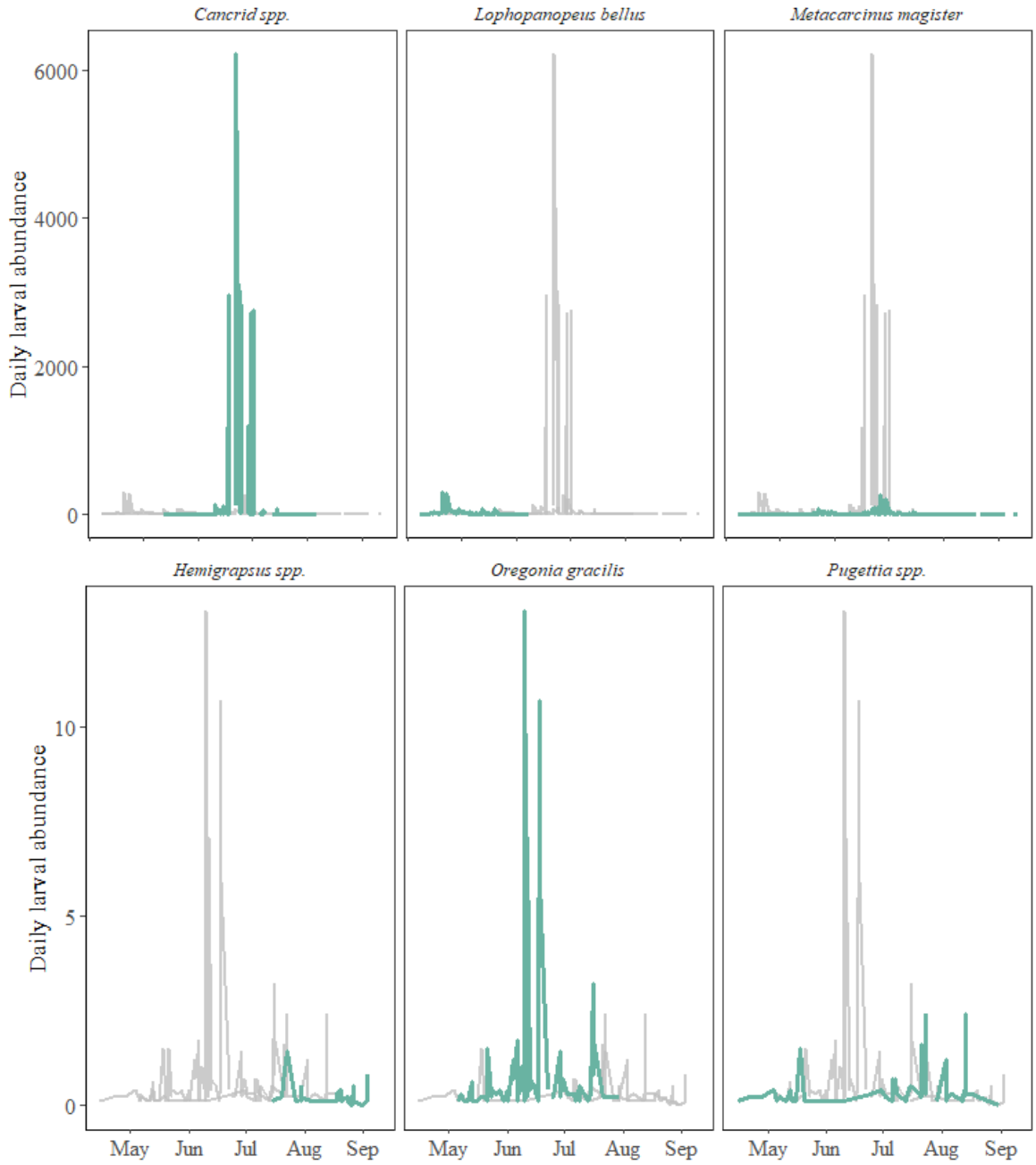

Figure 10. Daily larval crab catches (all sites combined) of *Cancrid* spp. (*Cancer productus* and *Glebocarcinus oregonensis*), *Hemigrapsus* spp., *Lophopanopeus bellus*, *Metacarcinus magister*, *Oregonia gracilis*, and *Pugettia* spp. (April to October 2019). Gray lines represent the daily catch of all listed species and the overlaid green line represents the catch of the target species.

Dungeness crab larvae were present in varying abundances from May to September, however each of the other species captured in the light traps exhibited more discrete delivery periods. The first species present in larval traps was *L. bellus; L. bellus* megalopae were observed at sites starting in April 2020 and were present until mid-June (Figure 10). The total season abundance of *L. bellus* was highest at COR (n = 22,938) and lowest at ANA (n = 2,794) (Table 10). In addition, *Pinnixa* spp., *Placetron wosnessenskii*, *Pugettia* spp., and *Telmessus cheiragonus* megalopae were also first observed in April (Figure 10).

Starting in May, we began to observe *Acantholithodes hispidus*, *Cancrid* spp., *Fabia subquadrata*, *M. magister*, and *O. gracilis* in the traps. The Cancrid spp. were the most abundant species group in 2020, present in the highest

abundance at COR and ROS (n = 216,649 and 128,024, respectively) with far fewer megalopae at ANA (n = 2,794). Arriving concurrently with the *Cancrid* spp., *O. gracilis* were observed in low numbers from 6 May to 30 July 2020, with the highest catch (n = 223) occurring at ROS on 6 June 2020. The latest arriving megalopae were the *Hemigrapsus* spp. (due to logistical limitations we did not differentiate between *H. oregonensis* and *H. nudus*) and family Porcellanidae. On 8 June 2020 one Porcellanidae was observed at ROS, however no additional Porcellanidae megalopae were observed in 2020. *Hemigrapus* spp. were first observed on 15 July at OAK and last observed on 10 September at COR.

Environmental conditions

Surface water temperatures were qualitatively warmer and more variable across the season at ANA and OAK, relative to ROS and COR (Figure 11). At ANA, the lowest April to September temperatures were recorded in April (minimum = 8.9 ºC; monthly mean 10.8 ºC ± 0.02 SE) and the highest temperatures were recorded in August (maximum 20.0 ºC; monthly mean 15.5 ºC ± 0.03 SE). Water temperatures at COR similarly were lowest in April (minimum = 8.2 ºC; monthly mean 9.6 ºC ± 0.01 SE) and highest in August (maximum 14.9 ºC; monthly mean 12.4 ºC ± 0.02 SE). At ROS, the minimum temperature recorded was 8.3 ºC (April monthly mean 9.5 ºC ± 0.02 SE) and a maximum temperature of 15.8 ºC was recorded in August (monthly mean 12.8 ºC ± 0.02 SE). Although our temperature record at OAK was abbreviated and we missed the cooler season (early spring) the site was similar to other sites in the summer with surface water temperatures peaking in August (maximum 20.2 ºC; monthly mean 15.4 ºC ± 0.04 SE).

While the surface water temperatures were more moderate at COR and ROS relative to ANA and OAK, it is unlikely that temperature alone can explain the difference in megalopal abundance between the sites. Differences observed in the variability of water temperature between COR or ROS and ANA or OAK are likely due to COR and ROS's proximity to Deception Pass and the Strait of Juan

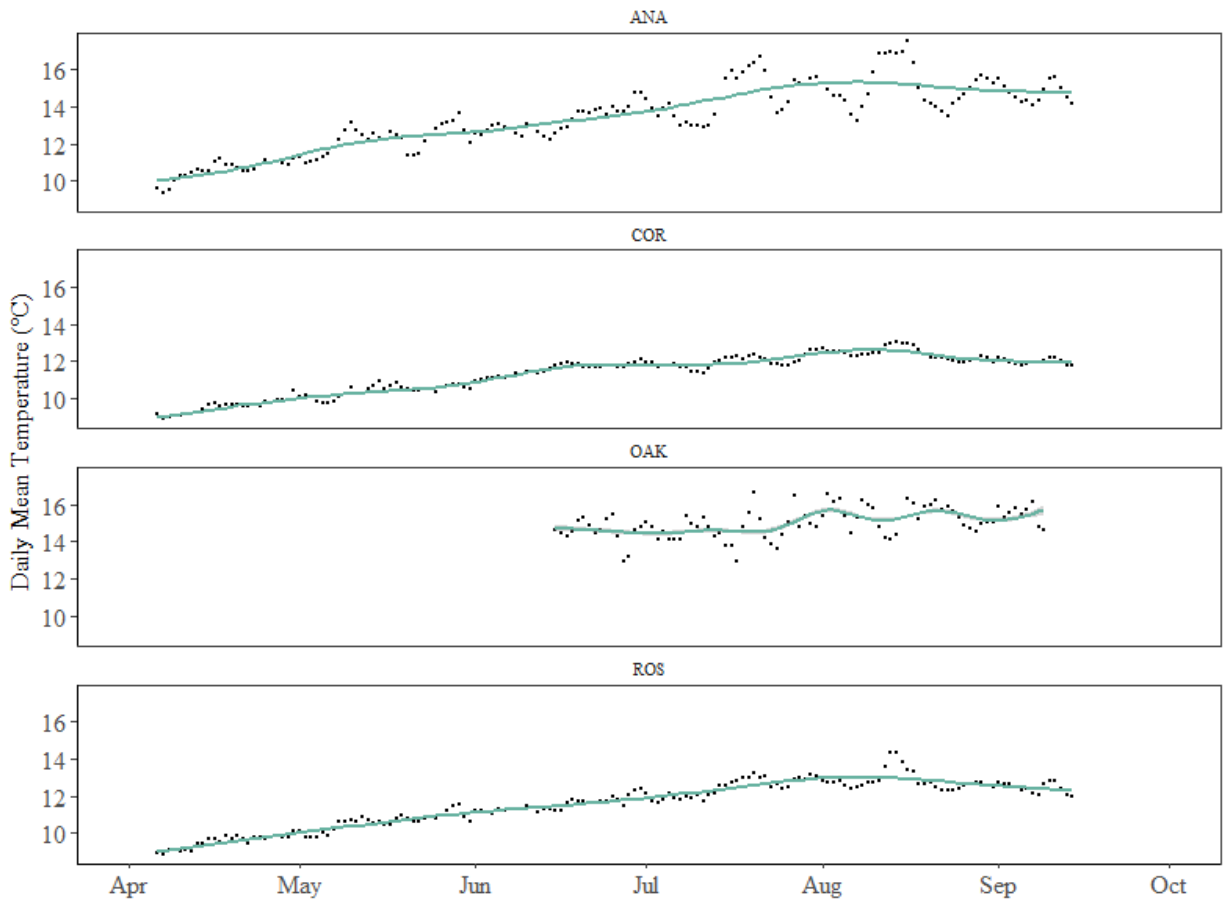

Figure 11. Mean daily surface water temperature [degrees Celsius (°C)]) with a smooth function trend line from April to September 2020 at Anacortes (ANA), Cornet Bay (COR), Oak Harbor (OAK), and Rosario (ROS).

de Fuca. The shallow sill at Deception Pass is likely to produce increased water column mixing as water is funneled through the Pass with each tidal exchange. The influence of the Strait at these sites is observed as relatively cooler temperatures of the water coming into Puget Sound from the Pacific (Masson 2006). In contrast, ANA and OAK are located in broad embayments where water residence time is likely higher and the surface waters are more influenced by ambient air temperatures and spring/neap tidal cycles. 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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