

Nisqually River Delta Summary: Early phase restoration performance and prey contributions to juvenile Chinook salmon within a habitat mosaic



Summary Report to:

Estuarine and Salmon Restoration Program. Project # 13-1583P

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Acknowledgments

Science support comes from the Estuary and Salmon Restoration Program (ESRP) awarded to USGS Western Ecological Research Center (WERC) to assess the relative contribution of invertebrates across the Nisqually River Delta landscape (ESRP Project # 13-1583P). Additional funding from USGS Land Carbon in partnership with USFWS was provided to identify the sources of primary producers that supported the secondary production of invertebrate prey via stable isotope analyses and partial salary support. This study was conducted in partnership with the Nisqually Indian Tribe (Tribe), which led all fish sampling efforts with which we coordinated the prey sampling timing and locations. We also partnered with USFWS, Billy Frank Jr. Nisqually National Wildlife Refuge (Refuge) which has been extremely supportive and engaged with applied research. The Nisqually River Foundation provided administrative support for fish technicians. This study benefited from USGS internship programs (Students in Support of Native American Relations-SISNAR, National Association of Geoscience Teachers-NAGT), and USGS WERC Wetland Restoration Program funds.

This research follows and builds upon earlier work in applying the monitoring framework to assess the effects of restoration on the Nisqually River Delta (*sensu* Simenstad and Cordell 2000: *opportunity, capacity, and realized function*) was funded by multiple sources including: EPA Tribal Assistance Grant, ESRP, USFWS (Inventory and Monitoring Program) NFWF, USGS (Science Support and internship programs [SISNAR and NAGT]). All fish work was led by the Tribe. Large scale restoration monitoring and applied research at the Nisqually Delta was initiated with the Refuge (G. Nakai, J. E. Takekawa, D. Roster, J. Barham, M Bailey), Tribe (C. Ellings, J. Dorner, S. Hodgson, J. Cutler, J. Moore), and USGS WERC (I. Woo, J. Y. Takekawa, S. De La Cruz, M. Davis, K. L Turner) and also included contributions by the Nisqually River Foundation (A. David, W. Duval).

The 2014-2015 USGS WERC team consisted of Isa Woo (Project PI), Susan De La Cruz (Station Supervisory Biologist, Station PI: station and programmatic priorities), Melanie Davis (Restoration Biologist: project coordinator, data management and analyses), Ashley Smith (Invertebrate Biologist: analyses, identification), William Chan (Invertebrate Biologist: identification), and Lennah Shakeri (Biologist: field data collection, macroinvertebrates). Technicians Sierra Blakely and Angelica Munguia, and National Association of Geoscience Teachers (NAGT) interns Anna Hissem and Larisa Lamere assisted with sample collection, invertebrate processing, and data management throughout the 2014 and 2015 field seasons.

Suggested citation:

Woo, I., M. Davis, and S. De La Cruz. 2017. Nisqually River Delta Summary: Early phase restoration performance and prey contributions to juvenile Chinook salmon within a habitat mosaic. U.S. Geological Survey Administrative Report to WA Department of Fish and Wildlife, Estuary and Salmon Restoration Program. 37 pp.

Background

The restoration of the Nisqually River Delta, southern Puget Sound, Washington represents one of the largest efforts toward reestablishing the ecosystem processes and function, particularly for salmonids to date. Since 1996, a series of phased dike removal restoration projects by the Nisqually Indian Tribe increased potential salt marsh habitat in southern Puget Sound by 50% and re-established tidal processes. Since 1996, the Nisqually Indian Tribe (Tribe) and Billy Frank Jr. Nisqually National Wildlife Refuge (Refuge) have restored approximately 365 ha of estuary habitat to tidal processes through multiple dike removal projects: 4 ha in 1996 (Pilot), 13 ha in 2002 (Phase I), 41 ha in 2006 (Phase II), and 308 ha on the Refuge in 2009 (Restored Refuge; Figure 1). The ultimate goal of the restoration was to increase the ability of the estuary to support a variety of wildlife such as waterbirds and native fish, especially the Nisqually fall Chinook salmon (*Oncorhynchus tshawytscha*), a federally threatened species with rich cultural significance (NCRT 2001).

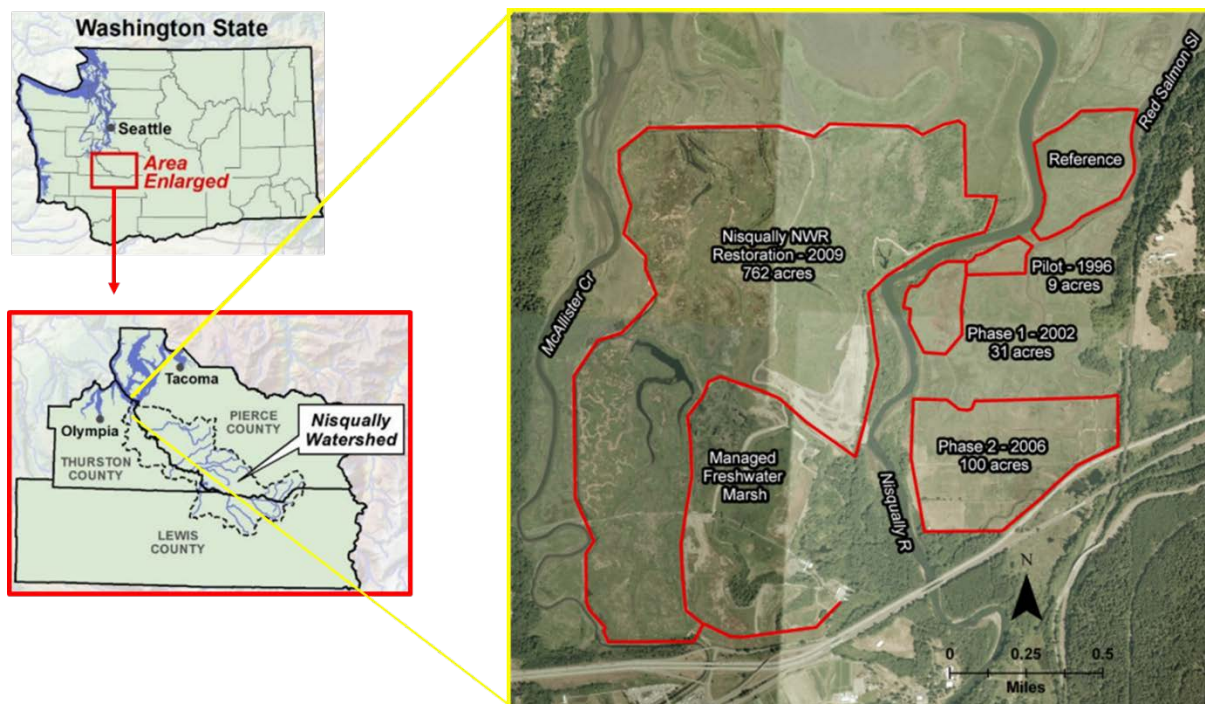


Figure 1. Phased estuarine restorations at the Nisqually River Delta in south Puget Sound.

PHASE I:

Assessing Restoration Performance

The restoring Nisqually River Delta (NRD) is an ideal site to use monitoring and applied science datasets to assess restoration effectiveness using the *Opportunity, Capacity, and Realized Function* framework set forth by Simenstad and Cordell (2000). Evaluating the effect of restoration on the growth and survival of salmon is challenging because, in addition to the lag time between the development of suitable habitat and prey resources, their densities are highly variable across space and time within the landscape mosaic (Simenstad & Cordell 2000; Kondolf et al. 2008). Furthermore, salmon populations are subject to variable outmigration success and adult return rates, both of which are impacted by broad-scale climactic and environmental factors outside of restoration influence (Greene et al. 2005; David et al. 2014). Response to restoration processes may be difficult to detect using fish catch data alone as such measurements cannot effectively capture how fish take advantage of increased prey abundance and expansion in available habitat (Simenstad & Cordell 2000). In light of these challenges, the Nisqually Monitoring Framework identifies restoration performance criteria in terms of opportunity potential (habitat accessibility), foraging capacity (conditions for prey resources and salmonid growth), and realized function (measurable foraging or growth response; Simenstad & Cordell 2000; Ellings 2011).

To assess restoration performance we compared two restoration sites (2009 Restored and 2006 Restored, locally known as Phase II) with marshes and channels that were not previously diked and not directly affected by the restoration Nisqually Reference (locally known as Animal Slough) on the northeast side of the Refuge, and the northern branch of Red Salmon Slough (RSS Reference) on the east side of the Nisqually River (Fig. 2).



Figure 2. Map of Restored and Reference channels

Methods

Opportunity: Access and habitat availability (Ellings et al. 2016)

Opportunity is defined in terms of habitat availability and accessibility (as in Simenstad and Cordell 2000). We addressed the functions of the restored NRD in terms of change in opportunity potential using metrics that are associated with the ability for juvenile salmon to access and benefit from restored habitat. Metrics included surface elevation and water levels (frequency and duration of inundation), channel area, channel depth, water temperature, and tidally based channel accessibility and landscape connectivity. We integrated monitoring data including physical parameters and proportional presence of salmon (fish catch surveys of natural-origin Chinook, hatchery-origin Chinook, and natural-origin chum salmon) to quantify opportunity potential as a result of large scale restoration (Ellings et al. 2016).

Water quality – Data loggers (Solinst® or Odyssey®) that measured temperature, conductivity, and water level were installed at the restored (2009 Restored and 2006 Restored) and reference (Nisqually Reference and RSS Reference) marshes, where fyke trap nets for fish sampling were set. Data loggers were programmed to measure temperature and water level at 6 or 15 minute intervals, and had enough on-board memory to collect information for up to 6 months. All loggers on the NRD were protected by PVC housing staked into the ground roughly 1.5 m deep with a metal pole. Loggers were exchanged, downloaded, and calibrated in the field every 6 months for data quality assurance. We used a Real Time Kinematic Global Positioning System (RTK GPS) to accurately measure sensor elevation and calibrate recorded water level values to actual tidal elevation.

Accessibility – To document historic channel morphology, we used a georeferenced, 1878 Puget Sound River T-sheet. We examined pre- and post-restoration conditions with false color infrared aerial photographs flown in summer 2005 and 2011 at low tide (<0m) during cloud-free days. We hand-digitized channel morphology on resulting georeferenced imagery with ArcGIS software (ESRI Inc., Redlands, CA, U.S.A.). We digitized channels with a width ≥ 15 m estimated at bank-full (using vegetation guidelines) as polygon features, whereas channels less than 15m were digitized as polyline features at a scale between 1:400 and 1:1,000. We also digitized fine channels as linear features as far as image resolution would allow. We also surveyed channel cross sections at sites on the east and west sides of the Nisqually River annually from 2009 to 2014. Tidal inundation and habitat connectivity was assessed by integrating a DEM (integrated LiDAR and bathymetry datasets) with hydrology monitoring datasets.

Capacity: Invertebrate Prey Production (Woo et al., 2018)

Capacity is defined in terms of the ability of the restoration to produce prey resources. We assessed the capacity of each habitat in the NRD for invertebrate prey production by measuring the abundance and composition of terrestrial, aquatic, benthic, and epifaunal (eelgrass) invertebrates. Results from this work is being summarized in a manuscript in revision (Woo et al. in revision). Invertebrate sampling was coordinated with the Nisqually Tribe to occur at fish sampling sites and immediately after fish sampling occurred so that we can assess invertebrate prey availability for juvenile Chinook. Also this will allow further analyses for comparing prey availability to actual prey consumption in Chinook gut contents. We analyzed capacity in terms of invertebrate community structure, overall invertebrate densities, and target prey species biomass. These invertebrate metrics can play a major role in supporting juvenile salmonids of different species, life history strategies, size classes, and origins, while the overall availability of target prey also contributes to the carrying capacity of various delta habitats (Figure 2).

Benthic – We collected three 10 cm diameter benthic core at 10 cm depth per site, along with accompanying water quality data (temperature, DO, conductivity, and salinity). Each core was sieved using the elutriation method within one week of collection. The sample was sieved using 500-micron sieve and the remaining sample matrix was preserved in a 70% ethanol/rose bengal solution. Samples were sorted at the Nisqually field station in Olympia and then shipped to the USGS San Francisco Bay Estuary (SFBE) field station where they were later identified, enumerated, and weighed for biomass.

Terrestrial – We set up six fall-out traps at each of the two restoring and two reference sites. We constructed fall-out traps using 55 cm x 38 cm Tupperware® bins with Styrofoam blocks attached to the bottom for floatation. Each bin was strapped to surrounding four metal poles pounded into the ground surrounded, which allowed the bin to move up and with the tide without minimal tipping. During each sampling period, traps were filled with roughly two gallons of soapy water and left to sit for 46-50 hours. To collect the invertebrates for processing, each trap was poured through a 150-micron sieve. Invertebrates and debris were then gently rinsed or tweezed out of the sieve and preserved in 95% ethanol. All preserved samples were shipped to the USGS SFBE field station where they were later identified, enumerated, and weighed for biomass.

To monitor adjacent vegetation, we used a 0.5 m x 0.5 m quadrat. At each fall-out trap on a bi-monthly basis, we recorded percent vegetation, water depth, percent canopy, the approximate percentage cover for each species, the stem density of each species, and the maximum height of each species. We also collected groundwater salinity data by digging a 15-cm hole proximal to the fall-out trap and measuring the salinity via YSI or with a salt refractometer.

Aquatic –Neuston sampling was conducted in April, May, June, and July of 2019-2012 in conjunction with fyke netting for juvenile salmon. A neuston net (0.4 m x 0.2 m, 0.130 mm mesh) was pulled along the surface of the channel along a 120° arc, measuring 3.848 m for an estimated total volume of 0.33 m³. We sieved the sample on-site by rinsing the contents of the collection cup into a 200ml jar with 95% ethanol. We then shipped all preserved samples to the USGS SFBE field station where they were later identified, enumerated, and weighed for biomass.

Realized Function: juvenile Chinook consumption and growth potential (David et al, 2014 and Davis et al., 2018)

Realized Function is defined in terms of the ability of target species (juvenile Chinook salmon) to functionally benefit from increased opportunity and capacity, and is measured in terms of consumption compared to prey availability, growth potential, bioenergetics, or residence time. The previous study by David et al. (2014) examined the realized function (as in growth potential) for restoring sloughs compared to reference channels and demonstrated the restoration benefits; however, the study only addressed tidal marsh habitat type.

Chinook consumption

Coarse- and fine-scale fish sampling methods were used to measure juvenile salmon distribution throughout the estuary. To conduct coarse-scale fish sampling, we used a standard Puget Sound beach seine measuring 37 × 2m with a 2.4m bag of 6mm mesh, set by boat and hauled to shore by hand. We sampled 30 sites between mid to high tide, encompassing freshwater, forested riverine tidal, emergent forested transition, estuary emergent marsh, delta mudflat, and near shore habitat types. Pre-restoration beach seine sampling events occurred twice monthly throughout the delta from February through October 2003–2006. Post-restoration sampling events occurred monthly February through October 2010–2012.

For fine-scale fish sampling, we used fyke nets measuring 280 cm deep with 3mm mesh and a live trap in the center of the net. We set fyke traps across the channel at a falling high tide on a neap tide series, removing the net after 4 hours or once the channel drained (whichever came first). Tidal channels within restored and reference marshes were typically trapped once or twice a month from April to July and occasionally in March and August for pre-restoration (2003–2006) and post restoration (2010–2012) sampling. All fish were captured and measured following standard procedures (Ellings & Hodgson 2007).

Percent Similarity Index

PSI was computed using the percent composition by number of Chinook diet items and the percent composition by number of sampled invertebrate community at each site (Bray and Curtis 1957):

We calculated PSI using the equation:

$$PSI_{ij} = \frac{2C_{ij}}{S_i + S_j}$$

where C_{ij} represents the sum of the lesser values for species common to fish diet i and site j , and S represents the total number of specimens counted. Thus, a PSI value of 0 represents complete dissimilarity in prey communities, and a PSI value of 1 represents complete overlap.

We calculated the PSI between each individual Chinook salmon and the benthic, terrestrial, and pelagic prey communities within its respective catch site. Comparisons between dietary and site-specific prey composition were only conducted between corresponding yearly and monthly time periods to ensure spatiotemporal overlap.

Juvenile Chinook Growth Potential (David et al. 2014)

David et al. (2014) compared juvenile Chinook growth potential from restoring and reference channels using a suite of monitoring data (USGS WERC) and fish studies (Tribe). Growth potential was simplified as: Growth = Consumption – (Metabolism + Wastes) using growth models from Hanson et al. (1997).

Model inputs included:

Consumer mass (from fyke trapping efforts)

Consumer energy density (from fyke trapping efforts)

Consumption rate (from separate consumption rate study)

Prey energy density (from invertebrate and diet analyses)

Water temperature (from monitoring data, hydrology level and temperature loggers)

For additional detail, please see David et al. (2014).

Results and Discussion

Opportunity: Access and habitat availability (summarized from Ellings et al. 2016)

- We observed rapid and substantial increase (roughly 45%) in the availability of major and minor sloughs across the delta following the restoration (Table 2; Ellings et al. 2016).
- Large channels increased in overall area by 42% and minor channels more than tripled in area following large scale restoration. Channels grew deeper at the 2009 restoration at a rate of roughly 6 cm/y, with channel erosion occurring more quickly in the years immediately post-restoration (i.e. 2010 and 2011; Ellings et al. 2016).
- At the 2009 restoration site, sediment deposition is occurring on the adjacent inland mudflats at a rate of roughly 2.5 cm/y (2010-2014; USGS WERC unpublished data), but

the timing and rate at which channels will reach an equilibrium with the new tidal prism and sediment supply remain uncertain (Ellings et al. 2016).

Table 1. Channel metrics from historical (~1878), pre-restoration (2005), and post-restoration (2011) conditions (*from Ellings et al. 2016*). Delta-wide measurements were obtained via channel digitization. Restored sites represent channel metrics for study areas only (Units 1-4 restored in 2009 and Nisqually Reference restored in 2006).

<i>Delta-Wide</i>			
<i>Habitat and Channel Metric</i>	<i>Historic (~1878)</i>	<i>Pre-restoration (2005)</i>	<i>Post-restoration (2011)</i>
Major (> 3rd order) channel area (m ²)	1624176	1599070	2272798
Major (> 3rd order) channel length (m)	33998	37091	85655
Major (> 3rd order) channel edge length (m)	70579	76570	173285
Major (> 3rd order) mean channel sinuosity	1.62	2.71	4.2
Minor (< 3rd order) channel area (m ²)	N/A	31018	97373
Minor (< 3rd order) channel length (m)	N/A	31018	97373
Minor (< 3rd order) channel edge length (m)	N/A	62036	194746
Minor (< 3rd order) mean channel sinuosity (K)	N/A	1.99	2.09

<i>Restored Sites</i>			
<i>Habitat and Channel Metric</i>	<i>Historic (~1878)</i>	<i>Pre-restoration (2005)</i>	<i>Post-restoration (2011)</i>
Major (> 3rd order) channel area (m ²)	427259	77710	528908
Major (> 3rd order) channel length (m)	16970	5708	38698
Major (> 3rd order) channel edge length (m)	35102	13759	81148
Major (> 3rd order) mean channel sinuosity	1.5	2.77	2.79
Minor (< 3rd order) channel area (m ²)	N/A	9040	57391
Minor (< 3rd order) channel length (m)	N/A	9040	57391
Minor (< 3rd order) channel edge length (m)	N/A	18080	114782
Minor (< 3rd order) mean channel sinuosity (K)	N/A	2.08	2.22

- Outmigrating juvenile salmon have an optimal temperature range of 12-15 °C dependent upon salinity (Clarke & Shelbourn 1985), highlighting the importance of monitoring temperature fluctuations in restored tidal channels. Overall, water temperatures at restored sites decreased roughly 0.154 °C annually across the delta from 2009 to 2014, while reference site water temperatures remained relatively stable (Figure 3; Ellings et al. 2016). Temperatures remained up to 1°C higher at inland sites than at seaward or reference sites as a result of their shallower depth and lack of emergent marsh vegetation (Ellings et al. 2016). As vegetation colonizes across the delta and channels continue to incise, water temperatures are expected to approach levels similar to reference sites, though this may not be the case at inland channels where sediment deposition is occurring (Rutherford et al. 1997; Johnson 2004).

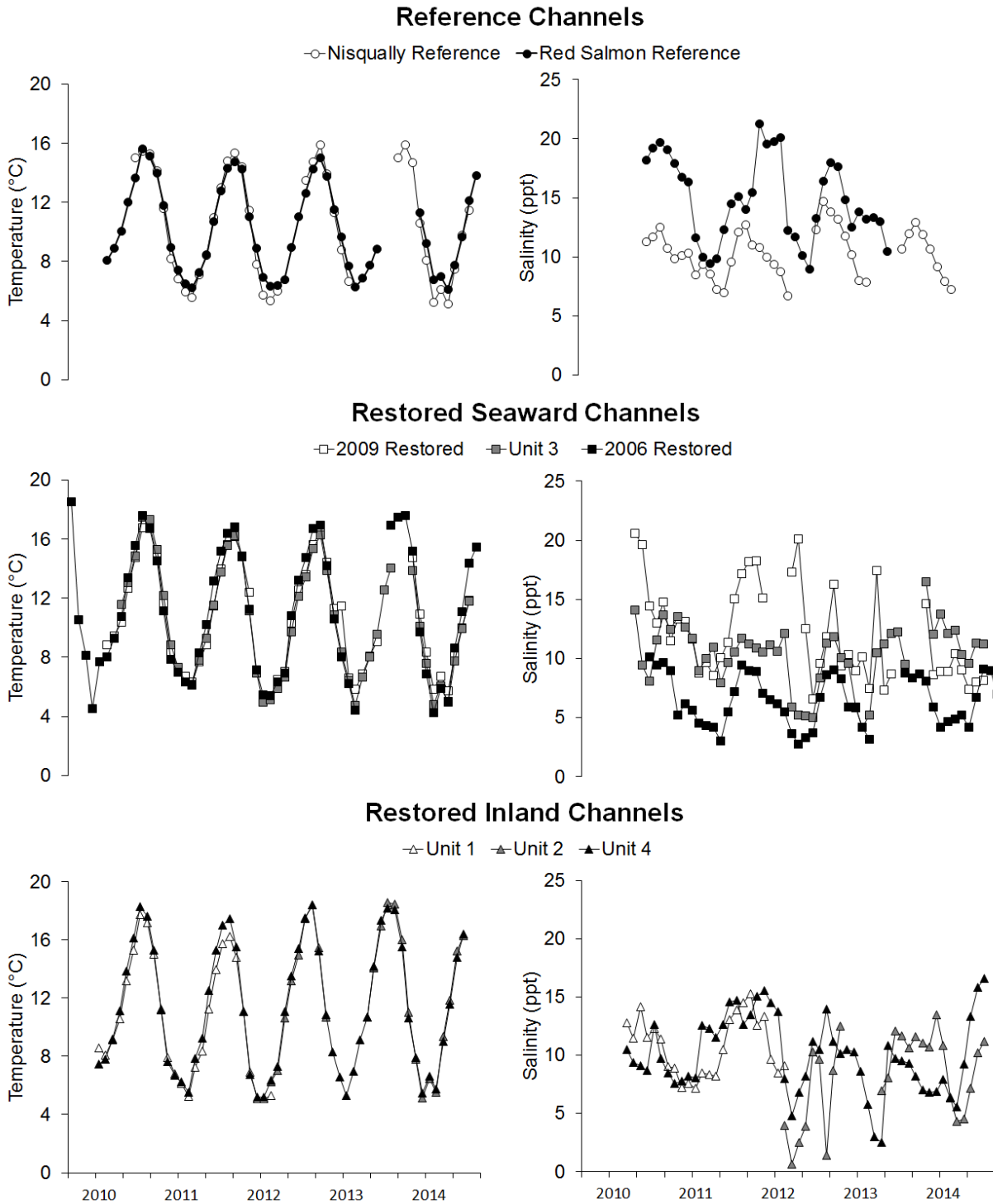
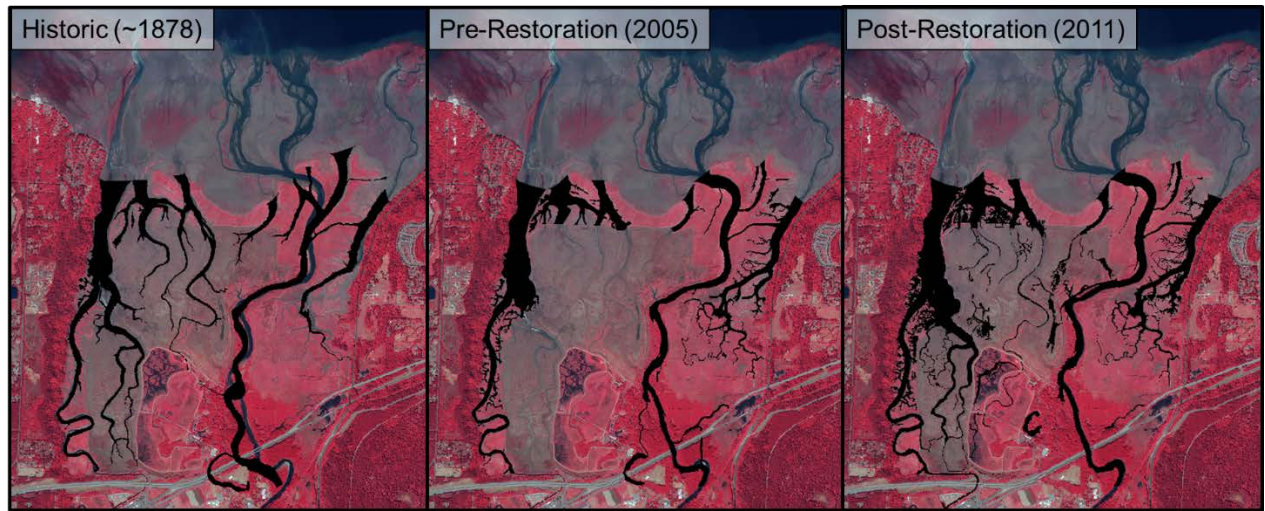


Figure 3. Temperature and salinity trends from 2010 to 2014 at reference and restored channels (from Ellings et al. 2016).

a)



b)

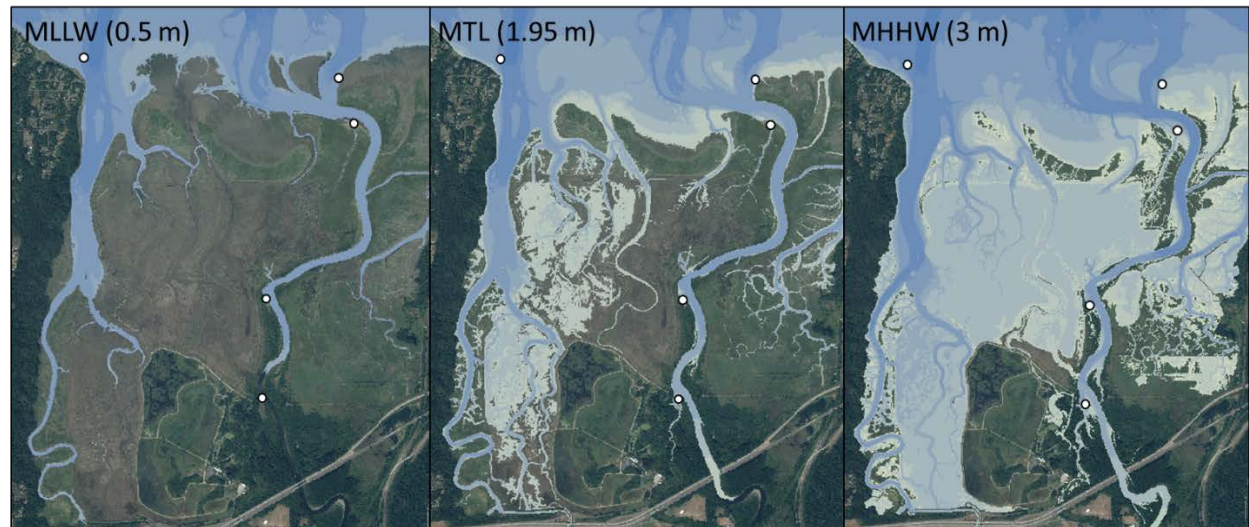


Figure 4. a) Digitized major channel morphology for historic (~1878), pre-restoration (2005), and post-restoration (2011) tidal channels on the Nisqually River Delta (from Ellings et al. 2016). b) Predicted tidal influence at all 5 sampling sites and calculated tidal datums for MLLW (0.5 m), MTL (1.95 m), and MHHW (3 m). Up-river sites (forested, transition) are not representative of true water depths due to freshwater influence from the Nisqually River.

- Our tidal inundation model estimated the amount of time tidal channels were accessible to salmon increased from 30% to 75% post-restoration (Figure 4). All the restoration sites for which habitat connectivity was analyzed experienced an increase in the number of available paths and tortuosity ratios following restoration, but none of the reference sites had large increases in accessibility.

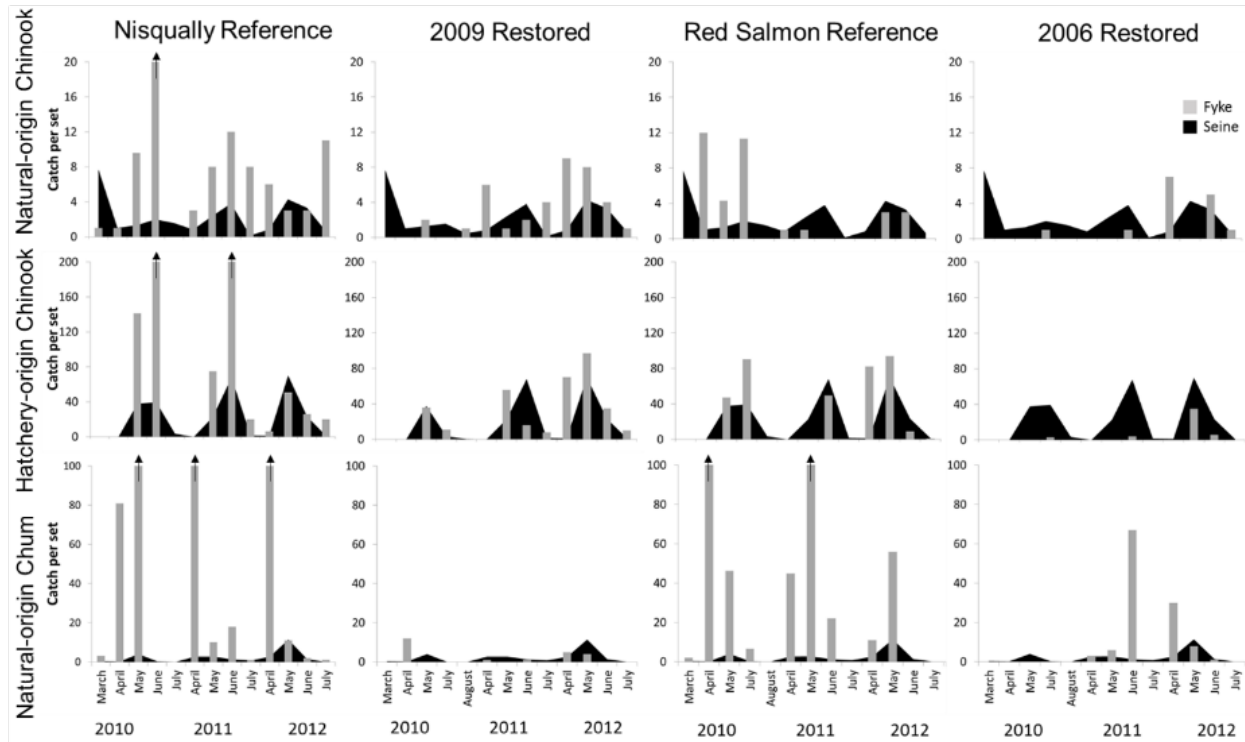


Figure 5. Proportional presence of natural origin Chinook (top), hatchery Chinook (middle), and natural origin Chum (bottom) at reference and restored sites from fyke catch (grey) compared to the surrounding beach seine captures in the delta (black).

- Salmon catch showed that smolts were using the 2009 restoration as early as one year post-restoration (Ellings et al. 2016). Natural-origin Chinook, the species most dependent on estuarine rearing habitat, were broadly distributed across the delta in space and time. Studies have demonstrated that natural-origin Chinook exhibit prolonged residencies in the delta (Lind-Null et al. 2008), suggesting that these individuals are more likely to take advantage of increased rearing opportunities following restoration.
- Natural-origin Chinook and in particular Chum salmon were captured in fyke traps in greater numbers in reference sites than at restored sites (Figure 5).
- While opportunity potential is a key measure of restoration success, habitat accessibility is only one metric with which managers can measure the viability of large-scale restoration projects. Other performance metrics, including the capacity of the site to support foraging juvenile Chinook (see Capacity section, below) or other wildlife, and the realized function of the site in terms of growth and bioenergetics (see Realized Function

section, below), are equally as crucial. Each of these indicators should be synthesized and evaluated to determine the success of estuary or wetland restoration projects.

Capacity: Invertebrate Prey Production (Woo et al., 2018)

- Summary of invertebrate prey capacity as a result of the restoration is in review (Woo et al., in revision), and is highlighted below. Invertebrate prey communities in general varied between Restored and Reference sites.

Benthic invertebrates

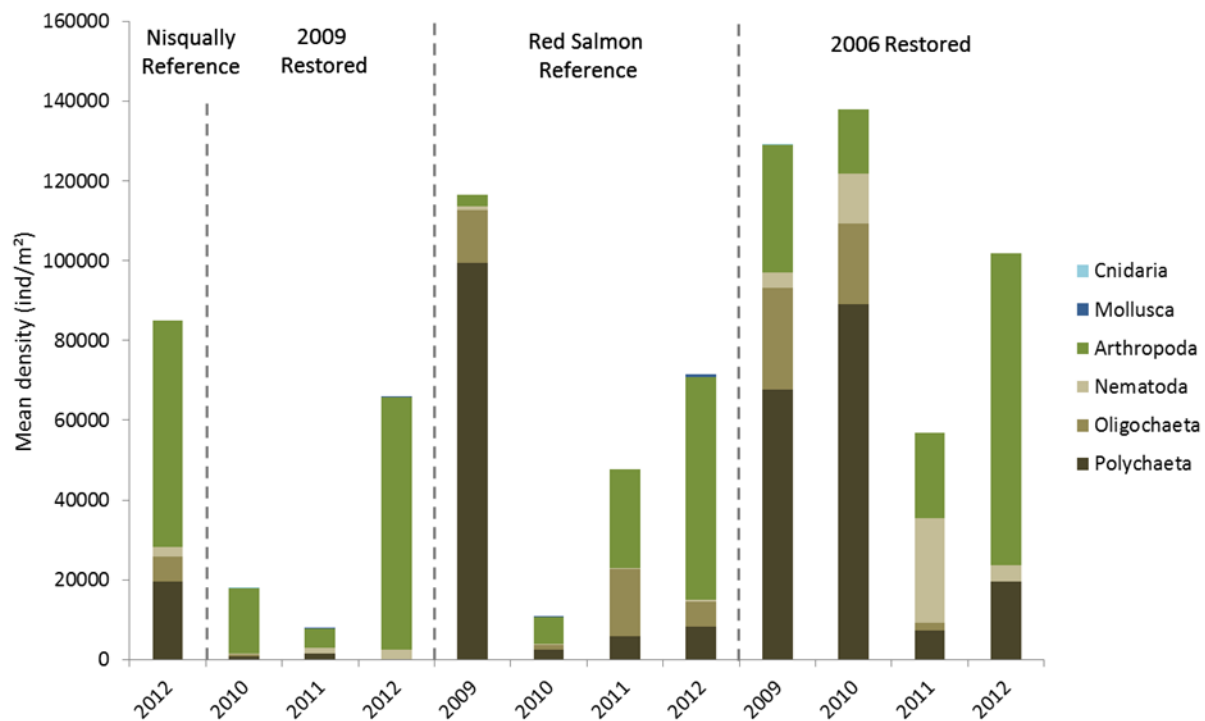


Figure 6. Benthic invertebrate densities by taxa at reference and restored sites from 2009-2012 (Woo et al., in revision).

- The 2006 Restoration on average produced the greatest density of benthic invertebrates, followed by Red Salmon Reference, Nisqually Reference (n=1), and 2009 Restoration. The 2009 Restoration was dominated by arthropods, while the Nisqually and Red Salmon reference sites and the 2006 Restoration had a more diverse invertebrate assemblage that included polychaetes, arthropods, oligochaetes, and nematodes (Woo et al, in review).

Terrestrial invertebrates

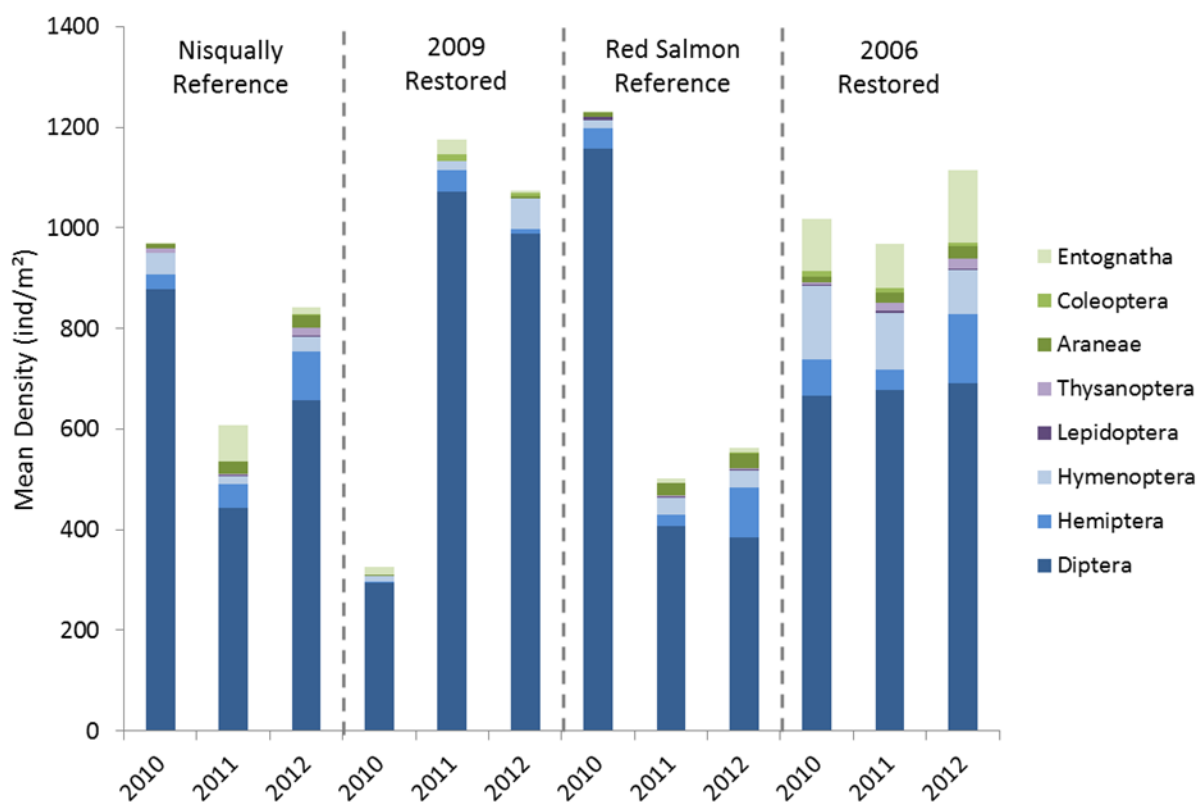


Figure 7. Terrestrial invertebrate densities by taxa at reference and restored sites from 2009-2012 (Woo et al., 2018).

- Flies (Diptera), true bugs (i.e, planthoppers, leafhoppers, aphids; Hemiptera), and other flying insects make up a large portion of juvenile salmon diet on the NRD (Pearce et al. 1982).
- Terrestrial invertebrate densities were dominated by dipteran flies at all sites.
- The 2009 Restoration produced densities similar to or greater than the Nisqually Reference two years following restoration.
- The 2006 Restoration produces consistently high densities of terrestrial invertebrates

Aquatic invertebrates

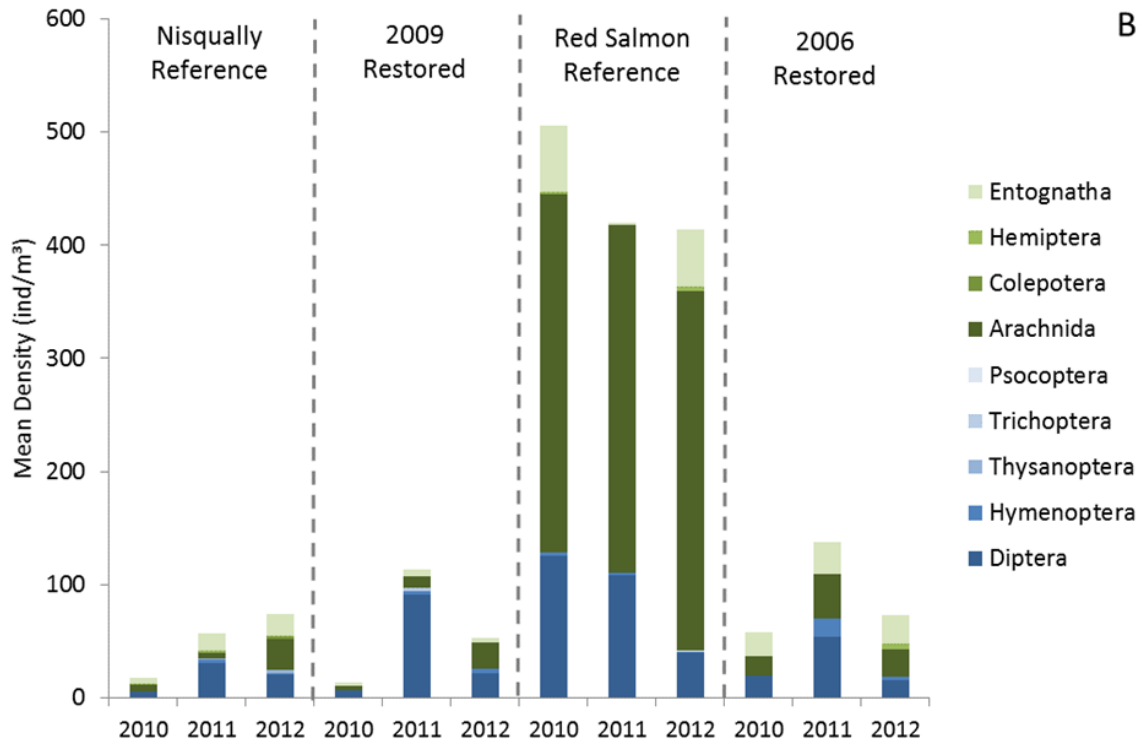
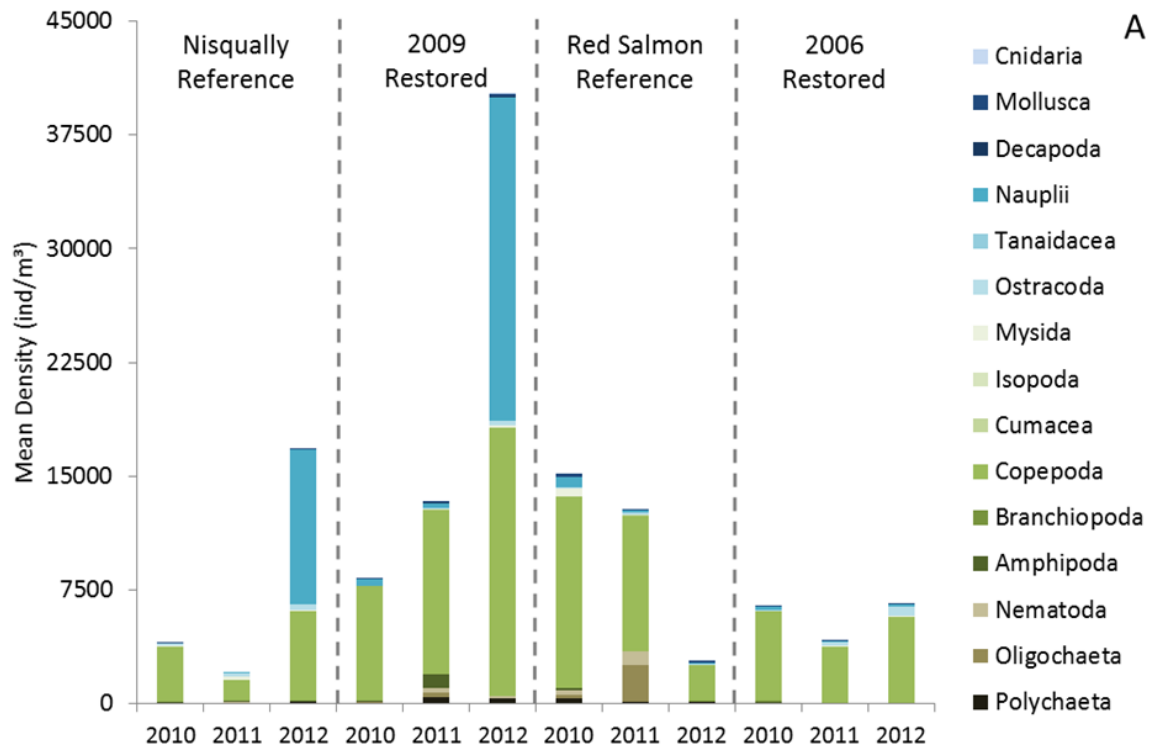


Figure 8. A) Planktonic and B) terrestrial drift invertebrate densities detected within aquatic samples by taxa at reference and restored sites from 2009-2012 (Woo et al., 2018).

- Aquatic neuston samples consisted of planktonic invertebrates (Figure 8a) and terrestrial drift (terrestrial derived insects and arachnids that fell into the water column, Figure 8b). Planktonic invertebrate species make up a good proportion of juvenile Chinook salmon diet at different life stages, with smaller size classes feeding on tiny crustaceans such as harpacticoid copepods, and larger size classes feeding on mysids (Pearce et al. 1982).
- Chum salmon tend to consume higher proportions of crustaceans as opposed to terrestrial invertebrates. Differences in juvenile salmon feeding strategies exemplify the need for a diverse prey community throughout the delta.

Realized Function: juvenile Chinook consumption and growth potential

- The realized function for juvenile Chinook following restoration is presented in two papers: Davis et al. (2018) and David et al. (2014). Results are highlighted below.

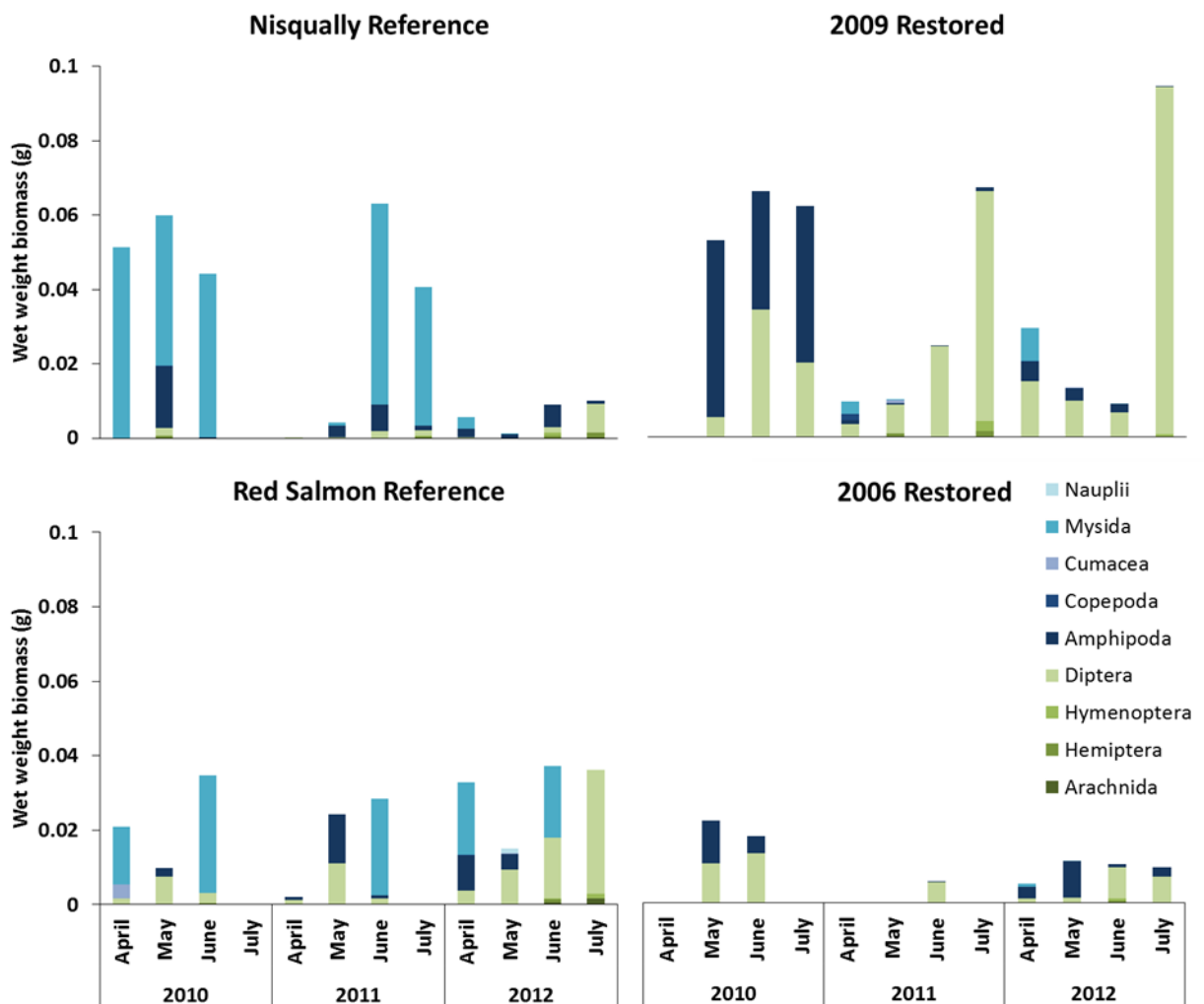


Figure 9. Invertebrate biomass by taxa at reference and restored sites from 2010-2012 (Davis et al., in review).

- Juvenile Chinook diet was comprised primarily of crustaceans such as amphipods, copepods, isopods, and mysids (Davis et al., 2018). Terrestrial invertebrates, including dipteran flies, fly larvae, and hymenopterans also contributed to gut biomass.
- At the forested site, terrestrial invertebrates were the dominant energy source, while at the transition, estuary, mudflat, and eelgrass sites, juvenile salmon preyed primarily on larger crustaceans such as amphipods and mysids (Davis et al., 2018). Foraging was most likely determined by the availability of distinct prey species in different habitat types, but size-specific preferences and gape limitations can also play a role (Brodeur 1991, Schabetsberger 2003).

Percent Similarity Index (PSI)

PSI between available invertebrate prey and actual consumed diet items, the relative importance of benthic, terrestrial, and aquatic invertebrates changed throughout juvenile Chinook seaward migration.

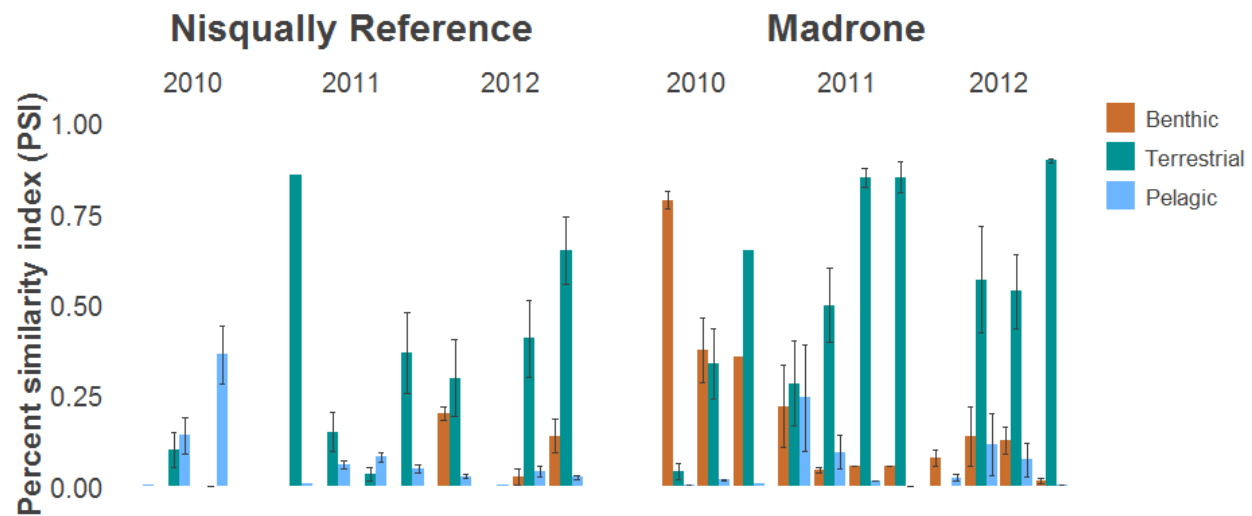


Figure 10. Mean seasonal differences in PSI between individual fish by reference and restored sites. Values averaged across 2010-2012; error bars represent ± 1 SE (Davis et al., 2018).

- The 2009 Restoration (Madrone) PSI illustrates shift in dietary similarity between 2010 and 2012 as a result of juvenile salmon switching their targeted prey from benthic to terrestrial invertebrates in the restoring marsh.

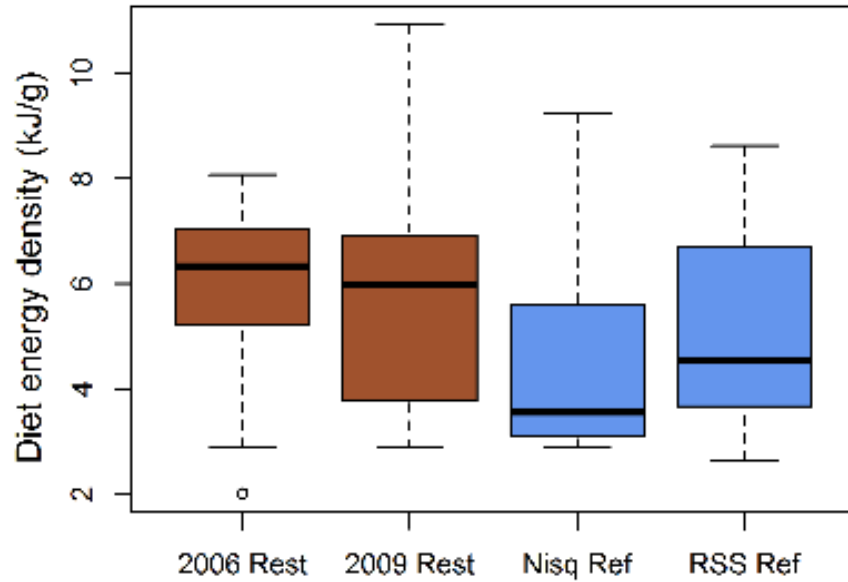


Figure 11. The energy density within juvenile salmon stomach contents between Restoration (2006 and 2009 Restored) and Reference sites (Nisqually and RSS Reference; David et al. 2014).

- The energy density found within juvenile Chinook diet samples found within restored sites were overall similar to that of reference sites.

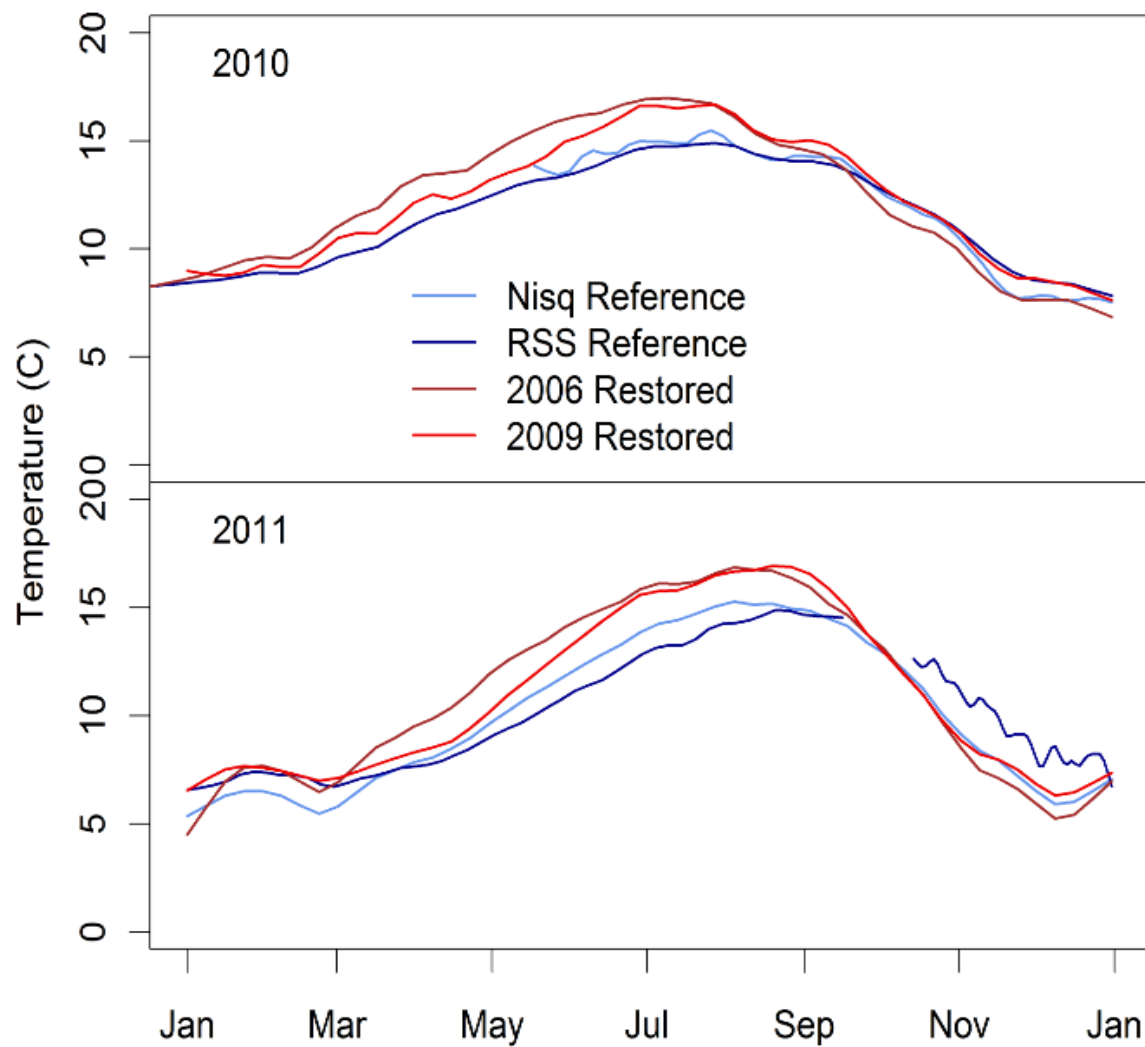


Figure 12. Water temperatures varied by Restored and Reference sites and month (David et al. 2014).

- Water temperatures over time for 2010 and 2011 show that restored sites were generally warmer than reference sites, which can negatively impact juvenile salmonids that rely on cold water temperatures.

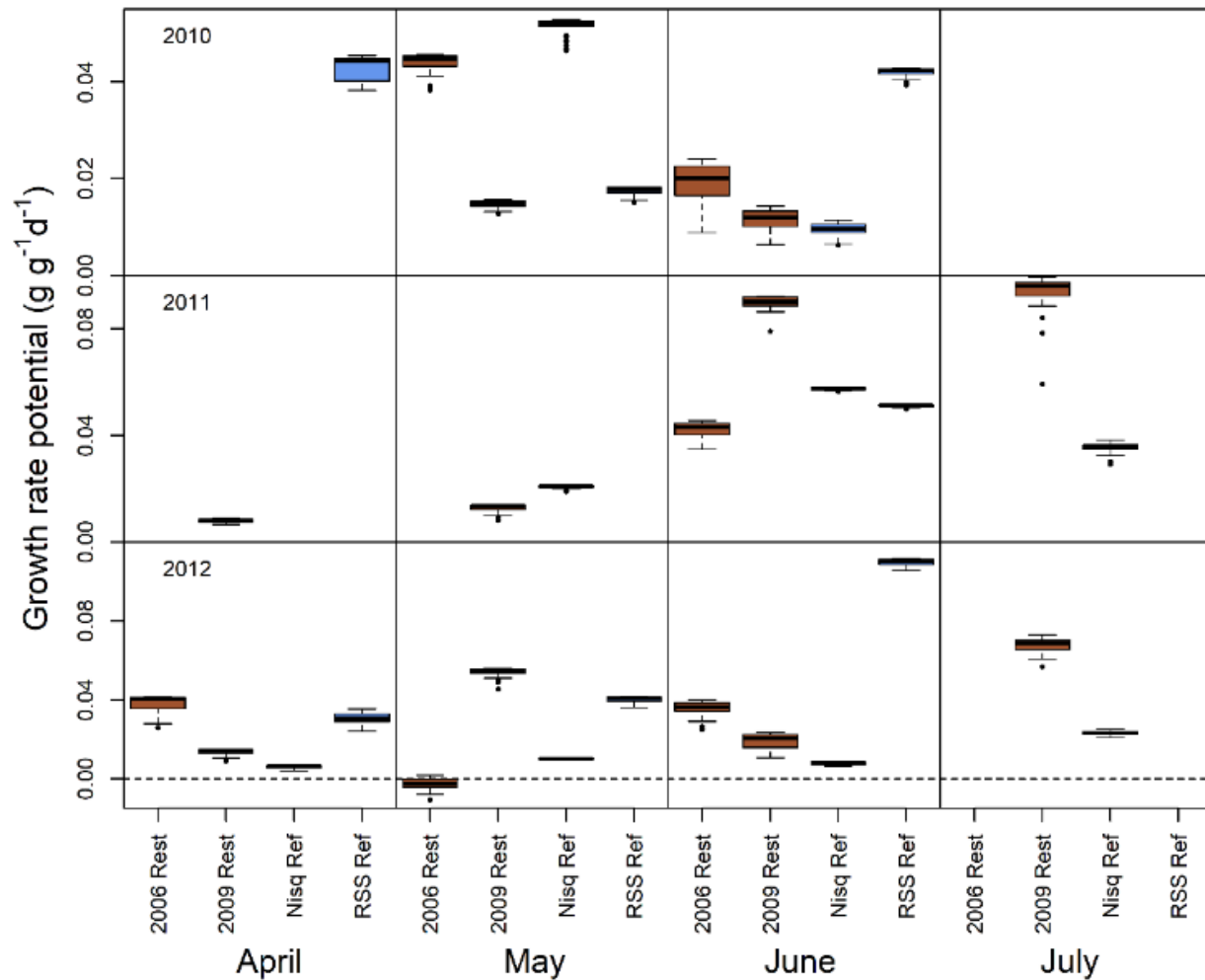


Figure 13. Modeled growth rate potential for juvenile Chinook salmon in 2010 (top), 2011 (middle), and 2012 (bottom) by month and site (David et al. 2014).

- The growth rate potential varied by month, year, and restoration status.
- The growth rate potential in the restoring sites were often equal to or greater than that of the comparable reference site, especially in June and July.

PHASE II:

ASSESSING THE CAPACITY OF THE NISQUALLY DELTA HABITAT MOSAIC

Since juvenile salmonids use the entire estuary during outmigration season, we broadened our research question from restoring and reference tidal marsh habitats to assess the relative contribution of invertebrates from all the major habitat types within the Nisqually River Delta: including Forested (dominated by riverine processes, mostly freshwater, edge of tidal influence); Transition (shrub-scrub habitat with trees that are shorter because of saline stress), Estuary Emergent Marsh (emergent tidal marsh), Delta Mud Flat (tidal flats with no emergent marsh), Eelgrass (eelgrass beds in the near shore environment; Figure 14). Below are highlights from the study with additional detail in the final report by Woo et al. (2016).

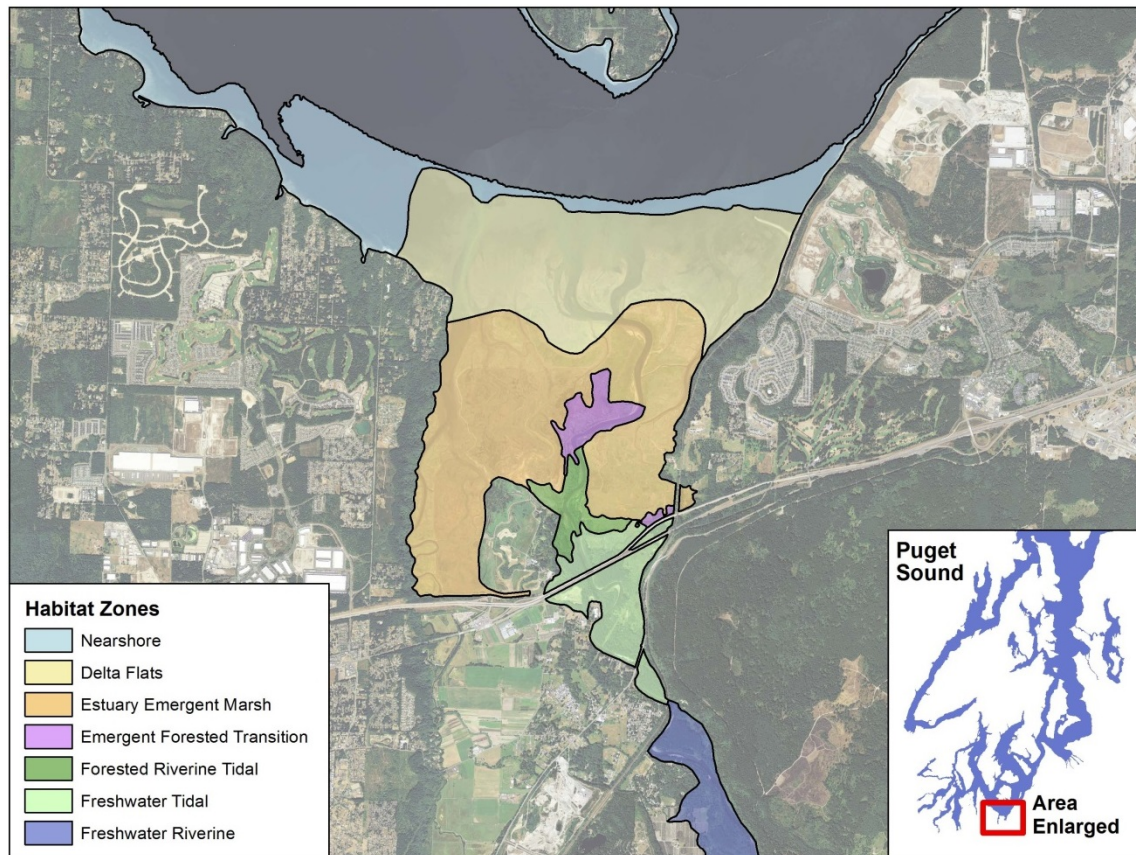


Figure 14. Post-restoration habitat zones on the Nisqually River Delta. USGS WERC sampling efforts focused on forested riverine tidal, emergent forested transition, estuary emergent marsh, delta mudflat, and nearshore habitat types along the Nisqually River Delta

We hypothesized that as juvenile Chinook were outmigrating through the habitat types within the Nisqually estuary, they were growing bigger and that the relative contribution of terrestrial, aquatic, and benthic invertebrates reflect the relative production of the invertebrates that are available in these habitat types (Figure 15). For instance in the Forested habitat type, we hypothesized that aquatic invertebrates would be most abundant and that terrestrial invertebrates would be dominant in the estuary emergent marsh, and in the mudflats benthic invertebrates would be dominant, and that epifauna would be most abundant in eelgrass habitat.

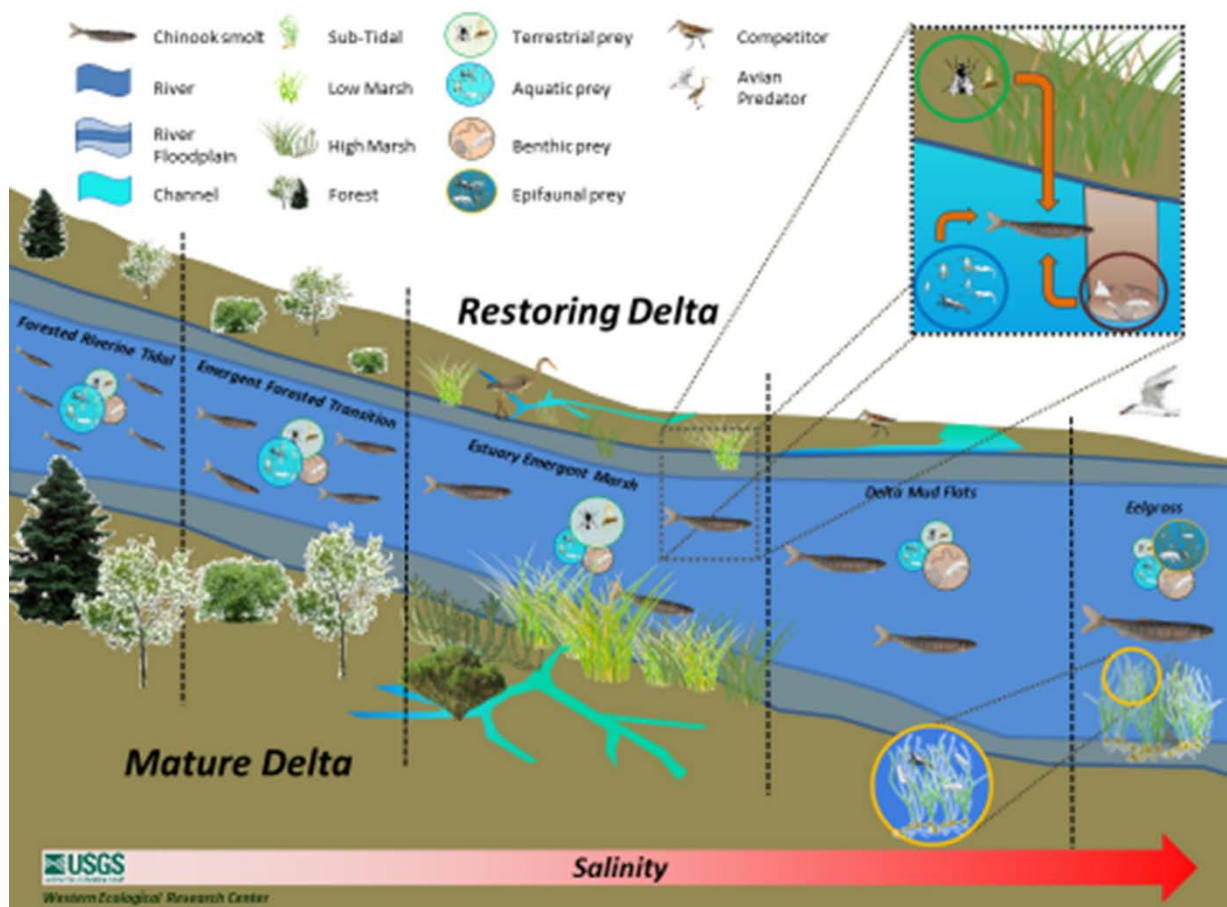


Figure 15. Conceptual model of juvenile Chinook salmon foraging on available terrestrial, aquatic, benthic, and epibenthic invertebrates as they migrate through forested riverine tidal, emergent forested transition, estuary emergent marsh, delta mudflat, and nearshore habitat types along the Nisqually River Delta.

Methods: Delta Habitat Mosaic

Hydrology

Data loggers (Solinst® or Odyssey®) that measured temperature, conductivity, and water level were installed at the forested riverine, forested transition, and emergent estuary marsh habitat types. This included one existing Solinst logger that was installed at Animal Slough (our estuary emergent marsh site; Figure 16) on June 21, 2010. Additionally, we installed two Odyssey data loggers in February 2014 to measure water quality at our transition and forested sites. Early in the 2014 field season, coarse woody debris destroyed the data logger at the transition site. This logger was subsequently replaced in October 2014 at a different location protected from continual flooding and debris. We did not install data loggers at our mudflat or eelgrass sites, but a Solinst logger installed at the mouth of Six Gill slough in April 2010 allowed us to produce a tidal datum for conditions on the NRD during the 2014 and 2015 outmigration seasons.

We used barometrically-compensated water level data from data loggers within the Estuary and Transition habitat types (Figure 16) to produce a tidal datum for 2014 and 2015 conditions on the NRD. This included elevations at mean low low water (MLLW), mean low water (MLW), mean tidal level (MTL), mean high water (MHW), and mean high high water (MHHW). We also used water level data and a local 2011 DEM to calculate the amount of time habitat was available for juvenile salmon foraging during the outmigration season at the estuary, mudflat, and eelgrass sites. Accessibility was more difficult to assess at the forested and transition sites due to high seasonal variation in freshwater input from the Nisqually River. The Odyssey loggers installed at forested and transition sites measured temperature and salinity only, and did not account for variation in water level through time. To approximate accessibility at the riverine sites, we incorporated water level data from a Solinst LT logger installed up river at the I-5 bridge from July 2009 through October 2014. Although these data did not provide exact water level elevation values at the forested and transition sites, they did provide information as to when freshwater flows were higher than average during the 2014 outmigration season.

Invertebrates

Invertebrate sampling was conducted twice a month and was coordinated with the timing of the Tribe's beach seining schedule. Sampling for the 2014 and 2015 field seasons began during the first week of March and ended in the third week of July, for a total of ten sampling periods each year (Table 2). We collected aquatic and benthic samples at all five habitat types (forested riverine tidal, emergent forested transition, estuary emergent marsh, delta mudflat, and eelgrass; Figure 14, 16). Additionally, we collected terrestrial invertebrate samples at three sites (forested, transition, and marsh), and epifaunal invertebrate samples at our eelgrass site.

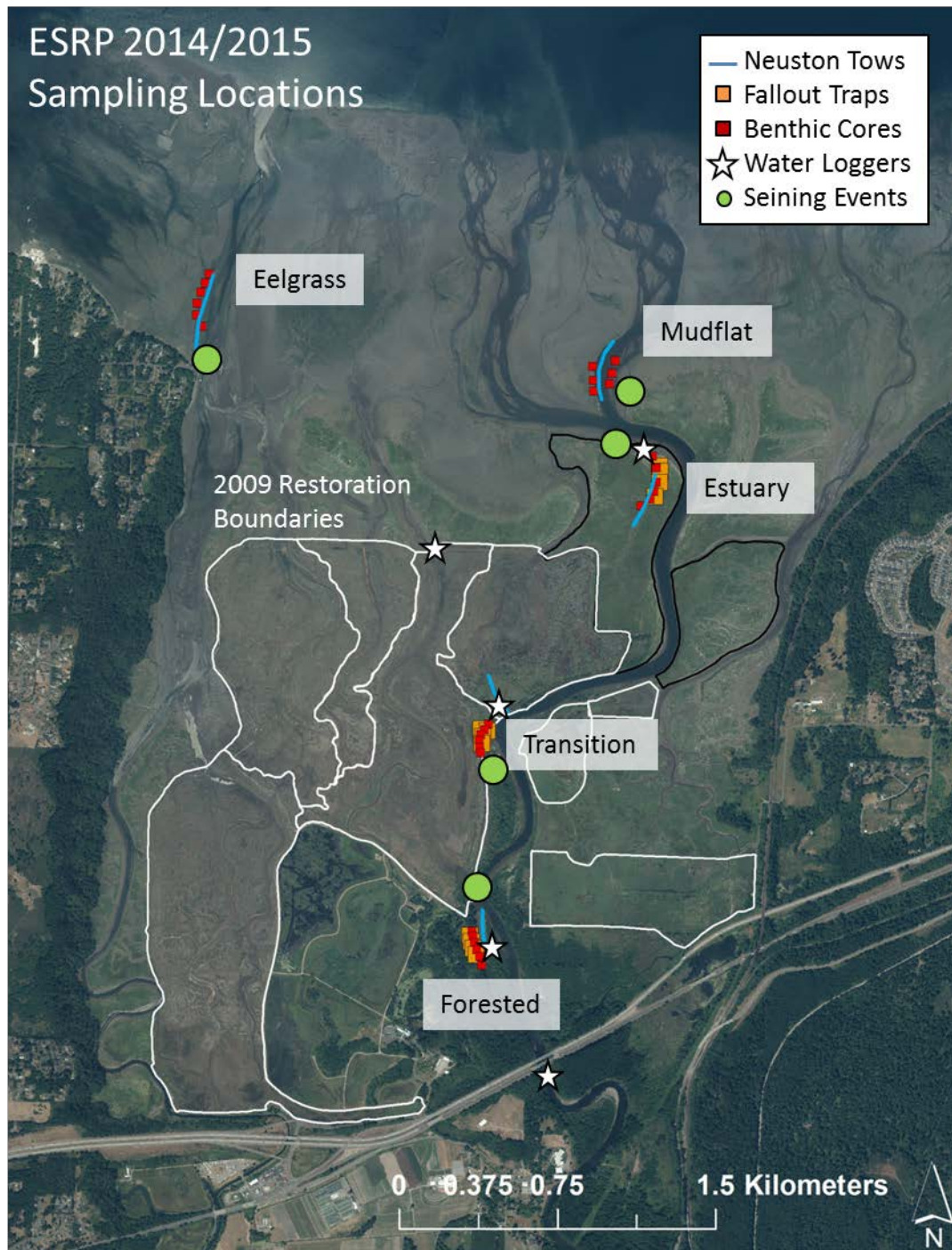


Figure 16. Sampling map for biophysical variables, invertebrates (benthic cores, fallout traps, neuston tows), and fish (beach seining) for 2014 and 2015 sample years.

Table 2. Invertebrate sampling events at all sites for the 2014 and 2015 salmon outmigration seasons.

		Sampling Period										TOTAL
		1	2	3	4	5	6	7	8	9	10	
	Sampling Type	March A	March B	April A	April B	May A	May B	June A	June B	July A	July B	
Forested Riverine	Benthic Core	6	6	6	6	6	6	6	6	6	6	60
	Fallout Trap	4	4	4	4	4	4	4	4	4	4	40
	Neuston Tow	2	2	2	2	2	2	2	2	2	2	20
	Epifaunal											
Forested Transition	Benthic Core	6	6	6	6	6	6	6	6	6	6	60
	Fallout Trap	4	4	4	4	4	4	4	4	4	4	40
	Neuston Tow	2	2	2	2	2	2	2	2	2	2	20
	Epifaunal											
Emergent Estuary Marsh	Benthic Core	6	6	6	6	6	6	6	6	6	6	60
	Fallout Trap	4	4	4	4	4	4	4	4	4	4	40
	Neuston Tow	2	2	2	2	2	2	2	2	2	2	20
	Epifaunal											
Delta Mudflat	Benthic Core	6	6	6	6	6	6	6	6	6	6	60
	Fallout Trap											
	Neuston Tow	2	2	2	2	2	2	2	2	2	2	20
	Epifaunal											
Eelgrass Beds (McAllister, Cormorant, Hogum, Red Salmon)	Benthic Core	6	6	6	6	24	24	24	24	24	24	168
	Fallout Trap											
	Neuston Tow	2	2	2	2	8	8	8	8	8	8	56
	Epifaunal	10	10	10	10	40	40	40	40	40	40	280
	TOTAL 2015	62	62	62	62	116	116	116	116	116	116	944
	TOTAL 2014/2015	124	124	124	124	232	232	232	232	232	232	1888

*Three additional eelgrass sites (Cormorant, Hogum, and Red Salmon Slough) were added in May to accompany fish sampling by WFRF.

*Sampling at McAllister, Cormorant, Hogum, and Red Salmon Slough continued through September 2014 and 2015.

Benthic

We collected six 2.5 cm x 10 cm benthic core samples per habitat type, along with accompanying water quality data (temperature, DO, conductivity, and salinity). Cores were spaced roughly 50 m apart and occurred at the same location during each sampling period. We used a 2.5 cm benthic coring device to collect samples, and each core was split into a 5 cm top section and a 5 cm bottom section in stored in a 1-qt Ziploc® bag for later processing. To prepare benthic samples for identification and enumeration, each core was sieved using the elutriation method within one week of collection. Sample bags were carefully rinsed into clean 19-liter (5-gallon) buckets and gently sprayed to break apart the cores. The water and mud were then poured through a 500-micron sieve and all collected debris was preserved in a 70% ethanol/rose bengal solution. Samples were sorted at the Nisqually field station, and were identified, enumerated, and weighed for biomass using stereo-dissection microscopes at the USGS SFBE field station.

Terrestrial

We set up four fall-out traps at the forested, transition, and marsh sites. We constructed fall-out traps using 55 cm x 38 cm Tupperware® bins and Styrofoam blocks for floatation. Each trap was attached to a set of four metal poles pounded into the ground along the surface of the channel. Wire loops around the poles allowed the traps to move up and down with the tide without tipping

or overflowing. During each sampling period, traps were filled with roughly two gallons of soapy water and left to sit for 46-50 hours. To collect the invertebrates for processing, each trap was removed from the metal poles and poured through a 150-micron sieve. Invertebrates and debris were then gently rinsed or tweezed out of the sieve and preserved in a 200 ml jar of 95% ethanol. All fall-out trap samples were shipped to the USGS SFBE field station for identification, enumeration, and biomass.

To monitor adjacent vegetation, we used a 0.5 m x 0.5 m quadrat. We performed vegetation surveys at each fall-out trap on a bi-monthly basis, making sure to sample from the same side (N, S, E, W) each time. For each quadrat, we reported percent vegetation, water depth, percent canopy, the approximate percentage cover for each species, the stem density of each species, and the maximum height of each species. We also collected groundwater salinity data by digging a 15-cm hole proximal to the fall-out trap and measuring the salinity via YSI or with a salt refractometer (Sper Scientific).

Aquatic

We collected near surface aquatic invertebrate samples at each habitat type by towing a 1.5-meter-long, 150-micron neuston net attached to an extending pole. Neuston tows were performed for 3 minutes at the surface of the water and for 6 minutes at up to a meter below the surface. A flow meter (General Oceanics Inc.) was attached to the mouth of the net with rubber straps and zip ties to monitor the volume of water entering the net during each tow. We performed sample processing on-site by rinsing the contents of the collection cup with 95% ethanol into a 200 ml jar. We then shipped all preserved samples to the USGS SFBE field station for identification, enumeration, and biomass.

Epifaunal

We collected ten eelgrass blades per sampling period at our Eelgrass habitat site (Figure 16). We plucked individual plants at the root by hand and then placed each sample in its own 200 ml jar of ocean water. Within two days of collection, we carefully washed the samples through a 500-micron sieve, and all debris and invertebrates were transferred to a 200 ml jar of 95% ethanol for later identification and enumeration. To calculate biomass, we measured each blade and recorded the number of nodes for each sample. We then dried each eelgrass plant on a paper plate to obtain dry weight.

Fish sampling

The tribe conducted beach sein sampling and collected gut samples from 72 juvenile Chinook from the 2014 field season and 68 juvenile Chinook from the 2015 field season. In 2015, juvenile Chinook were captured in the transition, estuary, and mudflat sites only, so we were unable to conduct a percent similarity index (PSI) at the forested or eelgrass sites. Samples were stored on

ethanol at USGS SFBE field station and Nisqually Tribe Department of Natural Resources. Samples were identified to the same taxonomic level as invertebrate samples from the field.

Stable isotope analysis

In summer 2015, we conducted a full suite of stable isotope sampling at all 5 ESRP study sites (as part of a separately-funded USGS study led by Woo et al.), including particulate organic matter, primary producers, invertebrates, and juvenile salmon. We collected 988 samples across 5 habitat types (295 primary producers, 620 invertebrate prey, 89 juvenile Chinook). Plant samples were also processed (cleaned, dried, and weighed), invertebrate samples were prepped (gently washed, pooled to obtain sufficient biomass, and kept frozen), and fish muscle tissue were processed (fileted and kept frozen) and then sent to the Northern Arizona University Colorado Plateau Stable Isotope Laboratory for CNS isotope analysis. Partial support for isotopic analyses was provided by the USGS-FWS partnership for the Nisqually Carbon project.

Results and Discussion: Delta Habitat Mosaic

Our study sites associated with the five main habitat types (Forested, Transition, Estuary, Delta, and Eelgrass) were directly connected to the main stem or mouth of the Nisqually River or McAllister Creek, meaning that salmonid accessibility was primarily limited by inundation frequency. Here we focused on assessing the *Capacity* (invertebrate production) and *Realized Function* (isotopes, Percent Similarity Index, and ultimately bioenergetics) of the connected and integrated landscape mosaic. Below are general summary analyses from the final report (Woo et al. 2016). Additional analyses are underway and planned for a more complete synthesis of these large datasets for joint USGS-Tribe-USFWS publications (authors' unpublished data).

Hydrology

- Inundation duration was directly related to the elevation of each sampling site. The Eelgrass site (near the mouth of McAllister Creek) was accessible to juvenile Chinook 86% of the time, the Delta mudflat site was available 80% of the time, and the Estuary site was available 68% of the time. Both the Forested and Transition sites along the Nisqually River were probably available more than 90% of the time as a direct result of riverine freshwater influence; however, these sites were also more affected by flooding and drought conditions. Drought conditions and record low freshwater flow from the Nisqually River led to pulses in salinity that reached the forested site.
- Mean temperatures varied over time and habitat type, with temperatures exceeding 18°C value for potential impairment for juvenile salmonids (Newman and Rice 1997, Moyle and Cech 2000) in late summer months (July and August) in 2014 (Figure 17). 2015 represented an anomalous year of record temperatures, where the 18°C threshold was reached in June, July, and August.

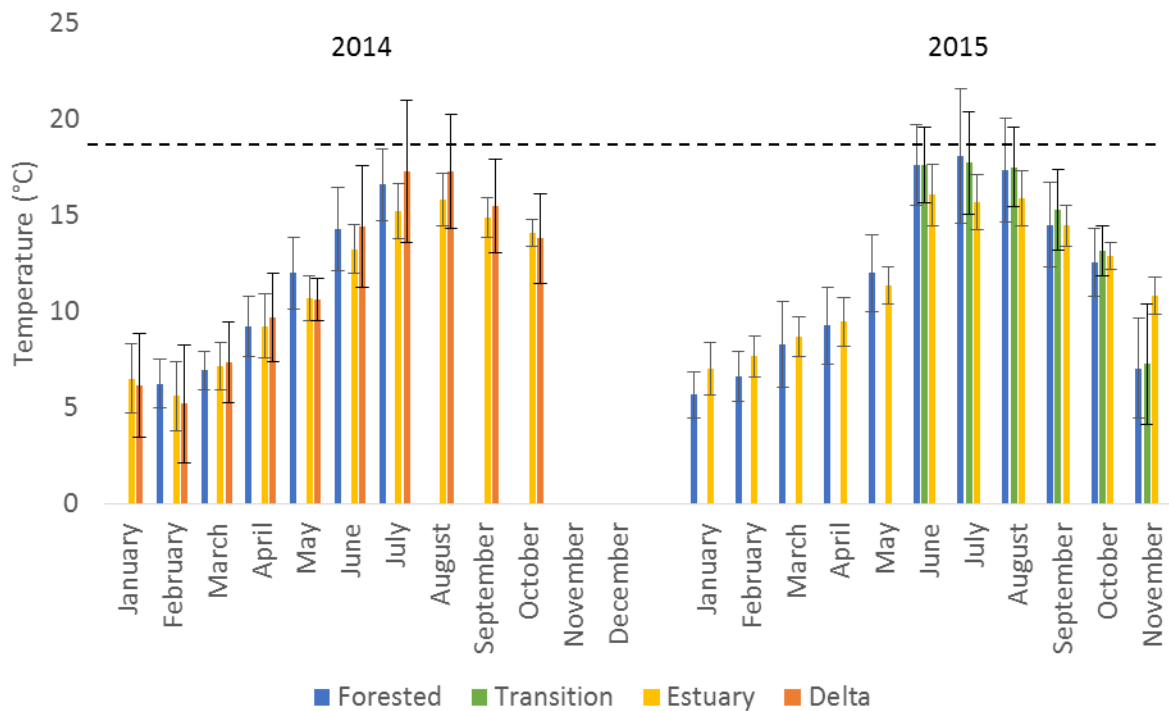


Figure 17. Mean $\pm$ SD temperature values for forested, transition, estuary emergent marsh, and delta sites during the 2014 and 2015 field seasons. The black dashed line represents the temperature above which juvenile salmon growth potential is potentially impaired (18°C; Newman and Rice 1997, Moyle and Cech 2000).

Invertebrates: Delta Habitat Mosaic

Habitats along the juvenile salmon outmigration gradient represented a broad diversity of benthic, terrestrial, and aquatic invertebrate taxa, including non-target prey and target potential prey items (Figure 18-20). General patterns of invertebrate prey densities varied by month, habitat type, and invertebrate strata (benthic, terrestrial, aquatic, and epifaunal), providing clear benefits to foraging salmonids.

Benthic Invertebrates

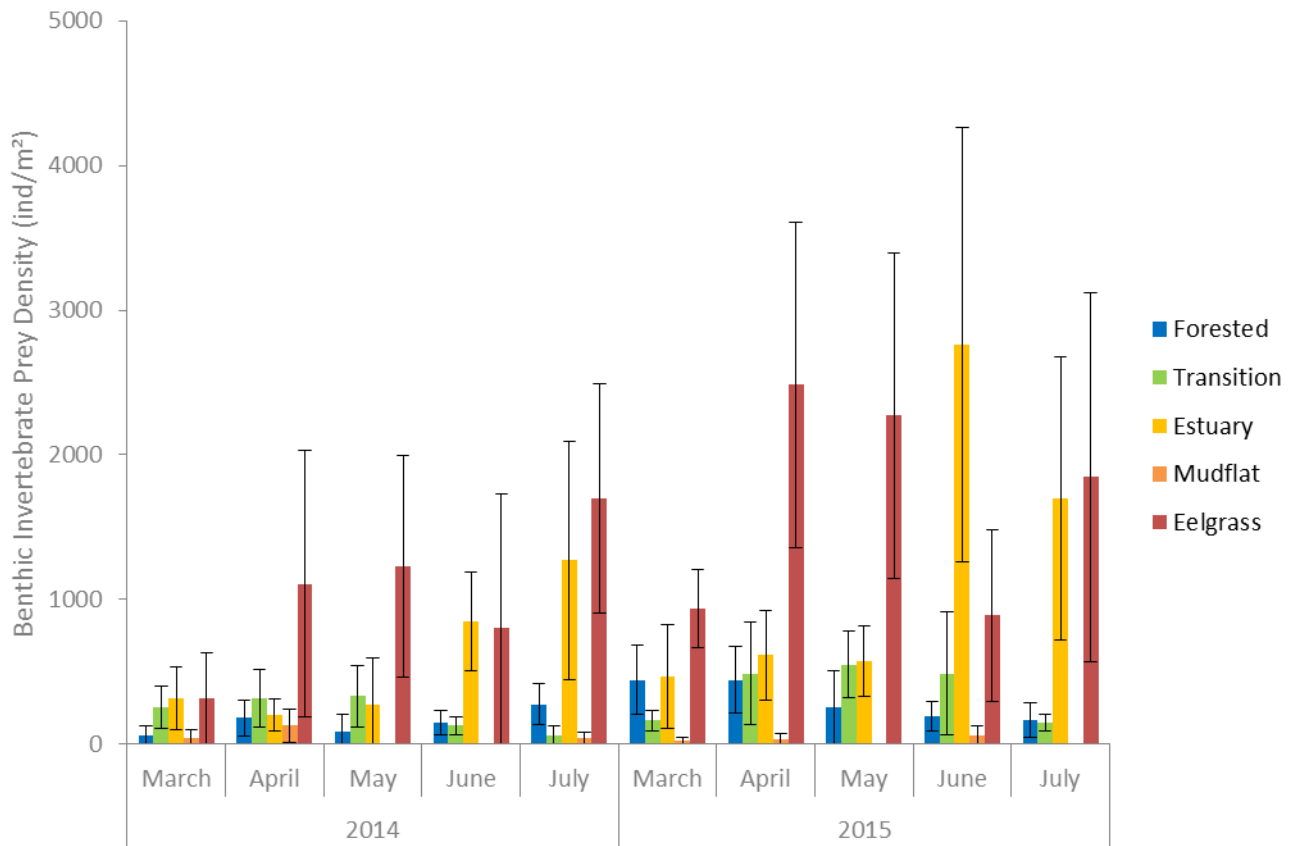


Figure 18. Total benthic invertebrate prey densities by month and site. Error bars represent ± 1 S.D. From Woo et al. 2016.

- Benthic invertebrate densities were markedly higher in some habitats than others, but this did not necessarily translate to a greater abundance of prey species. For instance, at the transition site, benthic invertebrates were fairly abundant, but most of the community was comprised of gastropods, that are not typical prey items. Estuarine habitat had the greatest overall densities of benthic invertebrates, but most of the species represented were polychaete and nematode worms, which are also considered non-target prey species (Woo et al. 2016). While non-target species such as polychaetes, nematodes, gastropods, and bivalves are incidentally consumed by juvenile Chinook salmon, they do not comprise a large proportion of their diet at the Nisqually River Delta (Pearce et al. 1982, authors unpublished data).
- Common benthic invertebrate prey species for juvenile Chinook were greatest in estuarine and eelgrass habitat, with overall increases in availability observed later in the spring and summer at all sites.
- Peak amphipod densities were observed during May, June, and July. Tanaids were observed almost exclusively in eelgrass habitat, and were present more frequently in

April and May. Conversely, dipteran larvae were found more often in tidally-influenced forested and transition habitats, earlier in the outmigration season (Woo et al. 2016).

- Eelgrass habitat comprised the greatest densities of target invertebrate prey and Estuary habitat also produced relatively high invertebrate densities particularly in the months of June and July (Figure 18). This is consistent with other studies, which have also shown that eelgrass beds support denser and more complex invertebrate communities than adjacent, unvegetated habitat (Bostrom and Bonsdorff 2000, Hosack et al. 2006).

Terrestrial Invertebrates

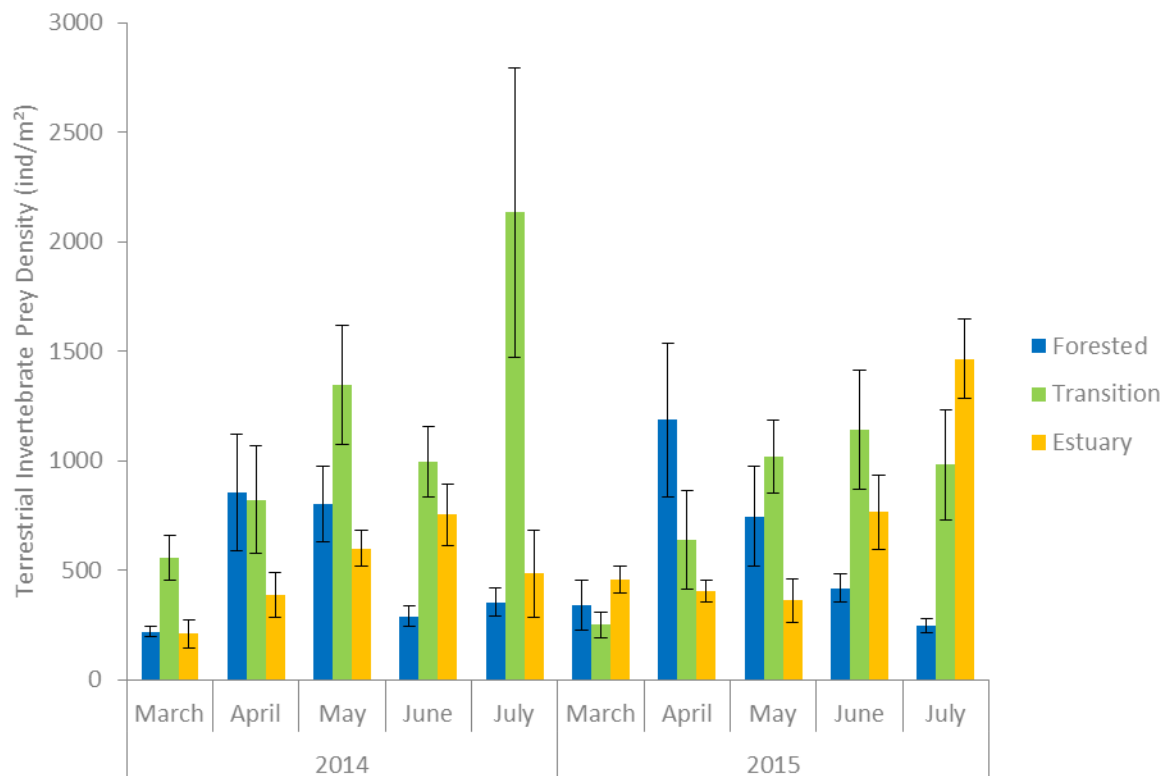


Figure 19. Total terrestrial invertebrate prey densities by month and site. Error bars represent ± 1 S.D. From Woo et al. 2016.

- Terrestrial invertebrate communities at all three sites sampled (forested, transition, estuary) consisted primarily of arachnid (e.g., spiders), dipteran, and hymenopteran species (e.g. wasps, bees, and ants) with significant inputs from insect larvae and collembolan (i.e., springtails; Figure 19, Woo et al. 2016).
- The greatest densities of terrestrial invertebrates (particularly collembola and hemipteran species) were observed in transition habitat (Figure 19).
- Terrestrial prey densities were positively correlated with vegetative cover at the forested, transition, and estuary sites, again highlighting the importance of overhanging vegetation for surface-gleaning smolts.

- At the transition marsh site, we captured twice as many invertebrates than at the forested or estuary sites (Figure 19). The transition site is comprised of tall, overhanging plant species such as Lyngbye's sedge, reed canarygrass, and rushes that provide habitat structure for terrestrial insects and arachnids. The estuary emergent marsh is dominated by low marsh plant species such as pickleweed and saltgrass and it contained more dipteran fly species compared to other insects or arachnids.

Aquatic Invertebrates

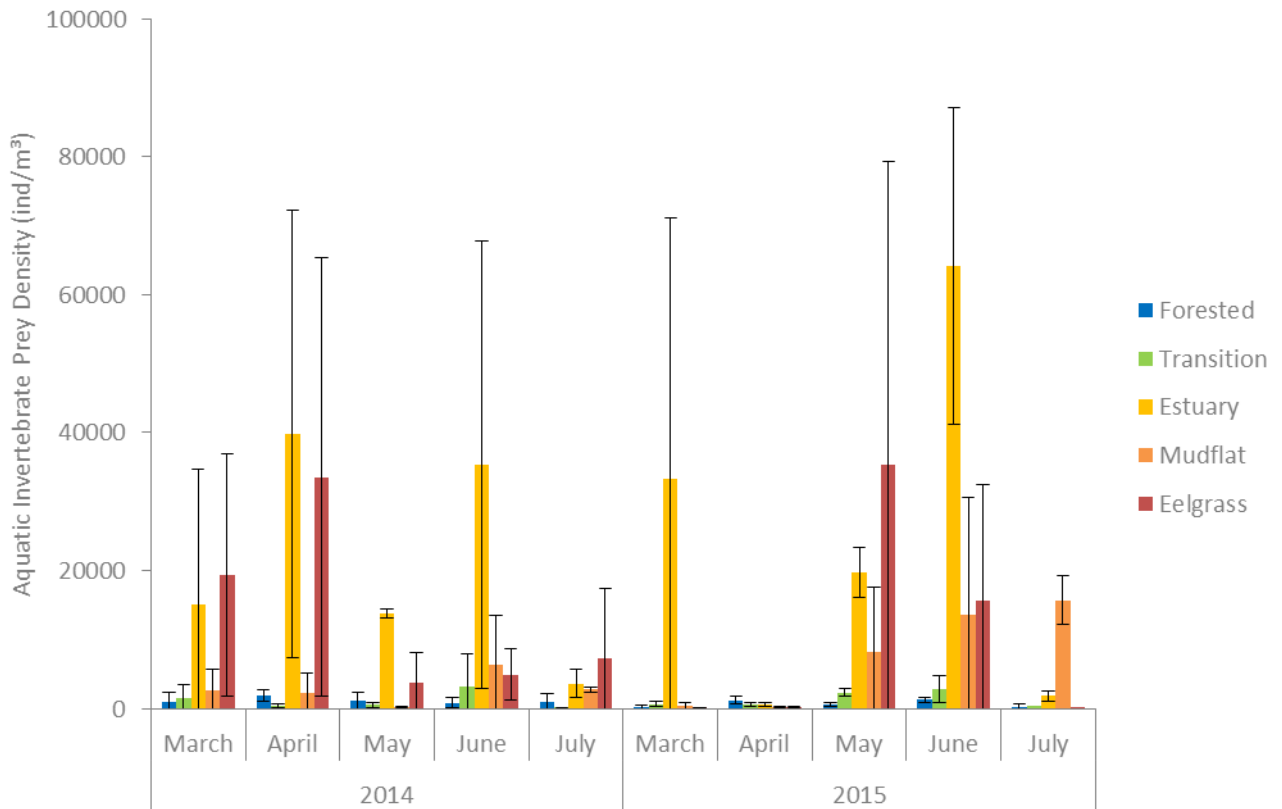


Figure 20. Total aquatic (plankton and drift) invertebrate prey densities by month and site. Error bars represent ± 1 S.D. From Woo et al. 2016.

- Planktonic invertebrates varied by habitat type (Figure 20). In all five habitat types, copepods (Calanoida and Harpacticoida) made up a majority of observed plankton species. Ostracods were also prevalent at the forested site, and pulses of Cirripedia nauplii (barnacle larva) dominated samples in spring 2014 at the mudflat and eelgrass sites (Woo et al. 2016).
- Target aquatic prey species were most plentiful at the estuary and eelgrass sites (Figure 20). Amphipod abundances were greatest at the estuary emergent marsh site. Calanoid and harpacticoid copepods made up the greatest proportion of aquatic samples at all sites.

These copepods were most commonly detected at the estuary emergent marsh and eelgrass sites during May and June.

- Mysids, which contributed a large proportion of total prey biomass, were most prevalent at the estuary, mudflat, and eelgrass sites. Both cumaceans and tanaids were found almost exclusively at the eelgrass site.
- The contribution of terrestrial drift invertebrates were relatively small (<10%) at estuary, mudflat, and eelgrass sites, whereas drift invertebrates contributed substantially to total invertebrate densities at the forested and transition sites.
- The abundance of drift invertebrates seemed related to vegetation structure. Drift was less common at the estuary site, which was dominated by shorter low marsh species like pickleweed, and at the mudflat and eelgrass sites, where the terrestrial marsh was further away. While the forested site had a tall dense canopy cover and the transition site also had tall adjacent overhanging vegetation like Lyngbye's sedge.

Epifaunal invertebrates

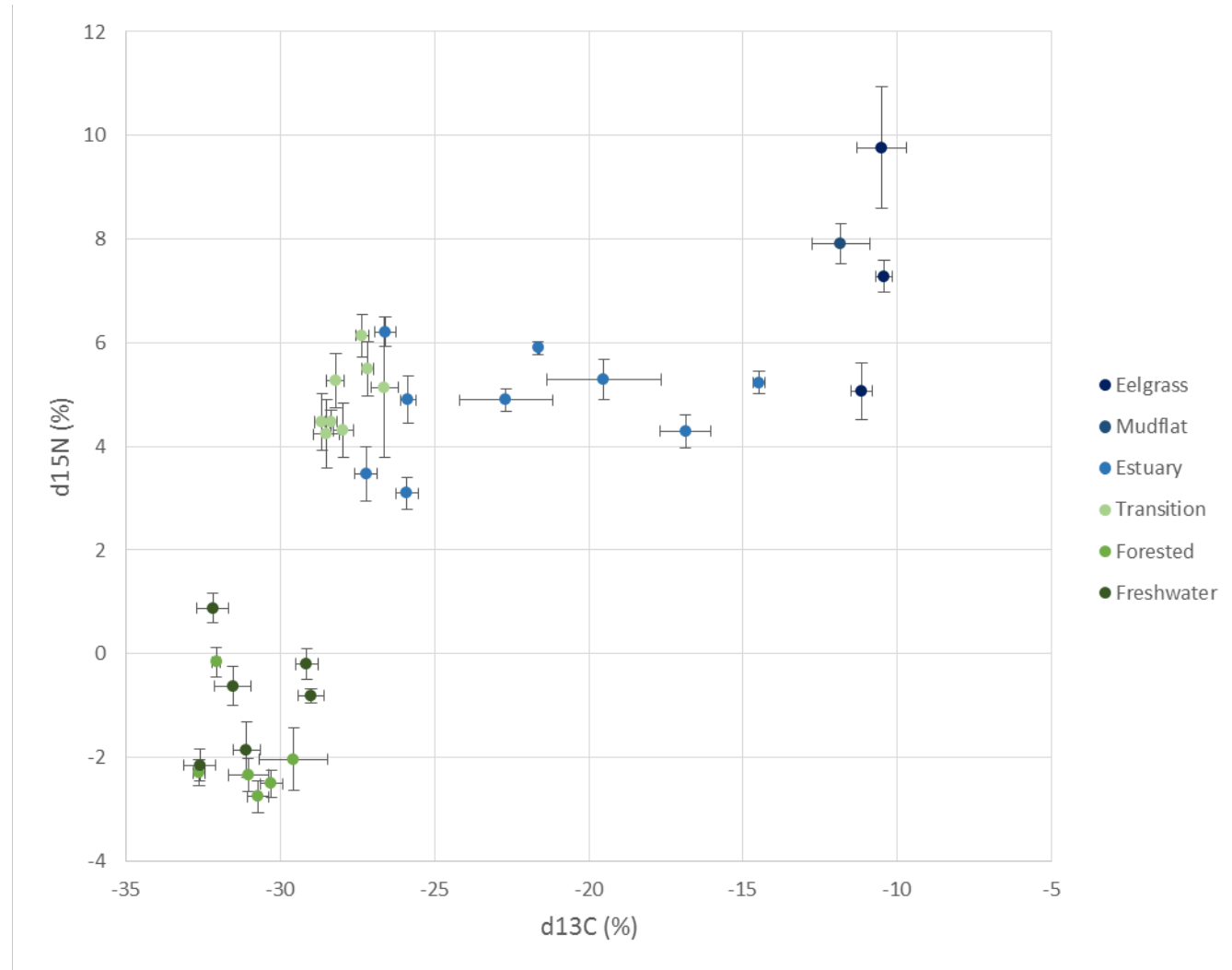
- The epifaunal invertebrate community at the McAllister Creek eelgrass bed site was characterized by high densities of crustaceans, with a significant contribution from polychaete and nematode worms (Woo et al. 2016). Overall abundances increased fairly steadily throughout the outmigration season, with peak abundances occurring in July. Polychaete worms appeared later in the sampling season, while crustaceans such as amphipods and copepods were fairly prevalent throughout the spring and summer months. In terms of overall prey densities, epifaunal prey peaked during late spring/early summer in both 2014 and 2015.

Biomass

- Overall prey biomass differed between 2014 and 2015. Higher temperatures in summer 2015 may have promoted greater invertebrate productivity at the estuary, mudflat, and eelgrass sites (Tumbiolo and Downing 1994), despite being potentially detrimental to the physiological functioning of fry and smolts (David et al. 2014).
- Total prey biomass was highest at the estuary, delta, and eelgrass sites, primarily in June and July with wide differences between 2014 and 2015 (Woo et al. 2016). In 2014, the mudflat and eelgrass sites contributed the greatest amount of prey biomass in all months, while in 2015, the estuary site also contributed substantial amounts of prey biomass. The forested site consistently had the lowest biomass estimates throughout the year.
- Trends in invertebrate prey biomass availability were driven primarily by large species such as mysids, which made up 40 - 80% of total prey biomass estimates, but <12% of all observed aquatic invertebrates in terms of density (Woo et al. 2016).

Realized Function: Delta Habitat Mosaic

Stable isotope analysis



Percent Similarity Index (PSI)

PSI between available invertebrate prey and actual consumed diet items, the relative importance of benthic, terrestrial, and aquatic invertebrates changed throughout juvenile Chinook seaward migration.

- Juvenile Chinook diet varied between sites, with more terrestrial invertebrate prey species consumed at the forested site, and more large crustaceans consumed in the transition, estuary, delta, and eelgrass sites (Woo et al. 2016, authors' unpublished data). Percent similarity between available prey and those found in diet samples were lowest at the estuary and transition sites, suggesting that juvenile Chinook were not necessarily consuming the most abundant prey species in the estuary and nearshore habitats (Davis et al. in review).
- At the forested and transition sites, gut samples were most similar to benthic invertebrate communities (Woo et al. 2016, authors' unpublished data). At the estuary site, gut contents were more similar to terrestrial invertebrates, such as dipteran flies and hymenopterans. PSI values were lowest at the mudflat site, where energetically-rich mysids dominated. Finally, at the eelgrass site, aquatic invertebrates in the eelgrass bed were most similar to those found in Chinook guts, although the sample size at this site was relatively small.
- Although invertebrate abundances varied by site, juvenile Chinook gut energetic content did not differ between sites, indicating that juvenile Chinook were effectively foraging in and benefitting from prey resources throughout the entire habitat mosaic (Woo et al. 2016, authors' unpublished data).
- Hatchery-origin juvenile Chinook showed strong stable isotope signatures associated with hatchery food, which declined for individuals that were caught further out on the delta (Woo et al. 2016, authors' unpublished data).
- Natural-origin Chinook had more varied dietary sources and included greater proportions of freshwater and estuarine terrestrial invertebrates than hatchery-origin Chinook. This indicates a greater use of upstream food sources derived from riparian habitat. Natural-origin Chinook have been shown to have several life history strategies, and may therefore have a greater tendency to move freely between estuarine and nearshore habitat dependent upon tide, temperature, and prey availability (Bottom et al. 2005b).
- Hatchery-origin juveniles derive a small amount of energy from freshwater habitat after release, suggesting the greatest amounts of potential competition occur when foraging for aquatic prey in estuarine and delta habitats.

Conclusions and Future Research

Understanding the interaction between habitat capacity, density dependence, and salmon distribution across a connectivity gradient is a priority for salmonid stock management and habitat restoration activities. Our analyses thus far indicate that access through the historic

distributaries would improve connectivity and likely help maintain several of the metrics examined here, including channel depth, temperature, and salinity. We also show that restoration can lead to invertebrate prey densities similar to that of reference sites within two years following restoration (Woo et al, 2018), and that juvenile Chinook are able to take advantage of increased prey availability (Davis et al., in review). In regards to early phase restoration sites, a bioenergetic growth potential model illustrates the tradeoff of young restoration site that was not well-vegetated producing abundant invertebrate prey resources, but also yielding high temperatures that may limit the realized benefit of newly accessible and productive habitat (David et al. 2014).

Within the landscape habitat mosaic, total invertebrate abundance and biomass varied by habitat type and environmental strata (terrestrial, aquatic, and benthic strata). Initial isotopic analyses indicate that natural-origin juvenile Chinook foraged indiscriminately between the entire habitat mosaic from freshwater to eelgrass, while hatchery-origin juvenile Chinook tended to bypass the freshwater and transition zones. Analyses that integrate diet, isotope, and prey availability datasets by habitat are underway to synthesize the relative contribution of each habitat type for the overall condition of the Nisqually River Delta. Future analyses will incorporate habitat-specific contribution for bioenergetics growth models (Davis et al., in prep). We anticipate that these results will provide science-based tools for management issues (i.e., density dependency effects for hatchery and natural-origin fish or habitat enhancements for increased connectivity or habitat size). For instance, the transition zone has high capacity for invertebrate production and fish access yet has a relatively small footprint on the landscape. Habitat enhancements to create a more balanced habitat mosaic can help optimize habitat use for both natural-origin and hatchery juvenile Chinook.

As the 2009 restoration progresses, we expect that the amount of estuary emergent marsh and the quality of restored tidal channels will approach that of the previously-unaltered reference channels, particularly at higher elevation sites. Targeted monitoring efforts incorporating post-restoration biophysical data and climate change forecasting will aid in optimizing the estuarine and nearshore landscape for outmigrating salmonids.

Future directions also include:

- Bioenergetics integrating habitat types (Davis et al. dissertation in prep)
- Completing analyses and writeup on longterm waterbird trends (Woo et al., in prep)
- Assessing the multispecies benefit of estuarine restoration: integrating fish and waterbirds
- Optimizing sampling design to balance the need to address management questions and priorities with funding constraints. Identifying key model variables and data needs to inform monitoring efforts.
- Integrate foodwebs with ecosystem services (i.e., carbon sequestration, Nisqually Carbon project, Woo et al. 2016b)

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