Dungeness Crab (*Cancer magister*) Megalopae: Peak Abundance of from San Diego, CA. to Puget Sound, WA.

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Background & Scope

"Ocean acidification expected to accompany climate change may slow development and reduce survival of the larval stages of Dungeness crab, a key component of the Northwest marine ecosystem and the largest fishery by revenue on the West Coast, a new study has found. The research by NOAA Fisheries' Northwest Fisheries Science Center in Seattle indicates that the declining pH anticipated in Puget Sound could jeopardize populations of Dungeness crab and put the fishery at risk. The study was recently published in the journal *Marine Biology*. Ocean acidification occurs as the ocean absorbs carbon dioxide from the combustion of fossil fuels. Average ocean surface pH is expected to drop to about 7.8 off the West Coast by 2050, and could drop further during coastal upwelling periods. Larvae hatched at the same rate regardless of pH, but those at lower pH took longer to hatch and progressed through their larval stages more slowly. Scientists suggested that the lower pH may reduce the metabolic rate of embryos. That could extend their vulnerable larval period, or could jeopardize the timing of their development in relation to key food sources, researchers suggested." - NWFSC

This bibliography was developed in support of the Ocean Acidification Program in their preparation for scheduling ship-time for the FY20 survey of the California Current Ecosystem to obtain both carbonate chemistry and Dungeness crab megalopae samples. This bibliography is meant to be a representative look at the literature surrounding peak abundance of Dungeness crab megalopae along the West Coast of the U.S. in order to provide timetables for successful future research.

Section I – Most Relevant

Articles that speak explicitly about timing and peak abundance of megalopae in specific locations.

Section II – Related

Articles that include information on megalopae timing and abundance, however do not contain information on specific locations.

Section III – Supplemental

Articles that speak more generally on larval transport, larval stages, predation timing, or focus on later stages of crab development.

Sources Reviewed

The following databases were used to identify sources: NOAA's Institutional Repository, Clarivate Analytics' Web of Science: Science Citation Index Expanded and Social Science Index; JSTOR; EBSCO's Academic Search Complete; ProQuests' Earth, Atmospheric & Aquatic Science Collection including ASFA; and BioOne Complete. Online search engines for gray literature were also used. Only English language materials were included.

Section I: Most Relevant

Fisher, W., & Velasquez, D. (2008). Management Recommendations for Washington's Priority Habitats and Species: Dungeness Crab Cancer magister. Washington Department of Fish and Wildlife. Retrieved from https://wdfw.wa.gov/publications/00028

This report provides recommendations for Dungeness Crab management and includes sections on habitat requirements for subadulst and adults , limiting factors to survival and metamorphosis, fishery impacts, contaminants and water quality, and disease.

Hobbs, R. C., Botsford, L. W., & Thomas, A. (1992). Influence of Hydrographic Conditions and Wind Forcing on the Distribution and Abundance of Dungeness Crab, Cancer Magister, Larvae. *Canadian Journal of Fisheries and Aquatic Sciences, 49*(7), 1379-1388 https://doi.org/10.1139/f92-153

The distribution of larval Dungeness crab (Cancer magister) was sampled by joint U.S.A./U.S.S.R. ichthyoplankton surveys off the coasts of Washington, Oregon, and northern California involving more than 120 stations from 5 to 360 km offshore and between 40 and 48°N latitude in each of the five years 1981–85. Observed cross-shelf distributions of megalopae were consistent with a mechanism by which diel vertical migratory behavior of the late-stage megalopae in the presence of wind-induced currents results in onshore transport to favorable settlement areas. Total onshore transport for 45 d prior to sampling, estimated as the effects of wind on a passive particle at the surface at night and in the Ekman layer during the day, was correlated with the nearshore megalopal abundance. Mean larval densities for each of the five cruises declined exponentially with time of year of the cruise. This implied (1) an instantaneous mortality rate of $0.066 \cdot d^{-1}$ and (2) that survival is independent of inter-annual variation in environment. Abundance of megalopae was not correlated with station hydrographic data (salinity, temperature, and dissolved oxygen) nor chlorophyll levels (satellite data from the Coastal Zone Color Scanner).

Hodgson, E. E., Essington, T. E., & Kaplan, I. C. (2016). Extending Vulnerability Assessment to Include Life Stages Considerations. *PLoS ONE, 11*(7), e0158917 https://doi.org/10.1371/journal.pone.0158917

Species are experiencing a suite of novel stressors from anthropogenic activities that have impacts at multiple scales. Vulnerability assessment is one tool to evaluate the likely impacts that these stressors pose to species so that high-vulnerability cases can be identified and prioritized for monitoring, protection, or mitigation. Commonly used semi-quantitative methods lack a framework to explicitly account for differences in exposure to stressors and organism responses across life stages. Here we propose a modification to commonly used spatial vulnerability assessment methods that includes such an approach, using ocean acidification in the California Current as an illustrative case study. Life stage considerations were included by assessing vulnerability of each life stage to ocean acidification and were used to estimate population vulnerability in two ways. We set population vulnerability equal to: (1) the maximum stage vulnerability and (2) a weighted mean across all stages, with weights calculated using Lefkovitch matrix models. Vulnerability was found to vary across life stages for the six species explored in this case study: two krill–Euphausia pacifica and Thysanoessa spinifera, pteropod–Limacina helicina, pink shrimp–Pandalus jordani, Dungeness crab–Metacarcinus magister and Pacific hake–Merluccius productus. The maximum vulnerability estimates ranged from larval to subadult and adult stages with no consistent stage having maximum vulnerability across species. Similarly, integrated vulnerability metrics varied greatly across species. A comparison showed that some species had vulnerabilities that were similar between the two metrics, while other species' vulnerabilities varied substantially between the two metrics. These differences primarily resulted from cases where the most vulnerable stage had a low relative weight. We compare these methods and explore circumstances where each method may be appropriate.

Johnson, J., & Shanks, A. L. (2002). Time Series of the Abundance of the Post-Larvae of the Crabs Cancer Magister and Cancer Spp. On the Southern Oregon Coast and Their Cross-Shelf Transport. *Estuaries, 25*(6A), 1138-1142 https://doi.org/10.1007/BF02692211

Using stationary zooplankton nets that fished the tidal current we measured the daily abundance of Cancer crab megalopae near the mouth of Coos Bay, Oregon, during the 1997 spring settlement season. During the spring of 1997, the coastal waters were dominated by a significant El Nino event. Sea surface temperatures (SST) were higher than normal, upwelling indices were an order of magnitude smaller than during the two previous springs, and upwelling favorable winds were weak. Daily catches of Cancer magister megalopae ranged from 0 to 78 with 61% of the total catch occurring during four pulses. Peak catches tended to occur every 13.6 d close to 13.8 d average period between spring tides. Significant cross correlations were found between the maximum daily tidal range and the catch of C. magister megalopae; large catches tended to occur 4 to 7 d after the spring tide. Daily catches of Cancer oregonensis and Cancer productus ranged from 0 to 307 with catch significantly positively cross correlated to the maximum daily tidal range at a lag of -5 days suggesting that the largest catches tended to occur after the spring tides. We hypothesize that a tidally-generated phenomenon internal waves, transported Cancer megalopae shoreward and caused the observed variation in their abundance in Coos Bay.

Moloney, C., Botsford, L. W., & Largier, J. (1994). *Development, Survival and Timing of Metamorphosis of Planktonic Larvae in a Variable Environment: The Dungeness Crab as an Example* (Vol. 113). https://doi.org/10.3354/meps113061

We use models to show how a variable environment can affect development, survival and timing of metamorphosis of meroplanktonic larvae. For a general case, we use an analytical model to explore the effect of temperature-dependent development and mortality rates on temporal patterns of metamorphosis. The distribution of metamorphosis over time is a lagged version of the pattern of larval release, distorted by changes in development and mortality rates. If temperature causes development rate to increase (decrease) linearly with time through the larval period, the timing of metamorphosis has a short (long) temporal range, a large (small) amplitude, and is shifted to the left (right). This implies that at locations with a decreasing trend in development rate (e.g. due to decreasing temperature), the timing of metamorphosis is more sensitive to larval release time than at locations with an increasing trend. Mortality of larvae can be influenced directly by the environment through sub-optimal conditions, or indirectly by environmentally induced changes in development rate, which change the duration of the larval period. If mortality rate is constant, the longer the larval period the greater the mortality. However, this result is not true if mortality rates change with the environment in the same way that development rates change. The common assumption of constant mortality rates needs to be critically reassessed. To apply these results to a specific example, we develop a model of the temperature- and salinity-dependence of Dungeness crab Cancer magister Dana larval development, using available laboratory data. We then use historical records of daily sea surface temperatures and salinities to examine the impact of these 2 variables on larval development and survival at coastal sites along the U.S. west coast. Based on calculations from 7 locations over a total of 233 yr, Dungeness crab larvae can take between 74 and 182 d to metamorphose, depending on location, year and time of release. Larvae in the northernmost part of the study region (Washington) have the longest mean annual development times (133 to 163 d), those in central and northern California have intermediate development times (81 to 134 d), and those in southern California have the shortest development times (74 to 84 d). Greatest relative intra- and interannual variability in mean development times and survival occurred in upwelling areas off central California. Observed latitudinal differences in timing of metamorphosis from zoeal to megalopal stages were consistent with differences predicted by the model. We conclude that variability in temperature and salinity can cause Dungeness crab larval periods to vary by a factor of 2. For meroplanktonic populations in general, complicated patterns of metamorphosis can result from variable temperatures during the larval period, even if hatching of larvae occurs at a constant rate.

Pauley, G. B., Armstrong, D. A., & Citter, R. V. (1989). Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrate. US Army Corps of Engineers, TR EL-82-4 Retrieved from https://www.nwrc.usgs.gov/wdb/pub/species_profiles/82_11-121.pdf

This species profile is one of a series on coastal aquatic organisms, principally fish, of sport, commercial, or ecological importance. The profiles are designed to provide coastal managers, engineers, and biologists with a brief comprehensive sketch of the biological characteristics and environmental requirements of the species and to describe how populations of the species may be expected to react to environmental changes caused by coastal development. Each profile has sections on taxonomy, life history, ecological role, environmental requirements, and economic importance, if applicable. A three-ring binder is used for this series so that new profiles can be added as they are prepared. This project is jointly planned and financed by the U.S. Army Corps of Engineers and the U.S. Fish and Wildlife Service.

Pool, S. S., & Brodeur, R. D. (2006). *Neustonic Mesozooplankton Abundance and Distribution in the Northern California Current, 2000 and 2002.* National Marine Fisheries Service Retrieved from http://nepglobec.bco-dmo.org/projects/neustonic_meso.pdf

Most plankton surveys off Oregon and northern California have focused along one transect off Newport, Oregon, or only on the ichthyoplankton in the water column and at the ocean surface. Therefore as part of juvenile salmonid (Oncorhynchus spp.) ocean sampling funded by U.S. Global Ocean Ecosystem Dynamics, a study was undertaken to collect neustonic mesozooplankton from Crescent City, California, to Newport, Oregon, during four cruises in June and August 2000 and 2002. These collections were made for comparison with stomach contents of juvenile salmonids; however this technical memorandum does not include that comparison. It contains the results of our analysis of the species composition, relative abundances, and spatial distributions of the neuston on a point-by-point basis for both years instead of using geostatistics as previously done for only 2000 by Reese et al. (2005). In addition to regular sampling we conducted two diel studies in 2002 to examine temporal variations of the neustonic mesozooplankton population.

Reilly, P. (1983). Dynamics of Dungeness Crab, Cancer Magister, Larvae Off Central and Northern California. In *Life History, Environment, and Mariculture Studies of the Dungeness Crab, Cancer Magister, With Emphasis on The Central California Fishery Resource*. Wild, P. and Tasto, R. Eds. Retrieved from http://content.cdlib.org/view?docId=kt1k4001gs&query=&brand=calisphere

The Dungeness crab, Cancer mil/fister, passes through five zoeal stages and one megalopal stage after hatching from eggs carried on the abdominal pleopods of the female (Figure 25) . A pre-zoeal stage of approximately 1 O to 1 S min duration has been observed in the laboratory and, although it has not been collected in the field, is considered a normal developmental stage (MacKay 1934; Buchanan and Milleman 1969) . The zoeae are entirely planktonic. The megalopa, the final larval stage, is planktonic until settling to the bottom and molting to the first post-larval instar. The larval stages range in length (tip of rostral spine to end of telson) from approximately 2.5 mm for stage I zoeae to 11 .0 mm for megalopae (Poole 1966) . Several field studies report on the occurrence of Dungeness crab larvae. Various observations in the Gulf of the Farallones off San Francisco are recorded in California Department of Fish and Game research cruise reports between 1956 and 1970. Dungeness crab larvae were recorded at a Gulf station during a pre-design study on marine waste disposal (Brown and Caldwell 1973). Wickham (1979b) collected megalopae in plankton tows and on the hydroid Vele/la ve/ella in ocean waters near Bodega Head, California. Lough (1974 and 1976) found all zoeal stages and megalopae in Oregon waters in 1970 and 1971 . Mayer (1973) reported the occurrence of megalopae in Similk Bay, Washington. On the east coast, Sandifer (1973 and 1975), in a study of decapod crustacean larvae in and near Chesapeake Bay, reported on the occurrence of rock crab, C irroratus, larvae and discussed transport and recruitment of larval stocks. Nevertheless, Dungeness crab larval dynamics and life history were not well understood when we began our study. The purpose of our study was to investigate Dungeness crab larval life history and relate field observations of distribution, relative abundance, and behavior to possible mechanisms associated with the decline and continued low level of the crab resource in central California. Our studies were conducted from 1975 to 1980.

Roegner, G. C., Armstrong, D. A., Hickey, B. M., & Shanks, A. L. (2003). Ocean Distribution of Dungeness Crab Megalopae and Recruitment Patterns to Estuaries in Southern Washington State. *Estuaries, 26*(4), 1058-1070 https://doi.org/10.1007/BF02803363

We investigated the distribution of meroplankton and water properties off southern Washington and simultaneously measured time series of larval abundance and water properties in two adjacent estuaries, Grays Harbor and Willapa Bay. The cruise period, in late May 1999, coincided with large variation in the alongshore wind stress that caused dynamic change in the position of the Columbia River plume, coastal upwelling and downwelling, and offshore phytoplankton production. In the coastal ocean, meroplankton groups responded differently to this wind event and the associated advection of water masses. Dungeness crab (Cancer magister) megalopae were largely indifferent to the wide salinity variation, and were found throughout the surveyed area in both plume and recently upwelled waters. Megalopae of kelp crab (Pugettia producta) and hermit crab (Pagurus spp.) were more abundant in upwelled water and low numbers were caught in the plume water. Barnacle cyprids appeared to track the advective transport suggesting that they may be more passively dispersed. Within the estuaries, hydrography responded rapidly and synchronously to variation in wind stress. Intrusions of both plume and newly upwelled waters were detected at estuarine sites, depending on the type of water present at the coast, indicating a tight link between the estuaries and the coastal ocean in this region. A 90-d record of C. magister megalopae abundance was made at 3 estuarine sites using light traps. The bulk of the C. magister recruitment was limited to a relatively brief period in late May through June. Within this window, megalopae occurred in distinct pulses of 3-5 d interspaced with periods of low or zero abundance. C. magister megalopae recruited to the estuaries over a wide range of wind forcing, and were transported into the estuary within varied water types. There were no periodic patterns indicative of spring-neap tidal variations in the abundance time series. Abundance was only weakly cross-correlated between the adjacent Grays Harbor and Willapa Bay estuaries, which contrasts with the more synchronous estuarine-coastal linkages measured for water properties. These results suggest the interaction of larval aggregation size in the ocean with estuary-ocean exchange processes likely controls patterns of estuarine recruitment.

Roegner, G. C., Armstrong, D. A., & Shanks, A. L. (2007). Wind and Tidal Influences on Larval Crab Recruitment to an Oregon Estuary. *Marine Ecology Progress Series, 351*, 177-188 https://doi.org/10.3354/meps07130

We investigated wind and tidal forcings that may facilitate transport of crab megalopae to a northeast Pacific coastal estuary. Daily abundance of crab megalopae was estimated from light trap collections made from March 1998 through December 2001 in Coos Bay, Oregon, USA. The Dungeness crab Cancer magister dominated the catch; Cancer Group I (C. productus and C. oregonensis), Hemigrapsus oregonensis and Pachygrapsus crassipes megalopae were also abundant enough for statistical evaluation. The abundance time series data were analyzed in relation to mean daily wind stress, maximum daily tidal range, and mean daily temperature residuals using cross- correlation and cross-Fourier techniques. Variation in wind stress had little relation to variation in crab megalopae abundance. Rather, crab megalopae were found to recruit to the estuary at periods close to the spring-neap tidal frequencies. Increased catches were not coincident with spring tides; most tests indicated that ingress occurred at times ranging from several days after spring tide to near the neap tide, but this varied among species and years. Tidal forcing appears to control crab recruitment to this estuarine system.

Roegner, G. C., Daly, E. A., & Brodeur, R. D. (2013). Surface Distribution of Brachyuran Megalopae and Ichthyoplankton in the Columbia River Plume During Transition from Downwelling to Upwelling Conditions. *Continental Shelf Research, 60*, 70-86 https://doi.org/10.1016/j.csr.2013.04.007

In the California Current coastal boundary zone, the spring transition between downwelling and upwelling conditions, along with the fluctuating structure of the Columbia River plume, creates highly dynamic interactions. In this study, we investigated whether the surface distribution of brachyuran larvae and ichthyoplankton would track the dynamics of the Columbia River plume. By happenstance, the cruise period coincided with the spring transition from downwelling to sustained upwelling conditions in 2010, a year when the transition was delayed and Columbia River flow was substantially higher than average. We used time series of wind and freshwater input to evaluate the influence of physical forcing on oceanographic patterns, and sampled hydrography and surface plankton concentrations within a 182 km(2) grid off Willapa Bay, WA. Additionally, two longer transects, one cross-shelf and the other along-shore, were made to discern the extent of plume influence on larval crab and fish abundance. We found that plume waters that were trapped in a northward-flowing coastal-boundary current during downwelling conditions were advected offshore after several days of upwelling-favorable winds. Neustonic collections of brachyuran larvae and ichthyoplankton varied in response to this large seaward advective event. Megalopae of cancrid crabs exhibited patterns of both offshore transport (Cancer oregonensis/productus) and nearshore retention (C. magister). Additionally, abundant numbers of large juvenile widow (Sebastes entomelas) and yellowtail (S. flavidus) rockfish of a size appropriate for settlement were sampled during a period when ocean conditions favored high recruitment success. These results demonstrated that the response of planktonic crab larvae and ichthyoplankton to large-scale advection varied by species, with larger and more vagile fish exhibiting less evidence of passive transport than smaller crab larvae. Importantly, portions of the planktonic fish and crab community were able to maintain nearshore distributions in favorable settlement habitat, despite physical advection offshore.

Shanks, A. (2015). *Report on the Recruitment of Dungeness Crab Megalopae During the 2015 Recruitment Season.* Retrieved from https://oregondungeness.org/wp-content/uploads/2016/09/2015-Shanks-Annual-report.pdf

Light trap sampling began on 27 March 2015 with a trap placed near the end of F dock in the Charleston Outer Boat Basin. Daily sampling continued through 30 September 2015. Total catch of Dungeness crab megalopae for the recruitment season was 44,000

Shanks, A., Roegner, C., & Miller, J. (2010). Using Megalopae Abundance to Predict Future Commercial Catches of Dungeness Crabs (Cancer Magister) in Oregon. *California Cooperative Oceanic Fisheries Investigations Reports, 51 Retrieved from* http://calcofi.org/publications/calcofireports/v51/Vol51_Shanks_pg106-118.pdf

We explore the possibility of predicting the commercial catch of Dungeness crabs (Cancer magister) from the abundance of returning megalopae. In the first six years of a nine-year time series (1997–2001, 2006– 2009), there is a strong relationship between megalopal abundance and Oregon commercial catch, and early spring transitions led to higher numbers of returning megalopae. During this period, we could make reasonable predictions of commercial catch. In the last three years (2007–2009), megalopal abundance ranged from 1.2 to 2.4 million animals. The previous relationship between megalopal abundance and commercial catch is unlikely to hold given these huge abundances; densitydependent factors should lead to an asymptotic relationship between the number of returning megalopae and commercial catch and, if this holds, commercial catch should be predictable. The high abundances of megalopae do not appear to be due to improved larval growth conditions, but significant correlations between megalopal abundances and hydrographic and climatic indices suggest that reduced northward and enhanced southward transport during the pelagic phase may have contributed to the huge returns.

Shanks, A. L. (2013). Atmospheric Forcing Drives Recruitment Variation in the Dungeness Crab (Cancer Magister), Revisited. *Fisheries Oceanography, 22*(4), 263-272 https://doi.org/10.1111/fog.12020

For 12 yr (1997–2001, 2006–2012) daily abundance of Cancer magister megalopae was measured in Coos Bay, Oregon. Before 2007 from 2000 to 80 000 megalopae were caught annually. In 2007, catch jumped and has since varied from 164 000 to 2.3 million. The step change in catch size appears related to a shift to negative Pacific Decadal Oscillation (PDO) values. Late season catches, which cannot be due to local spawning, are negatively correlated to the PDO, suggesting that these megalopae derive from north of the California Current. During periods of lower and higher catches, annual returns of megalopae were significantly negatively correlated to the day of the year of the spring transition and positively correlated to the amount of upwelling during the settlement season. The size of the Oregon commercial catch lagged 4 yr to allow for growth of recruits into the fishery is set by the number of returning megalopae; the relationship is parabolic. At lower returns, the population is recruitment limited, but at higher returns, density-dependent effects predominate and set the commercial catch. Lagged commercial catches in Washington and Northern and Central California were also related to the number of megalopae returning to Coos Bay, suggesting that the forces causing variation in larval success are coast wide. If high return rates are due to a PDO regime shift, then for years to decades the commercial catch may be set by density-dependent effects following settlement and the huge numbers of returning megalopae may impact benthic community structure.

Shanks, A. L., & Roegner, G. C. (2007). Recruitment Limitation in Dungeness Crab Populations Is Driven by Variation in Atmospheric Forcing. *Ecology, 88*(7), 1726-1737 https://doi.org/10.1890/06-1003.1

Ecologists have long debated the relative importance of biotic interactions vs. abiotic forces on the population dynamics of both marine and terrestrial organisms. Investigation of stock size in Dungeness crab (Cancer magister) is a classic example of this debate. We first tested the hypothesis that adult population size was set by larval success. We found that during a five-year sampling period, adult crab population size from Oregon through central California, USA, as measured by the commercial catch, varied directly with the number of terminal-stage larvae (megalopae) returning to Coos Bay, Oregon, four years earlier; adult population size was largely determined (> 90% of the variation) by success during the larval stage. We then tested whether biotic interactions or abiotic forces caused the variation in larval success. Most of the variation (> 90%) in the number of returning megalopae is explained by the timing of the spring transition, a seasonal shift in atmospheric forcing that drives ocean currents along the west coast of the United States. Early spring transitions lead to larger numbers of returning Dungeness megalopae, while in four other crab taxa, species with very different life history characteristics, early-spring transitions lead to lower numbers of returning megalopae. During the past roughly 30 years, the size of the commercial catch of Dungeness crab is significantly and negatively correlated with the date of the spring transition throughout the California Current system. Long-term variation in the date of the spring transition may explain a major crash in the Dungeness crab fishery in central California, which began in the late 1950s. The data suggest that Dungeness crab population size is determined by variation in larval success and that a significant portion of this variation is due to the timing of the spring transition, a large-scale climatic forcer.

Shenker, J. M. (1988). Oceanographic Associations of Neustonic Larval and Juvenile Fishes and Dungeness Crab Megalopae Off Oregon. *Fishery Bulletin, 86*(2), 299-317 Retrieved from https://spo.nmfs.noaa.gov/content/oceanographic-associations-neustonic-larval-and-juvenile-fishes-and-dungeness-crab-megalopae

The larval and juvenile fishes and crabs inhabiting the neustonic zone within 50 km of the coast were sampled biweekly from April through July 1984, with a Manta net (mouth 1.0 m wide x 0.7 m deep) and a large neuston trawl (mouth 3.5 m wide x 1.0 m deep). Nocturnal sampling accounted for nearly all the ichthyoneuston and zooplankton taken. Dungeness crab megalopae were the most abundant species. Although present throughout the survey, the great majority were found in very large aggregations along visible convergence zones or in association with Velella velella . Discrete groups of abundant larval and juvenile fishes were found prior to upwelling (Parophrys vetulus, Scorpaenichthys marmoratus, Hemilepidotus spinosus, Hexagrammos sp., and Anoplopoma fimbria) and after its onset (Engraulis mordax and Sebastes spp.).

Wild, P. W., & Tasto, R. N. (1983). *Life History, Environment, and Mariculture Studies of the Dungeness Crab, Cancer Magister, with Emphasis on the Central California Fishery Resource.* State of California, Resources Agency, Dept. of Fish and Game [Sacramento].

This report describes the results of the California Department of Fish and Game's Dungeness Crab Research Program (1974–1980) plus several related studies and provides a detailed history of the California fishery. The Dungeness Crab Research Program was developed in response to a severe and sustained decline in central California Dungeness crab landings; this decline is the primary focus of the investigations presented in this report. Research results are presented for life history, environmental, and mariculture studies relating to egg, larval, juvenile, and adult stages of the Dungeness crab. Specific areas of study include stock identification; larval and juvenile dynamics focusing on movement, distribution, relative abundance, age and growth, and predation; impacts of commercial trawl fishing; ocean climate and its effects on life cycle stages and fishery landings; reproduction; pollution such as chlorinated wastewater, toxic trace elements, pesticides and PCB's, and hydrocarbons; and laboratory culture techniques. This report concludes with a summary of the Dungeness crab life cycle and research results and a discussion of management options and further research needs.

Section II: Related

Armstrong, J. L., Armstrong, D. A., & Mathews, S. B. (1995). Food Habits of Estuarine Staghorn Sculpin, Leptocottus Armatus, with Focus on Consumption of Juvenile Dungeness Crab, Cancer Magister. *Fishery Bulletin, 93*(3), 456-470 Retrieved from https://spo.nmfs.noaa.gov/sites/default/files/pdf-content/1995/933/armstrong.pdf

The impact of predation by staghom sculpin, Leptocottus armatus, on newly settled Dungeness crab, Cancer magister, in the Washington coastal estuary of Grays Harbor was studied. Staghorn sculpin are known to be generalist, opportunistic feeders, with relatively high food requirements for estuarine growth during warm summer months. During late spring or early summer, vast numbers of crab megalopae reach the estuary and settle on intertidal flats and in subtidal channels. During the next two months the young-of-the-year (0+) crab population is rapidly reduced by predation, including cannibalism. Crab without appropriate refuge habitat are highly vulnerable to predation by fish, and accordingly survival ofyoung crab is highest in intertidal shell and eelgrass beds. Abundance and summer growth ofcrab and sculpin within the estuary were documented by monthly trawling surveys (April to August) in 1989. Stomach contents ofsculpin were analyzed to characterize the overall summer diet, to note monthly shifts in major prey items within two age classes ofsculpin (0+ and 1+), and to contrast sculpin prey consumed in eelgrass with that consumed in shell habitats. The }lredominant prey species varied across the categories above but generally included ghost and blue mud shrimp, Neotrypaea californiensis and Upogebia pugettensis, a nereid polychaete (Nereis brandti), juvenile Dungeness crab, Cancer magister, and sand shrimp (Crangon spp.). Some combination of these species composed 85% ofthe total diet lon the basis ofpercentage oftotal Index of Relative Importance; %IRI) across time and between habitats.Acomparison ofdiets ofsculpin collected at ee19rass and shell habitats was significantly different; a strong preponderence of 0+ crab were consumed at the shell habitat. Nereis brandti was the most important prey for 0+ sculpin, whereas Neotrypaea californiensis was the most important for 1+ and older sculpin. The importance ofshell as refuge habitat for C. magister and the apparent contradiction in the observation that a large number of0+ crab were taken by sculpin at the shell habitat are discussed.

DeBrosse, G., Sulkin, S., & Jamieson, G. (1990). Intraspecific Morphological Variability in Megalopae of Three Sympatric Species of the Genus Cancer (Brachyura: Cancridae). *Journal of Crustacean Biology, 10*(2), 315-329 Retrieved from https://www.jstor.org/stable/1548490

Selected morphological traits were documented for megalopa gonensis, and C. productus collected at three sites within the offshore sites in the eastern Pacific Ocean. Variation in select species, among individuals within species, and among region measurement were those proposed in the literature as diagnosti Cancer. For each of three species of Cancer collected, substan size and appendage setation was documented. Although individ lected morphological traits from published reports, published those measured in the present study. Significant differences amo size and setation in C. magister, with the clearest differences collected offshore and within the Puget Sound basin. Result magister can be separated from those of C. productus and C. oreg the latter two species cannot be separated with certainty on th the literature as diagnostic. Differences between offshore and in lopae of C. magister may reflect hydrographic features of the origin. Variability in morphological traits must be included in an identification and may contribute to analysis of broader ecological issues.

Dinnel, P. A., Armstrong, D. A., & McMillan, R. O. (1993). Evidence for Multiple Recruitment-Cohorts of Puget Sound Dungeness Crab, Cancer Magister. *Marine Biology, 115*(1), 53-63 https://doi.org/10.1007/BF00349386

While sampling intertidally in Puget Sound, Washington, USA, for juvenile Dungeness crab (Cancer magister) in 1984, we found evidence of two distinct "cohorts" of the same year-class based on sizes of first-instar juveniles (J1) and the spatial/temporal patterns of settlement. In 1988, three distinct cohorts were observed to settle in Puget Sound and its approaches. Settlement of one cohort occurred during May in the Strait of Juan de Fuca and in those areas of Puget Sound closest to the Strait. J1 individuals of this cohort were large (x=7.4 mm carapace width, CW) and comparable in both size and timing of settlement to populations along the Washington coast (e.g. Grays Harbor and Willapa Bay). Initial settlement density of the May cohort was as high as 215 crabs/m2 in intertidal eelgrass beds along the Strait of Juan de Fuca and decreased to <2 crabs/m2 within Puget Sound and the Strait of Georgia. A second cohort apparently originated in Hood Canal (a deep inland fjord), its size upon settlement in June was significantly smaller (J1 x= 5.3 mm CW) than the May cohort, and it was limited to Hood Canal and areas of Puget Sound close to the mouth of Hood Canal. A third cohort, which settled in late July and August, was the smallest of the three cohorts (J1 x= 4.8 mm CW), and was widely distributed around Puget Sound from Seattle in the south to the USA/Canadian border in the north. We hypothesize that most juvenile recruitment in Hood Canal and Puget Sound originates from parental stocks endemic to their respective basins ("Hood Canal" and "Puget Sound" cohorts), but that, on occasion, oceanographic conditions allow substantial influx of Pacific Ocean Dungeness crab larvae ("oceanic" cohort) through the Strait of Juan de Fuca into Puget Sound. Tracking of spatial/temporal settlement patterns and comparison of J1 sizes proved useful for estimating the probable sources and dispersion of Dungeness crab larvae. Differences in size and time of settlement between various larval cohorts of C. magister may prove useful as "biomarkers" for tracing circulation patterns within and between inland waters of Washington and the Pacific Ocean. Causes of smaller size and later settlement of the "Puget Sound" cohort relative to oceanic conspecifics of the same year-class are discussed.

Eggleston, D. B., & Armstrong, D. A. (1995). Pre- and Post-Settlement Determinants of Estuarine Dungeness Crab Recruitment. *Ecological Monographs, 65*(2), 193-216 https://doi.org/10.2307/2937137

Abundance of early juvenile Dungeness crab (Cancer magister) is dramatically higher in intertidal shell habitats compared to mud habitats in several coastal estuaries of the Pacific Northwest. To define the mechanisms underlying this habitat-specific pattern in abundance, we concurrently examined four components of recruitment to intertidal shell and mud habitats at two locations within the Grays Harbor estuary (Washington, USA): (1) water column supply of crab megalopae (postlarvae); (2) settlement patterns of crab megalopae 48 h after settlement substrates were deployed; (3) density of first benthic juvenile instars (J1) 48 h after deployment of such substrates; and (4) density of early juvenile crab in shell and mud habitats over a 4-mo period. We also describe the physical processes likely to be influencing postlarval supply within Grays Harbor, and take advantage of natural variation in postlarval supply between two locations, in combination with a predator exclusion experiment, to define the relative importance of postlarval supply vs. post-settlement survival in regulating population size of juvenile crab in certain intertidal habitats.

Water column postlarval supply (measured with plankton and neuston nets, and artificial settlement substrates) in terms of both megalopal density (number per cubic metre) and flux (number per hour) was significantly higher in the southern part of the estuary vs. the northern part during a week-long settlement pulse. Our field observations and measurements suggest that spatial variation in postlarval supply was due to local differences in winddriven surface currents, since tidal current speeds in the two locations were similar. Moreover, there was no correlation between current speed and flux of megalopae over the bottom. There was generally no difference in postlarval supply between shell and mud habitats. Our experimental results further indicate that: (1) the abundance of recently settled crab megalopae in 0.25 m2 settlement trays was significantly higher in shell than in mud habitats, irrespective of whether the trays were placed in 3-5 ha of shell vs. mud; (2) there was a positive and significant correlation between postlarval supply and density of megalopae in shell and mud habitats; and (3) there was a positive and significant correlation between postlarval supply and density of J1 instars only in habitats where specific predators were excluded. Once the number of J1 instars at both geographic locations was reduced to similar levels, equivalent but steadily decreasing densities persisted throughout the summer growing season. The decoupling of settlement patterns and density of J1 instars took place within our 48-h sampling interval. Thus, future attempts to examine the correspondence between larval supply and post-settlement abundance of marine benthic species with planktonic larvae should do so at extremely small temporal scales or a critical life history phase may be overlooked. The results from this study demonstrate that substrate selection can affect distribution of juvenile crab, and that predation (including cannibalism) is a key factor regulating local population size of early juvenile crabs in intertidal habitats where postlarval supply is relatively high.

Fernandez, M., Armstrong, D., & Iribarne, O. (1993). First Cohort of Young-of-the-Year Dungeness Crab, Cancer Magister, Reduces Abundance of Subsequent Cohorts in Intertidal Shell Habitat. *Canadian Journal of Fisheries and Aquatic Sciences, 50*(10), 2100-2105 Retrieved from https://search.proquest.com/docview/16736193?accountid=28258

Arrival and settlement of successive cohorts of Dungeness crab, Cancer magister, megalopae were observed in Grays Harbor, Washington, in 1991. The first cohort of megalopae entered the estuary between May 15 and 20 and settled in ("occupied") previously constructed artificial, intertidal oyster shell habitats at densities ranging from 155 to 196 first instar juvenile (J1) crabs/m super(2). Subsequently, a second set of shell habitats was constructed that did not contain crabs of the first cohort ("unoccupied"). Between June 15 and 18, when crabs of the first cohort were a mix of seco1nd and third instars, a second cohort of megalopae settled in both occupied and unoccupied shell habitat at respective J1 crab densities of 9-37 and 168-298 crabs/m super(2). The possible roles of cannibalism, competition, and conspecific avoidance are proposed as alternative hypotheses to explain significantly lower density of the second cohort in shell habitats previously occupied by larger conspecifics of the first cohort.

Gunderson, D. R., Armstrong, D. A., Shi, Y.-B., & McConnaughey, R. A. (1990). Patterns of Estuarine Use by Juvenile English Sole (Parophrys Vetulus) and Dungeness Crab (Cancer Magister). *13*(1), 59 https://doi.org/10.2307/1351433

Extensive trawl surveys were conducted in two large estuaries (Grays Harbor and Willapa Ba the Washington coast during 1983-1987, and in adjacent areas of the open coast. These surveys have shown th both English sole and Dungeness crab rely heavily on these estuaries as nursery areas, although the pattern of utilization differs substantially. Juvenile migration patterns can show substantial interannual variability and can only be delineated by concurrent surveys in both coastal and estuarine areas, conducted over a period of several years. English sole eggs and Dungeness crab larvae are released in coastal waters. Larvae of both species transform to the benthic stage in both coastal and estuarine areas, but most English sole eventually migrate into the estuaries during the first year of life, even if initial settlement is along the open coast. By the time English sole have attained a length of 55 mm (TL), most of them are found in estuaries. English sole begin emigrating from the estuaries at about 75 mm, and few remain there during the second year of life. In contrast, Dungeness crab appear to remain in the area of initial settlement throughout the first year of life. Growth is substantially faster in estuaries where 0 + crab reach a mean size of about 40 mm carapace width (CW) by September, with those off the coast are only about 14 mm CW. Juveniles remain in the area of settlement over their first winter but, in contrast to English sole, most coastal 1 + crab immigrate to estuaries to join siblings that settled there the previous year. By September of the second year, crab at about 100 mm CW emigrate to the open coast where they reach maturity. Advantages to juvenile stages that reside in estuaries are discussed in terms of accelerated growth at higher temperatures and potentially greater food supplies than found nearshore along the coast.

Jamieson, G. S., & Phillips, A. (1993). Megalopal Spatial Distribution and Stock Separation in Dungeness Crab (Cancer Magister). *Canadian Journal of Fisheries and Aquatic Sciences, 50*(2), 416-429 https://doi.org/10.1139/f93-047

During the day, Dungeness crab (Cancer magister) megalopae from off the outer coasts of Vancouver Island and Washington are aggregated at about 25 m whereas those from the Strait of Georgia are at about 160 m. At night, both populations of megalopae seem to be mostly in the top metre of water. Juan de Fuca Strait, which connects the Strait of Georgia to the Pacific Ocean, typically has an estuarine circulation, with outflow in the top 50–100 m and deeper inflow. Because the daylight to dark ratio when megalopae are present is about 3:1, the Strait of Georgia and outer-coast megalopae are mostly retained within their own systems by currents at their daytime depths. Occasional intrusions of outer-coast megalopae into Juan de Fuca Strait may occur when estuarine flow in the Strait temporarily breaks down following sustained, strong, southwesterly winds; such intrusions are typically restricted to the south and head of Juan de Fuca Strait, and even extensive ones do not carry megalopae far into the Strait of Georgia. The daily movement of larval crab to cold (<10 °C), deep water in the Strait of Georgia may explain, at least partially, the delay in seasonal timing of settlement and their smaller physical size at settlement compared with outer-coast megalopae.

Jamieson, G. S., & Phillips, A. C. (1990). A Natural Source of Megalopae for the Culture of Dungeness Crab, Cancer Magister Dana. *Aquaculture, 86*(1), 7-18 https://doi.org/10.1016/0044-8486(90)90217-B

One of the main requirements in the establishment of a viable aquaculture program for any species is a reliable source of young animals to be cultured. In a series of annual plankton surveys extending upwards of 140 km off the west coast of Vancouver Island, B.C., we have established that megalopae of Dungeness crab (Cancer magister) regularly occur in the neuston at night in offshore areas at densities greater than 5/m2 of sea surface. Zoeae of this species move into offshore waters, presumably to facilitate dispersal utilizing the region's longshore currents. However, many larvae cannot subsequently return to shore by the time they must settle, which they need to do to survive as juveniles. Off Vancouver Island, onshore movement is often prevented by longshore currents and so moderate collection of megalopae from offshore waters for later culture should not noticeably reduce recruitment of larvae to commercially fished, inshore populations. By searching out high concentrations of megalopae, it is estimated that catches in excess of 1 million late-stage megalopae can be obtained per night. Minimal incidental capture (5–10%) of other planktonic organisms occurs in May, and to achieve maximum growth by juveniles from warm summer waters, megalopae collection for culture is recommended to be done at this time.

Jamieson, G. S., Phillips, A. C., & Huggett, W. S. (1989). Effects of Ocean Variability on the Abundance of Dungeness Crab Megalopae. In *Effects of Ocean Variability on Recruitment and an Evaluation of Parameters Used in Stock Assessment Models.* R. J. Beamish & G. McFarlane (Eds.), (Vol. Canadian Special Publication of Fisheries and Aquatic Science, pp. 305-325). Ottawa, Ontario (Canada): Dept. of Fisheries and Oceans. Retrieved from http://www.dfo-mpo.gc.ca/Library/114022.pdf

The longshore and cross-shelf abundance of Cancer crab megalopae have been studied off the south coast of Vancouver Island since 1985. Megalopae occur in abundance from about 28 km to at least 170 km offshore, well beyond the general location (70 km offshore) of the continental shelf break (200 m depth). Intermoult staging of megalopae indicates that later stage megalopae are found progressively closer inshore, but in the study area, megalopae may not always reach the coast, which they must do in order to survive as settled juveniles. Since at least 1985, no substantive settlement has occurred in the commercial Dungeness (C. magister) fishing areas immediately around Tofino, British Columbia. Since Dungeness crab recruit to the fishery at 3-4 yr of age, a significant decrease in annual landing from this fishery is predicted over the next few years.
Environmental factors influencing the movement of megalopae have been investigated by documenting surface current patterns in the study area by means of drifters, estimating geostrophic flow patterns from STD data, and analyzing meteorological events as contributors to onshore larval movement. Results indicate that the patterns of currents and their relative velocities in the study areas differ on an annual basis. It appears that these current patterns affect where crab megalopae are concentrated in abundance and their subsequent ability to move onshore.

Lough, G. R. (1976). Larval Dynamics of the Dungeness Crab, Cancer Magister, Off the Central Oregon Coast, 1970-71. *Fishery Bulletin, 74*(2) Retrieved from https://spo.nmfs.noaa.gov/content/larval-dynamics-dungeness-crab-cancer-magister-central-oregon-coast-1970-71

The larval dynamics of the economically important Dungeness crab, Cancer magister, were investigated from plankton samples collected bimonthly during 1970 and 1971 along a trackline near Newport, Oreg. Larvae appeared at maximum densities (8,000/1,000 m3) within 15 miles ofthe coast in late January 1970 and remained in the plankton until late May for an approximate larval period of 130 days. The bulk of the larval population was retained in the nearshore area by the strong alongshore and onshore components ofthe surface currents and to some extent by the behavior oflarvae in determining their position in the water column. During the 1971 season, larvae appeared initially at about the same time and densities, but a mass mortality may have occurred in the early zoeal stages coinciding with the unusually severe weather in February and March. A significant difference between the 1970 and 1971 larval populations was suggested by analysis of covariance using sea surface temperature and salinity as environmental variables. However, the effect ofthe low temperature and salinity values that occurred during the winter of 1971 were not clearly indicated by multiple regression analyses oflaboratory experimental data to be the prime factors directly affecting larval survival. Neither did a gut-fullness study of planktonic larvae substantially explain the 1971 larval mortality. Therein various hypotheses are explored in view of the present knowledge of processes affecting larval survival and recommendations are suggested for further research.

McConnaughey, R. A., Armstrong, D. A., Hickey, B. M., & Gunderson, D. R. (1992). Juvenile Dungeness Crab (Cancer Magister) Recruitment Variability and Oceanic Transport During the Pelagic Larval Phase. *Canadian Journal of Fisheries and Aquatic Sciences, 49*(10), 2028-2044 https://doi.org/10.1139/f92-226

The influence of environmental variability on Cancer magister year class strength was examined using trawl survey data from the Washington coast, 1983–88. Average June–September estimates of early instar abundance within two coastal estuaries and the adjacent nearshore are compared with alongshore and cross-shelf transport vectors during the preceding 4- to 5-mo pelagic larval phase. Settlement in the study area varied interannually by nearly 40-fold and was inversely related to net alongshore (northward) transport during January–May. Settlement was confined to a relatively narrow band along the coast and in estuaries; new recruits were rarely encountered beyond 46 m depth, corresponding to a distance of ~15 km from shore. We found no evidence for sustained westward Ekman transport to account for progressive seaward transport of zoeae, as proposed by other authors. Rather, persistent landward transport of near-surface waters will tend to minimize advective loss of larvae to seaward while promoting retention in proximity to suitable juvenile and adult habitat nearshore. Temporal and spatial continuity of northward transport during the winter months, coupled with proximity to high-risk areas downstream, suggests that Washington C. magister populations are frequently dependent on larvae originating to the south for recruitment.

McMillan, R. O., Armstrong, D. A., & Dinnel, P. A. (1995). Comparison of Intertidal Habitat Use and Growth Rates of Two Northern Puget Sound Cohorts of 0+ Age Dungeness Crab, Cancer Magister. *Estuaries, 18*(2), 390 https://doi.org/10.2307/1352321

Density, habitat use, and growth of intertidal 0+ age Dungeness crabs, Cancer magister, were examine five northern Puget Sound (Washington, USA) sites between June 1984 and September 1987. Sampling was conduc biweekly during settlement, from June to September, and approximately monthly or bimonthly thereafter. Nort Puget Sound Dungeness crab populations appear to be largely supported by recruitment from inland parental stoc but a smaller proportion of recruits originate from coastal or oceanic stocks, as evidenced by earlier settlement a larger size of the first instar. Settlement of Dungeness crabs in inland waters typically peaked in August, and int variation in year-class strength at settlement (measured as intertidal density) was low relative to that reported fo crab populations. Spatial and interannual differences in settlement densities were mediated by high postsettlemen tality, which varied inversely with habitat complexity. Seasonal densities were highest in mixed sand and gravel overstory of attached or drift macroalgae, intermediate in eelgrass (Zostera marina), and lowest on open sand. Pos tlement growth rates corresponded to seasonal water temperatures and were greatest for the coastal cohort that in May and June. This cohort was larger as first juvenile instars (7.2 mm carapace width, CW) and grew rapidly at sum temperatures in excess of 15?C to a size (>30 mm CW) that allowed emigration from intertidal to subtidal are September. The late summer cohort settled in August at 5.3 mm CW and soon after was subjected to decreasing water temperatures. These crabs experienced little growth while overwintering in the intertidal, but growth rates inc in March, and the crabs emigrated in April and May, approximately 10 mo after settlement.

Miller, J. A., & Shanks, A. L. (2004). Ocean-Estuary Coupling in the Oregon Upwelling Region Abundance and Transport of Juvenile Fish and of Crab Megalopae. *Marine Ecology Progress Series, 271*, 267-279 https://doi.org/10.3354/meps271267

Numerous species of fish and invertebrates move between the continental shelf and estuaries during their early life-history. The physical mechanisms that regulate such movement and the extent of coupling between the near-shore ocean and estuaries are poorly understood. It is unclear how, or whether, similar physical mechanisms regulate transport to the outer coast and between the outer coast and estuarine areas. We used high frequency light trap collections at 2 sites, outer coastal and estuarine, to compare the timing and magnitude of the relative abundance of juvenile fish and crab megalopae. The time series of juvenile fish and crab megalopae were statistically compared with physical variables indicative of wind and tidal conditions to identify potential transport mechanisms. Species examined included juvenile Engraulis mordax (northern anchovy), Sardinops sagax (Pacific sardine), Sebastes melanops and S. caurinus (black and copper rockfish), and megalopae of Cancer magister (Dungeness crab), C. oregonensis and C. productus combined (pygmy and red rock crabs), and Pagurus spp. (hermit crabs). The abundances of juvenile E. mordax and S. sagax and C. magister megalopae in the estuary were significantly cross-correlated with abundances at the outer coast (at 0 to –4 d lags). These data support the idea that estuarine ingress may be a 2-stage process with initial arrival in the near-shore as the first stage and subsequent entrance into nearby estuaries as the second stage. Significant cross correlations between species abundance and physical variables indicative of wind-driven transport, both upwelling and downwelling-related, and tidal transport, specifically the spring-neap tidal cycle, were found at both the outer coast and estuarine site. These data indicate that both wind-driven and tidal transport may contribute to the cross-shelf transport and estuarine ingress of organisms.

Orensanz, J. M., & Gallucci, V. F. (1988). Comparative Study of Postlarval Life-History Schedules in Four Sympatric Species of Cancer (Decapoda: Brachyura: Cancridae). *Journal of Crustacean Biology, 8*(2), 187-220 https://doi.org/10.2307/1548312

Size-at-instar, growth-per-molt, reproductive schedules, and morphometric allometries were investigated in four sympatric species of Cancer (magister, the Dungeness crab, gracilis, productus, and oregonensis) in Garrison Bay, North Puget Sound. Complementary observations were made on mating systems, mortality, habitat utilization patterns, and feeding. Numerical methods were successfully employed to discriminate instars in size-frequency distributions. Growth pattern, contrary to our expectation, was determinate in the four species. Geographic variation in prereproductive growth rate of C. magister is attributed to environmental factors. It is suggested that an independent stock may inhabit the Strait of Georgia-North Puget Sound area.

Park, W., Douglas, D. C., & Shirley, T. C. (2007). North to Alaska: Evidence for Conveyor Belt Transport of Dungeness Crab Larvae Along the West Coast of the United States and Canada. *Limnology and Oceanography, 52*(1), 248-256 https://doi.org/10.4319/lo.2007.52.1.0248

We propose and evaluate the hypothesis that Dungeness crab (Cancer magister) larvae from the northwestern coast of the United States and Canada can be transported northward to southeastern Alaska. Larvae collected in southeastern Alaska during May and June 1997?2004 had abundances and stages that varied seasonally, interannually, and spatially. An unexpected presence of late-stage larvae in spring raises a question regarding their origin, and the most plausible explanation is that they hatched off the northern Washington and British Columbia coasts and were transported to southeastern Alaska. Buoy drift tracks support the hypothesis that larvae released off the northern Washington and British Columbia coasts during the peak hatching season can be physically transported to southeastern Alaska, arriving as late-stage larvae in May and June, when local larvae are only beginning to hatch. A northward spring progression of monthly mean 7°C SST isotherms and phytoplankton blooms provide further evidence that environmental conditions are conducive for larval growth and metabolism during the transport period. The proposed larval transport suggests possible unidirectional gene flow between southern and northern populations of Dungeness crabs in southeastern Alaska.

Section III: Supplemental

Armstrong, D. A., Rooper, C., & Gunderson, D. (2003). Estuarine Production of Juvenile Dungeness Crab (Cancer Magister) and Contribution to the Oregon-Washington Coastal Fishery. *26*(4), 1174-1188 https://doi.org/10.1007/bf02803372

Estuaries provide nursery habitat for juvenile stages of several conlnlercial decapod crustaceans worldwide, and those in the Northeastern Pacific are viewed as providing this function for Dungeness crab, Cancer mag/ster. It is difficult to ascertain the degree to which such estuarine production of juveniles eventually contributes to coastal adult populations and fisheries since there are no direct surveys of adult abundance. As other authors have done, we used fishery landings data to compute the long-term average contribution of 1+ juvenile crab populations reared in estuaries to future coastal fisheries. We focused on Oregon and Washington states, but grouped landings in two large geographic zones by combining fishery ports as adjacent to Large Estuarine Zones (LEZ; Grays Harbor and Willapa Bay, Washington, and both sides of tile Columbia River) and Small E.stuarine Zones (SEZ; all other ports in Oregon). Mortality estimates were used to reduce 1+ crab abundance to surviving legal nlales, and portrayed as percent of tile fisheries. Trends in the SEZ indicate that an average of only about 5-7% of estnarine production adds to the coastal adult population and contributes about $0.7 million to the fishery. The contribution is 25-30% in the LEZ (but may be higher since interannual density varies up to 5 times) and is worth about $3.9 million based on present ex-vessel value. Analyses of crab distribution and density indicate that the majority of an estuarine population (50-80%) is located in lower side channels (LSC) in spring and summer where temperature is higher and prey within and on adjacent intertidal flats is high. The potential average dollar value of equivalent legal nlale crab produced from the juvenile population is about $180 ha 1 in LSC (but $280 ha 1 in Grays Harbor where long-term density is highest), and lower in other estuarine habitats ($50-100 ha-l). Estuarine juvenile production provides a relatively stable source of recruits to coastal adult populations, and large systenls in tile LEZ are important nurseries. Since direct coastal settlement of larvae does occur but is highly variable, the estuarine contribution inay be especially important when physical forcing or unusual events lead to low survival of the coastal 0+ cohorL An unusually long period of very low landings in the LEZ from 1981-1987 is interpreted in light of the Mount St. Helens eruption (1980) and subsequent transport and deposition of very fine silt fractions over much of the LEZ nearshore shelf that may have adversely affected several year classes of small, early benthic phase juveniles at that time.

Galloway, A. W., Shanks, A. L., Groth, S., Marion, S. R., & Thurber, A. R. (2017). Massive Crab Recruitment Events to the Shallow Subtidal Zone. *Ecology, 98*(5), 1468-1470 https://doi.org/doi.org/10.1002/ecy.1740

During a SCUBA dive at Port Orford, Oregon, USA on 19 April 2016, Galloway observed a remarkably dense benthic aggregation of recently settled Cancer (Metacarcinus) magister megalopae, the final larval stage of decapod crustaceans, as well as new recruits (firstinstar settlers). Between 7 and 13 m depth (the deepest descent) and throughout the 45- min dive, every surface of the rocky reef, including sessile invertebrates, algae, vertical rock walls, and cobbles, in an estimated 100- m2 area, was completely covered with new recruits.

Litz, M. N. C., Miller, J. A., Copeman, L. A., Teel, D. J., Weitkamp, L. A., Daly, E. A., & Claiborne, A. M. (2016). Ontogenetic Shifts in the Diets of Juvenile Chinook Salmon: New Insight from Stable Isotopes and Fatty Acids. *Environmental Biology of Fishes* https://doi.org/10.1007/s10641-016-0542-5

Variations in marine prey availability and nutritional quality can affect juvenile salmon growth and survival during early ocean residence. Salmon growth, and hence survival, may be related to the onset of piscivory, but there is limited knowledge on the interplay between the prey field, environment, and salmon ontogeny. Subyearling Chinook Salmon (Oncorhynchus tshawytscha) and their potential prey were sampled in coastal waters offWillapa Bay, USA to explore this issue. Three seasonal prey assemblages were identified, occurring in spring (May), early summer (June – July), and late summer (August – September). The onset of piscivory, based on salmon stomach contents, fatty acids, and stable isotopes occurred later in 2011 compared to 2012, and coincided with the appearance of Northern Anchovy (Engraulis mordax). Salmon fork length (FL) and carbon isotope values (δ13C) increased with a fatty acid biomarker for marine phytoplankton and decreased with a freshwater marker, indicating dietary carbon sources changed as salmon emigrated from the Columbia River. Salmon FL also increased with nitrogen isotope ratios (δ15N), trophic position, and a fatty acid marker for piscivory – a consequence of the ontogenetic shift in diet to fish. Salmon grew faster and obtained larger size and condition by September 2011 compared to 2012, which was related to inter-annual differences in ocean conditions and the duration over which Northern Anchovy were available. Our results support the idea that juvenile salmon growth depends on the onset and duration of piscivory, suggesting both of these factors may be important components of lifetime growth and fitness.

McConnaughey, R. A., Armstrong, D. A., Hickey, B. M., & Gunderson, D. R. (1994). Interannual Variability in Coastal Washington Dungeness Crab (Cancer Magister) Populations: Larval Advection and the Coastal Landing Strip. *Fisheries Oceanography, 3*(1), 22-38 https://doi.org/10.1111/j.1365-2419.1994.tb00045.x

Substantial and unexplained variations in abundance characterize US west coast populations of Dungeness crab, Cancer mugister. It is likely that this variability reflects oceanic advection of larvae given the dynamics of the California Current system, the protracted (4-5 months) pelagic larval phase and the restrictive nature of juvenile habitat requirements. We compare 40 years of Ekman transport vectors during January-May (1947-1986) with time-lagged and stratified commercial landings for coastal Washington (195 1-1990). Persistent landward and net northward flow characterized the circulation of near-surface waters during the larval periods studied. A mechanism for progressive seaward transport of larvae through ontogeny, as proposed by others, was not apparent. Overall, above- (below-) average year classes were associated with relatively weak (strong) northward transport and, to a lesser degree, strong (weak) landward transport. Based on these analyses and in consideration of the prevailing coastal circulation, we propose that the relative magnitude of C. magister juvenile recruitment and, hence, incoming year class strength, reflects: (1) the proportion of larvae retained within a relatively narrow (5 15 km) and heterogeneous 'coastal landing strip', (2) the availability of suitable substrate within the coastal landing strip at time of settlement and (3) the magnitude of downstream advective losses (export) of larvae from the California-Oregon-Washington coastal system. Based on a consideration of the physics of the California Current system and the larval biology of the species, significant linkage of Dungeness crab populations along the west coast of North America is likely.

Park, W., & Shirley, T. C. (2005). Diel Vertical Migration and Seasonal Timing of the Larvae of Three Sympatric Cancrid Crabs,Cancer Spp., in Southeastern Alaska. *Estuaries, 28*(2), 266-273 https://doi.org/10.1007/bf02732860

Diel vertical migration (DVM) and seasonal timing of three sympatric Cancer spp. larvae were investigated in southeastern Alaska. Diel sampling was conducted at a station in Icy Strait at 0400, 0700, 1000, 1300 h in the first day, and 1300, 1600, 1900, and 2200 h in the second day from June to September 2001. Larvae were collected with Bongo nets (333 and 505 µm mesh) towed vertically from 20 m depth to the surface. During flood tides surface temperature increased slightly and salinity decreased; the reverse occurred during ebb tides. Zooplankton biomasses were higher in the early morning and evening than during the midday. A total of 4,482 larvae were examined for the study. Cancer oregonensis larvae were most abundant (4,238), followed by C. magister (205) and C. productus (39). Larval density peaked in June while no larvae were found in September. C. magister larvae had a crepuscular migration; larval abundance peaked in early morning and evening. C. oregonensis larvae comprised 94.6% of all Cancer spp. larvae collected and had a strong DVM in June. Earlier zoeal stages of C. oregonensis were relatively more abundant during midday, while later stages were more abundant at night. In July, later larval stages of C. oregonensis were distributed at the surface all day with a peak at 2200 h. Larvae of C. productus first occurred in July and peaked in August. C. productus had DVM but many were at the surface diurnally. C. magister and C. oregonensis larvae co-occurred seasonally as they do in the lower latitudes, e.g., Washington and British Columbia; however, C. productus appeared approximately 2 mo later than C. magister and C. oregonensis in southeastern Alaska.

Rasmuson, L. K. (2013). Chapter Three - the Biology, Ecology and Fishery of the Dungeness Crab, Cancer Magister. In *Advances in Marine Biology.* M. Lesser (Ed.), (Vol. 65, pp. 95-148): Academic Press https://doi.org/10.1016/B978-0-12-410498-3.00003-3

The Dungeness crab, Cancer magister, is a commercially important crustacean that ranges from the Pribilof Islands, Alaska, to Santa Barbara, California. Mating occurs between recently moulted females and post-moult males. After approximately 90 days, females release planktonic larvae into the water column. Stage-I zoea are found in the nearshore environment and subsequent zoeal stages are found at greater distances. After approximately 80 days, zoea moult into megalopa, which move first from the open ocean onto the continental shelf and then across the shelf to settle in the nearshore environment or estuaries. Crabs reach sexual maturity at 2–3 years of age. The fishery for C. magister is managed using a 3-S management strategy which regulates catch based on size, sex and season. As more fisheries seek sustainability certifications, the Dungeness crab fishery presents an excellent test case of how to sustainably manage a crustacean fishery.

Stevens, B., & Armstrong, D. A. (1984). Distribution, Abundance and Growth of Juvenile Dungeness Crabs, Cancer Ma- Gister, in Grays Harbor Estuary, Washington U.S. *Fishery Bulletin, 82*(3), 469-483 Retrieved from https://spo.nmfs.noaa.gov/content/distribution-abundance-and-growth-juvenile-dungeness-crabs-cancer-magister-grays-harbor

Dungeness crabs, Cancer magister, were collected biweekly or monthly from May 1980 to July 1981 in Grays Harbor, Washington. Age of each crab was estimated from width-frequency analyses, and the population density and growth rate were monitored for each age class over the 14-month period. In April 1980 and 1981, crabs entered the estuary either as megalops larvae that metamorphosed to first instar postlarvae or directly as first instars. Intertidal mudflats with beds of eelgrass (Zostera spp.) were important habitats for the first few postlarval stages. Some crabs may have emigrated from the estuary during their second year of life, whereas others dispersed throughout the estuary and appeared to emigrate at sexual maturity (about 2 years). No gravid females were ever found in the bay. Population size was estimated to range from 3.3 million crabs (winter) to 39.0 million crabs (summer); 74% ofthe summer population were early instars. Growth of early instars was rapid and resulted in a 282-fold increase in dry weight from May to September, but little growth occurred during the remainder ofthe year. Based on summer population abundance, it is estimated that this estuary could account for a substantial portion of recruitment to the offshore commercial fisheries