

Juvenile Chinook salmon response to dike setback restoration at Fir Island Farms in the Skagit River tidal delta, 2015 - 2018

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Fir Island Farms Restoration Project 4 days after tidal hydrology was restored.
Photo from <https://fortress.wa.gov/ecy/shorephotoviewer/Map/ShorelinePhotoViewer>



First day of beach seining Fir Island Farms after restoration (February 23, 2017).
Photo by Bob Friel/Seahawk Creative

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Abstract

Located within the Skagit River tidal delta, the Fir Island Farms Restoration project restored approximately 53 hectares (131 acres) of tidal marsh and tidal channels. We monitored habitat conditions and fish use of the restored area and reference sites during the juvenile Chinook salmon outmigration period for two years pre- (2015 and 2016) and post-restoration (2017 and 2018).

Prior to the dike setback, the existing gravity operated tide gate was expected to prevent fish and salt water from entering pre-existing channels ‘inside’ of Fir Island Farms. However, we observed the tide gate leaking and measured water surface elevation fluctuations synchronous with daily tidal cycles suggesting Fir Island Farms ‘inside’ habitat areas before restoration were subject to some tidal influence and potential passage of estuarine fish species into ‘inside’ areas of Fir Island Farms prior to restoration.

Over the four years of beach seine sampling, we caught over 80,000 fish comprised of 21 different species. Juvenile Chinook were caught upstream of the tide gate in 2015 and 2016 before restoration occurred confirming that the leaking tide gate did allow upstream fish passage. After restoration, in 2017 and 2018, juvenile salmon and estuarine fish species catches increased upstream of the removed tide gate, while three-spine stickleback catches declined. Prior to restoration in years 2015 and 2016, wild juvenile Chinook abundance for ‘inside’ habitat of Fir Island Farms was estimated at 118 and 566 fish per year. Following restoration, we estimated a total annual Chinook abundance in the ‘inside’ habitat areas of 50,522 and 11,124 in 2017 and 2018. We hypothesize that the large increase in juvenile Chinook abundance following restoration was due to unobstructed fish access to newly restored habitat and a ~30-fold increase in potential rearing habitat in the form of newly wetted area. Analysis of seasonal density of juvenile Chinook salmon at Fir Island Farms compared to long term monitored reference sites in the Skagit tidal delta suggests that the restored habitat of Fir Island Farms is utilized by juvenile Chinook consistent with levels of other areas within the Skagit tidal delta. Predicted juvenile Chinook carrying capacity for the Fir Island Farms restored area varies by tens of thousands of fish per year as a function of predicted habitat amount, from 8,000 to 50,000 juvenile Chinook. The 50,000 fish estimate is most consistent with habitat conditions observed in 2017 and 2018. Predictions of channel allometry suggests tidal channel area at Fir Island Farms will decline from the 7+ hectares observed immediately after restoration to a sustainable equilibrium amount of 2.22 hectares (0.89-5.52 80% CI) hectares. Consistent with projected declines in channel area, we hypothesize that use of the restored area by juvenile Chinook will also decline.

Prior to restoration, the magnitude in difference in annual growth rates of juvenile Chinook salmon upstream of the tide gate compared to reference sites, as inferred by seasonal changes in fork length, was highest compared to juvenile Chinook encountered in the ‘inside’ area post-restoration. Presumably the low densities of juvenile Chinook in the habitat upstream of the tide gate prior to restoration resulted in low competition for food and space. After restoration, the size difference between fish in the restoration site and those in the adjacent reference sites decreased. Although many mechanisms may have influenced this observation, we hypothesize that this

inferred reduction in growth may be due to increased competition for food as a result of increased fish abundance, despite the increase in juvenile rearing habitat.

We suggest periodic monitoring of habitat (channels, hydrology, vegetation) coupled with juvenile fish monitoring to determine the trajectory of fish response to habitat as they move toward their sustainable equilibrium conditions. The frequency of monitoring can be determined based on the expected rate of change in habitat trajectory.

Introduction

Delta habitats within the Skagit River Basin and other Salish Sea river estuaries have been identified as priority habitat for restoration for the benefit of juvenile Chinook salmon and other listed species by numerous regional planning processes (e.g., SRSC and WDFW 2005, the Puget Sound Chinook Recovery Plan, and the Puget Sound Nearshore Ecosystem Restoration Program, among others). Thus, significant public investment has been made in restoration actions within the Skagit River estuary, including planned restoration through dike setback and tidegate removal at Fir Island Farms, which occurred in late summer of 2016. The Fir Island Farms Restoration project is located on the WDFW Snow Goose Reserve on Fir Island in the Skagit River Delta. The project set back approximately 5,800 feet of an existing sea dike and restored 131 acres of tidal marsh and tidal channels².

This report describes monitoring results for fish and the local environment in response to Fir Island Farms Restoration. We monitored fish use of the restored area during the juvenile Chinook salmon outmigration seasons for two seasons pre- (2015 and 2016) and post-restoration (2017 and 2018). Primary monitoring questions addressed in the report are:

1. What fish species are present within the restored area?
2. How does juvenile Chinook salmon density and size vary by year and seasonally within and immediately adjacent to the restored area?
3. How does juvenile Chinook salmon abundance vary by year within the restored area?
4. How does seasonal juvenile Chinook salmon density in the restored area compare to long term monitored reference sites throughout the Skagit River estuary?
5. What is the carrying capacity of the restored area for juvenile Chinook salmon rearing?

Methods

Sampling frequency, timing, and site selection:

The fish monitoring design for Fir Island Farms relies on observations collected ‘before’ & ‘after’ restoration using a stratified random design for site selection with reference sites. We used beach seine methods after Beamer et al. (2014) during the full juvenile Chinook outmigration period (February through August) to compare results at Fir Island Farms with long term monitoring (reference) sites in the Skagit Delta (Greene et al 2015). Sampling occurred once per month in February and August and twice per month March through July, giving a total of 12 sampling days each year.

Before Restoration: For the pre-restoration time period (2015 and 2016), three beach seine sites were established downstream (i.e., spatial stratum: outside) of the tide gate located on No Name Slough and three beach seine sites were established upstream (i.e., spatial stratum: inside) of the tide gate (Figure 1). These six sites were established as index (i.e., repeatedly sampled) sites. Beach seining was conducted at the sites near the high tide stage but before the channels exceeded

² See https://wdfw.wa.gov/lands/wildlife_areas/skagit/fir_island_estuary_restoration.php for more details.

bankfull stage. We selected this tidal stage because 1) the water was confined to channel areas during this time and 2) we avoid high water velocities occurring on ebbing tides which makes seining difficult. A total of 6 beach seine sets were made for each sampling event for the before restoration years (2015 & 2016) (Table 1).

After Restoration: For the after restoration period in 2017 and 2018, the strategy was to sample in areas that were continually wetted including main channels and a low elevation flooded area along the south-eastern dike of the project area (Figure 2). We beach seined the previously established index locations of the pre-restoration period and set up new sites in the now accessible area of the three major channels upstream of the tide gate: Claude Davis Slough, No Name Slough, and the constructed channel which was referred to as “No Name Trib.” We also beach seined the low elevation impoundment area along the south-eastern dike. At the downstream side of the removed tide gate, the site ‘s1’ was not sampled after restoration because this site is now in the throat of the outlet channel and flows have changed the channel morphology (i.e., eroded the bank) so that retrieving the net was problematic. A replacement site ‘s5’ was established further downstream towards the bay front (Figure 2).

Post-restoration beach seine sampling sites were established in each restored main channel at 50-m intervals starting at the mouth of each channel, resulting in 8 potential sites in Claude Davis Slough, 7 in No Name Slough and 9 in No Name Trib. Four sets were made in each of these channels per sampling event. Each channel had one site designated as an ‘index site’ which was sampled each sampling day. Microsoft Excel software random number-generation was used to select the other three sites to seine in each channel for each sampling day. The impoundment area consisted of 1 index site and 7 potential sites of which 6 randomly selected sites were sampled on each sample day (Figure 2).

On a given sample day, beach seining would start at the sites in the lower portion of No Name Slough (the sites sampled in 2015 and 2016 upstream of the old tidegate) at the beginning of the flood tide on the neap tide series and work progressively upstream on the flood tide. Two crews were required to complete all sampling on a single flood tide. One crew worked in No Name Slough and No Name Trib while the other crew worked in Claude Davis Slough. The sites in the impoundment area and ‘outside’ of the removed dike were sampled once the tide was at or near high tide stage. Typically, a total of 24 beach seine sets were made for each sampling event for the after restoration years (2017 and 2018) (Table 1).

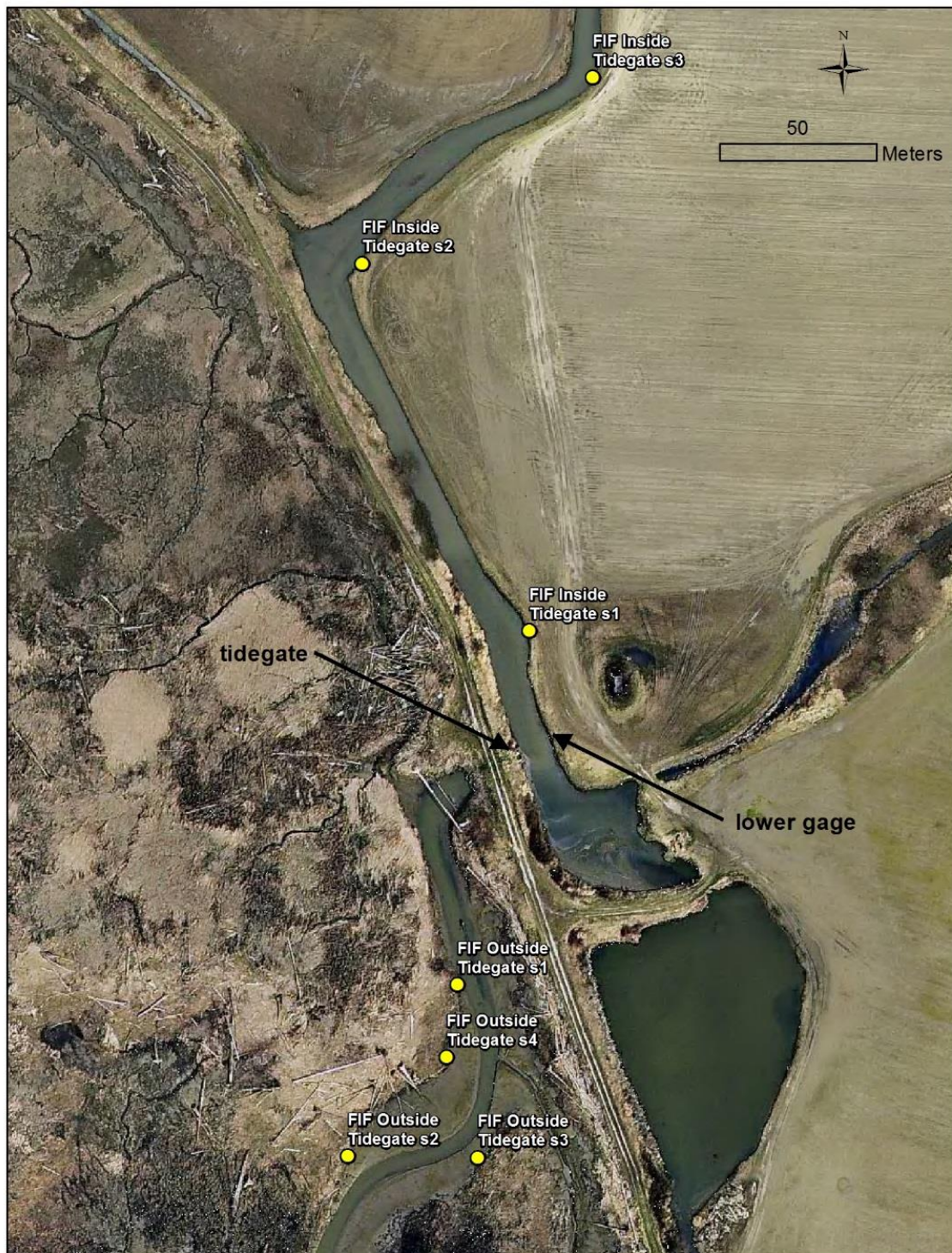


Figure 1. Sample site locations for pre-restoration fish monitoring in 2015 and 2016. The site FIF Outside Tidegate s4 was only sampled once on February 27, 2015. Photo was taken at low tide.



Figure 2 Sample site locations for post-restoration monitoring in 2017. Index sites are displayed as stars and randomly selected sites are circles.

Table 1. Number of beach seine sets made by month, year, and spatial strata at the Fir Island Farms Restoration Project.

Year	Month	Inside	Outside	Total
2015	February	3	4	7
	March	6	6	12
	April	6	6	12
	May	6	6	12
	June	6	6	12
	July	6	6	12
	August	3	3	6
	Total	36	37	73
2016	February	3	3	6
	March	6	6	12
	April	6	6	12
	May	6	6	12
	June	6	6	12
	July	3	3	6
	Total	30	30	60
2017	February	21	3	24
	March	42	7	49
	April	40	6	46
	May	32	6	38
	June	40	6	46
	July	21	3	24
	August	21	3	24
	Total	217	34	251
2018	February	22	3	25
	March	42	6	48
	April	40	6	46
	May	42	6	48
	June	42	6	48
	July	42	6	48
	August	21	3	24
	Total	251	36	287

Notes:

- In 2016 the sampling period was abbreviated and ended after the sample event on July 8th due to construction and the opening of the dike.
- In 2017 there was only one sample event in July due to the 4th of July Holiday. The preferred tidal criteria for sampling did not occur again until mid-July precluding a “makeup” sampling event for early July. We also missed sampling half of the ‘inside’ sites on May 5, 2017 due to equipment trouble.

Field Methods

We use a small net beach seine method to sample sites. Small net beach seine methodology uses an 80-ft (24.4 m) by 6-ft (1.8 m) by 1/8-inch (0.3 cm) mesh knotless nylon net. The net is set in “round haul” fashion by fixing one end of the net on the beach, while the other end is deployed by setting the net “upstream” against the water current, if present, and then returning to the shoreline in a half circle. Both ends of the net are then retrieved, yielding a catch. Average beach seine set area was 96 square meters. The net was deployed from a small skiff when sampling in the channel areas and was deployed on foot in the impoundment area along the dike. For each set, we identify and count fish by species. All the fish are returned alive to the water, with the exception of hatchery-origin salmon with coded-wire tags embedded in their snouts. These fish are sacrificed in order to read the tags. We do not report or discuss coded wire tag results in this report other than to say all tagged fish were from releases within the Skagit River. We also recorded the time and date of each set, the percent of set area (the area that the net covers compared to setting in a perfect half circle), and measure selected environmental conditions (salinity, temperature, dissolved oxygen (DO), and depth) that are present within the seined area at the time of seining. Water temperature, salinity, and DO are measured using a YSI Professional Plus Model meter. Depth is measured with a stadia rod.

General analytical approach

From fish and environmental data, we summarize all results into different variables based on their type (e.g., spatial, temporal, environmental, and fish) and application in statistical tests or graphical analyses (Table 2). For statistical tests, variables are categorized as dependent, factor, or covariate:

- A dependent variable is what you want to examine in a statistical test (i.e., response). Dependent variables are continuous and numeric.
- A factor is one or more categorical variables (grouping variables) that split the dataset into two or more groups. Factors are hypothesized to affect the dependent variable.
- A covariate is a quantitative independent variable that adds variability to the dependent variable.

Our general statistical approach uses ANOVA to test for mixed effects (factor and covariate) on selected dependent variables. Pairwise testing (such as Tukey's) were used for comparison between groups.

Specific statistical analyses are described within their section heading.

Table 2. List of variables used for Fir Island Farms Restoration project analyses.

Type	Variable name (description)	Value
Factor	restoration	before, after
	spatial	inside, outside
	year	2015, 2016, 2017, 2018
Factor or covariate (depending on analysis)	month	2, 3, 4, 5, 6, 7, 8
	week	week numbers 7-32
Response or covariate (depending on analysis)	Chinook density (Subyearling wild Chinook density in fish/ha)	Continuous numeric
	Chinook length (Subyearling wild Chinook fork length in mm)	
	Salinity (Water salinity at time of beach seining in PSU)	
	Temperature (Water temperature at time of beach seining in degrees C)	
	DO (Dissolved oxygen at time of beach seining in mg/l)	
	Depth (Maximum water depth within area seined in meters)	

Results and discussion

Local environment

In this section we explore whether the local environment (water temperature, salinity, dissolved oxygen, and depth) fish experience at Fir Island Farms varied as a result of the restoration project.

Temperature

We used ANOVA to determine factor and covariate influences on water surface temperature collected at the time of beach seining. Factors included in each ANOVA were: restoration (before or after), spatial (inside, outside) or year (2015, 2016, 2017, 2018), which was a replacement for the factor:restoration. Covariates included in each ANOVA were month, salinity and depth.

The final model uses 662 records of water surface temperature, has an R^2 of 0.832 and significant factors ($p < 0.001$) for year, and retained significant covariates ($p < 0.001$) for month, salinity, and depth. Model coefficients for covariates are: month = 3.241, salinity = -0.135, and depth = -1.517.

Not surprisingly, there is a strong seasonal increase in temperature from February through August and deeper more saline waters are also cooler (Figure 3). Somewhat surprisingly, the best model did not retain the factor, spatial. Apparently, there isn't a significant difference in mean water temperature inside or immediately outside of the Fir Island Farms Restoration area, at least based on our spot measurements at fish sites. Graphically, there appears to be more variability inside than outside post restoration (Figure 3). This makes sense, because after restoration, water was able to inundate a much larger spatial area within Fir Island Farms and included inundation of shallower habitats such as marsh and impoundment, in addition to the deeper channels which were wetted prior to restoration. However, the perceived increased temperature variability within Fir Island Farms may be driven by strong year differences coinciding with the years after restoration (Figure 4). Significant pairwise comparisons ($p < 0.05$) of the factor 'year' revealed that 2016 was on average 1.4 degrees colder than 2018 and 2017 was 1.3 degrees colder than 2018. No other year pairings were significantly different.

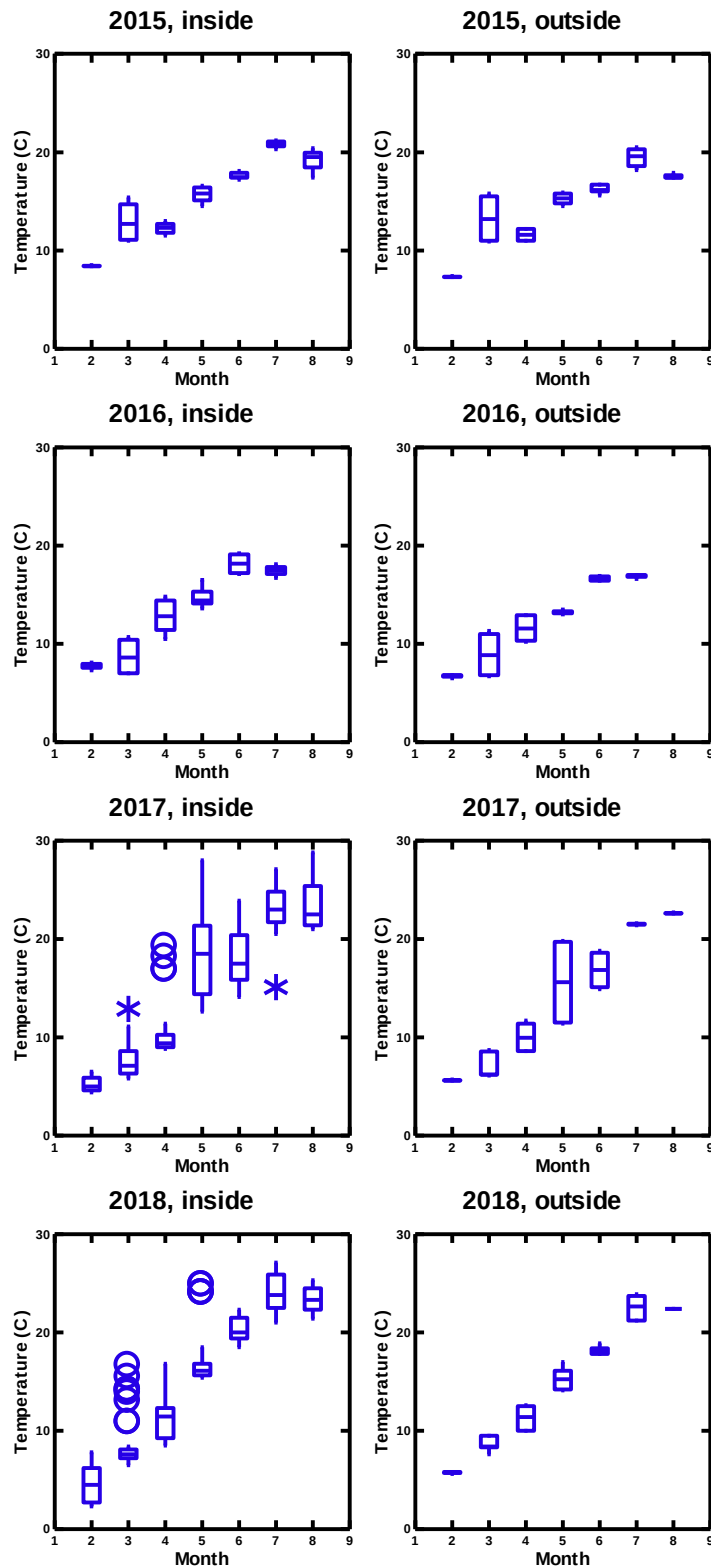


Figure 3. Boxplot of water temperature at Fir Island Farms beach seine sites by year, month, and spatial strata (inside, outside). Boxes show median, 25th and 75th percentiles. Whiskers show the 5th and 95th percentiles. Stars are observations that are still within the full distribution. Circles (if present) are outliers, i.e., observations outside the statistical distribution.

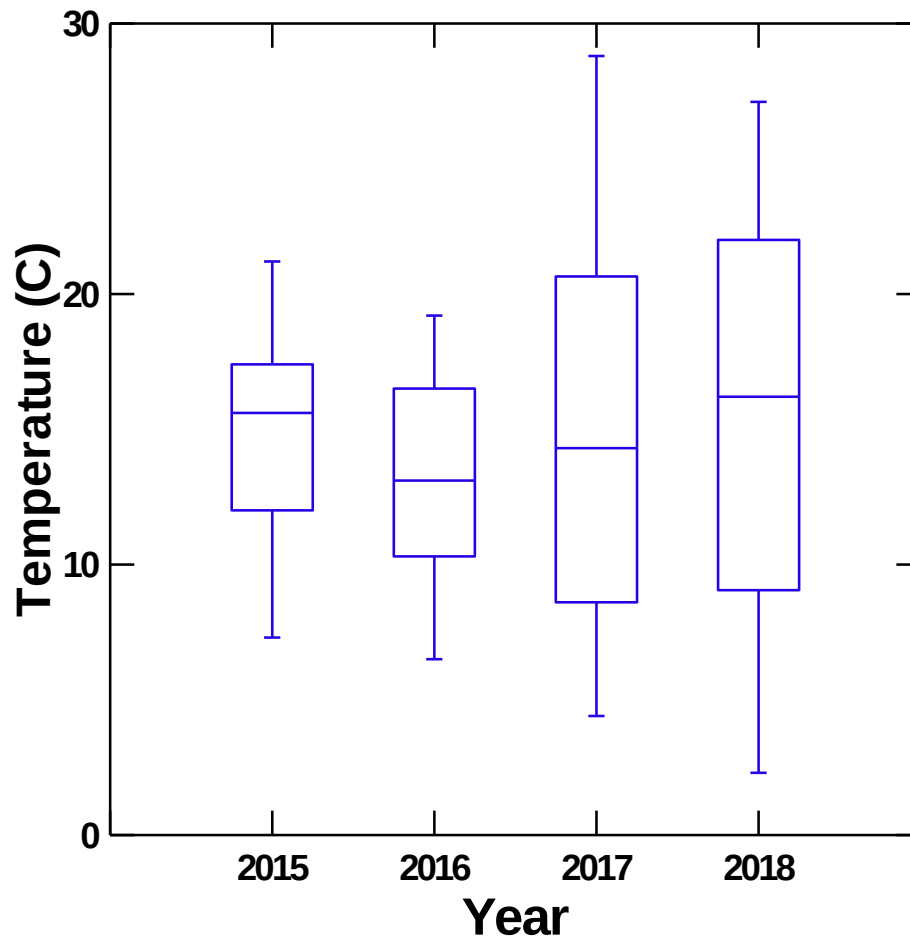


Figure 4. Boxplot of water temperature at Fir Island Farms beach seine sites by year. Boxes show median, 25th and 75th percentiles. Whiskers show the 5th and 95th percentiles. Stars are observations that are still within the full distribution. Circles (if present) are outliers, i.e., observations outside the statistical distribution.

Salinity

We used ANOVA methodology to determine factor and covariate influences on salinity collected at the time of beach seining. Factors included in each ANOVA were: restoration (before or after), spatial (inside, outside) or year (2015, 2016, 2017, 2018), which is a replacement for the factor, restoration. Covariates included in each ANOVA were month, temperature (or DO), and depth.

The final model uses 662 records of salinity, has an R^2 of 0.309 and significant factors and interactions ($p < 0.001$) for year, spatial and year*spatial. The model retained month as a significant covariate ($p < 0.001$). Model coefficient for month = 0.497.

There was a seasonal increase in salinity from February through August (Figure 5), but it was not as strong as what we observed for temperature. Salinity increased seasonally from February through August by about 0.5 PSU monthly. Overall, pairwise comparisons ($p < 0.001$) revealed 2015 was the most saline of all years; 2017 was the least saline of all years; and 2016 and 2018 were intermediate and not significantly different from each other. Somewhat surprising is the pairwise comparisons ($p = 0.011$) for 'spatial' found 'inside' areas were saltier than 'outside' areas, but by less than 1 PSU. Looking at this relationship further, pairwise comparisons ($p < 0.0001$) for 'year*spatial' found only 'inside' areas were saltier than 'outside' areas in 2015. No other 'year*spatial' pairings were significantly different.

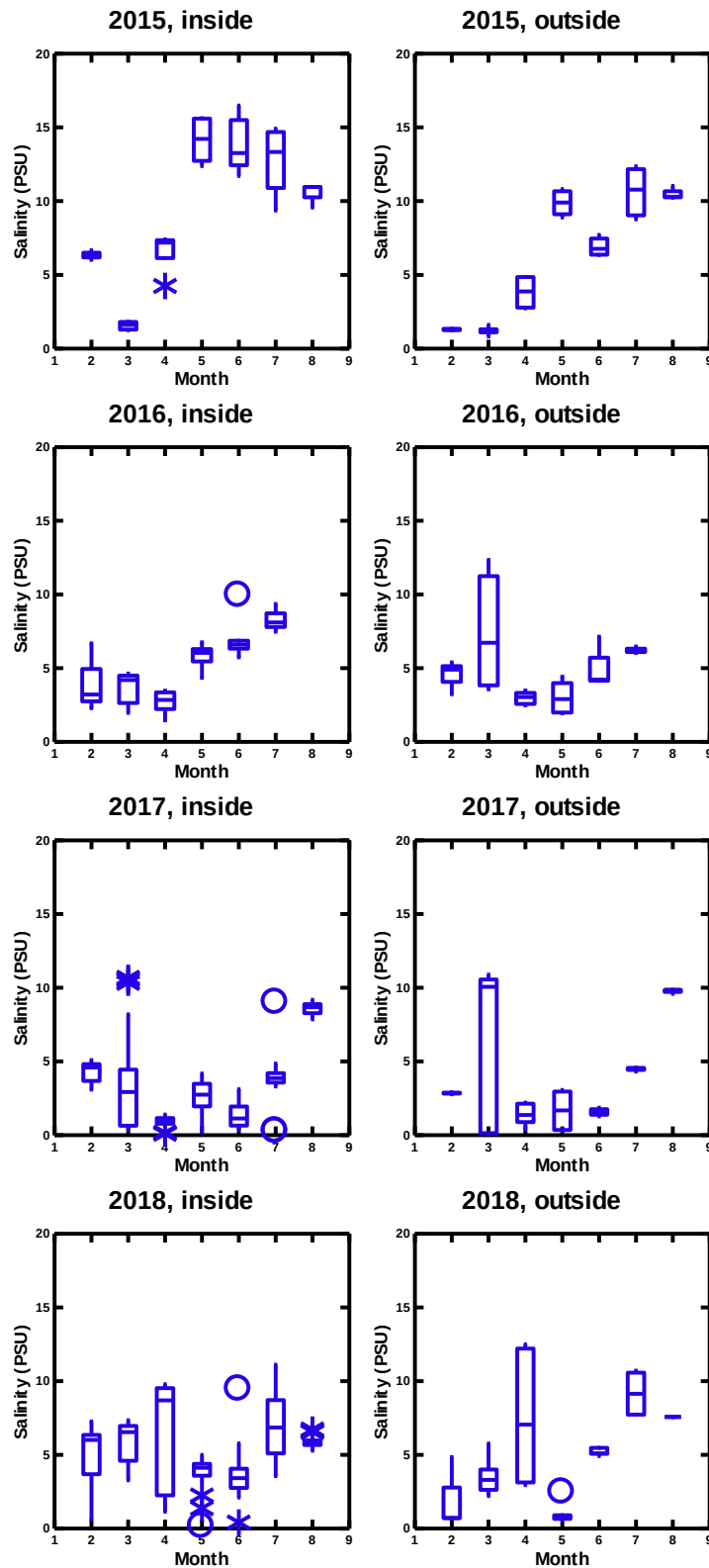


Figure 5. Boxplot of salinity at Fir Island Farms beach seine sites by year, month, and spatial strata (inside, outside). Boxes show median, 25th and 75th percentiles. Whiskers show the 5th and 95th percentiles. Stars are observations that are still within the full distribution. Circles (if present) are outliers, i.e., observations outside the statistical distribution.

Dissolved Oxygen

We used ANOVA methodology to determine factor and covariate influences on DO collected at the time of beach seining. Factors included in each ANOVA were restoration (before or after), spatial (inside, outside) or year (2015, 2016, 2017, 2018), which is a replacement for the factor, restoration. Covariates included in each ANOVA were month, salinity, and depth.

The final model uses 662 records of DO, has an R^2 of 0.436 and significant factors ($p < 0.001$) for year and spatial. The model retained month and depth as significant covariates ($p < 0.05$). Model coefficient for month = -0.666 and 0.362 for depth.

There was a seasonal decrease in DO from February through August (Figure 6). DO decreased seasonally from February through August by about 0.7 mg/l monthly and deeper water tended to have higher DO.

Pairwise comparisons ($p < 0.001$) revealed 2015 and 2016 were similar and had lower DO values than in 2017 and 2018, which were also similar (Figure 7). Overall, DO appears to have increased after restoration. Pairwise comparisons ($p < 0.001$) for 'spatial' found 'inside' areas were lower in DO than 'outside' areas by about 1 mg/l. Graphically (Figures 6 and 7), 'inside' areas seems to have more variable DO which make sense due to the higher degree of habitat diversity we sampled than just the three deeper channel sites downstream of the tide gate for 'outside.'

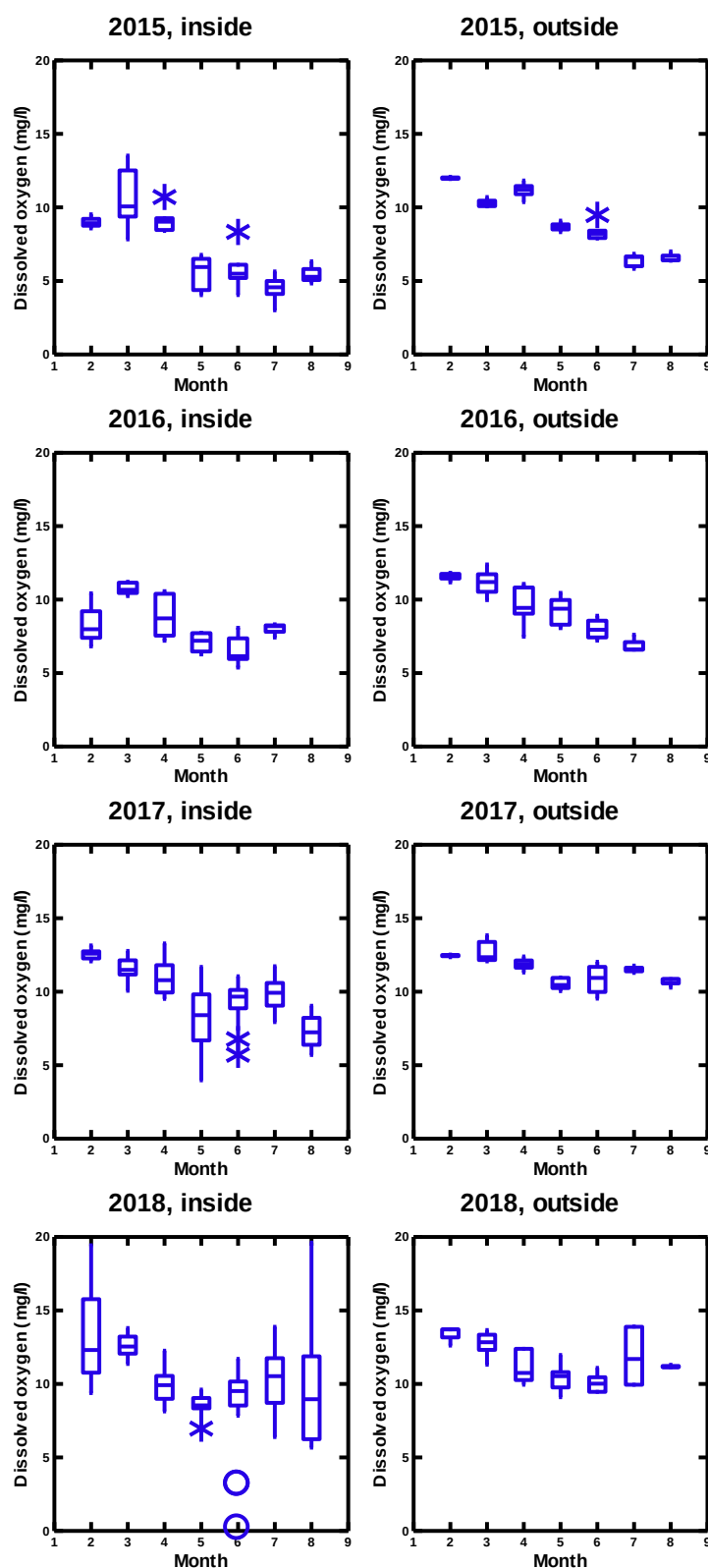


Figure 6. Boxplot of DO at Fir Island Farms beach seine sites by year, month, and spatial strata (inside, outside). Boxes show median, 25th and 75th percentiles. Whiskers show the 5th and 95th percentiles. Stars are observations that are still within the full distribution. Circles (if present) are outliers, i.e., observations outside the statistical distribution.

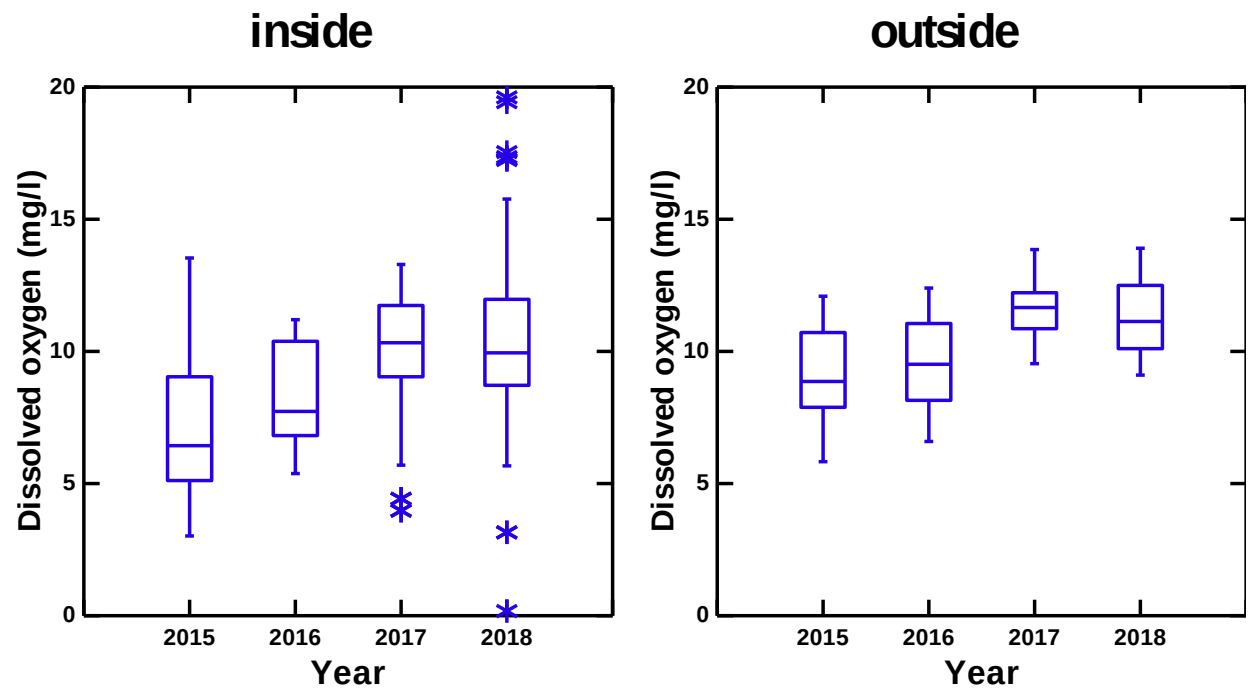


Figure 7. Boxplot of DO at Fir Island Farms beach seine sites by year and spatial strata (inside, outside). Boxes show median, 25th and 75th percentiles. Whiskers show the 5th and 95th percentiles. Stars are observations that are still within the full distribution. Circles (if present) are outliers, i.e., observations outside the statistical distribution.

Depth

We used ANOVA methodology to determine factor and covariate influences on DO collected at the time of beach seining. Factors included in each ANOVA were restoration (before or after), spatial (inside, outside) or year (2015, 2016, 2017, 2018), which is a replacement for the factor, restoration. Only month was included as a possible covariate.

The final model uses 662 records of DO, has an R^2 of 0.388 and significant factors ($p < 0.001$) for year and spatial and the interaction 'year*spatial.' Month was not significant.

Pairwise comparisons ($p < 0.01$) revealed 2015 and 2016 beach seined areas were similar and were shallower than areas seined in 2017 and 2018 which were also similar (Figure 8). Overall, water depth in 'inside' areas seined was shallower than 'outside' areas seined by about 0.8 meters. After restoration we sampled shallower habitats on average, which makes sense because of all the new marsh area, and our previous efforts were focused on channel habitats alone.

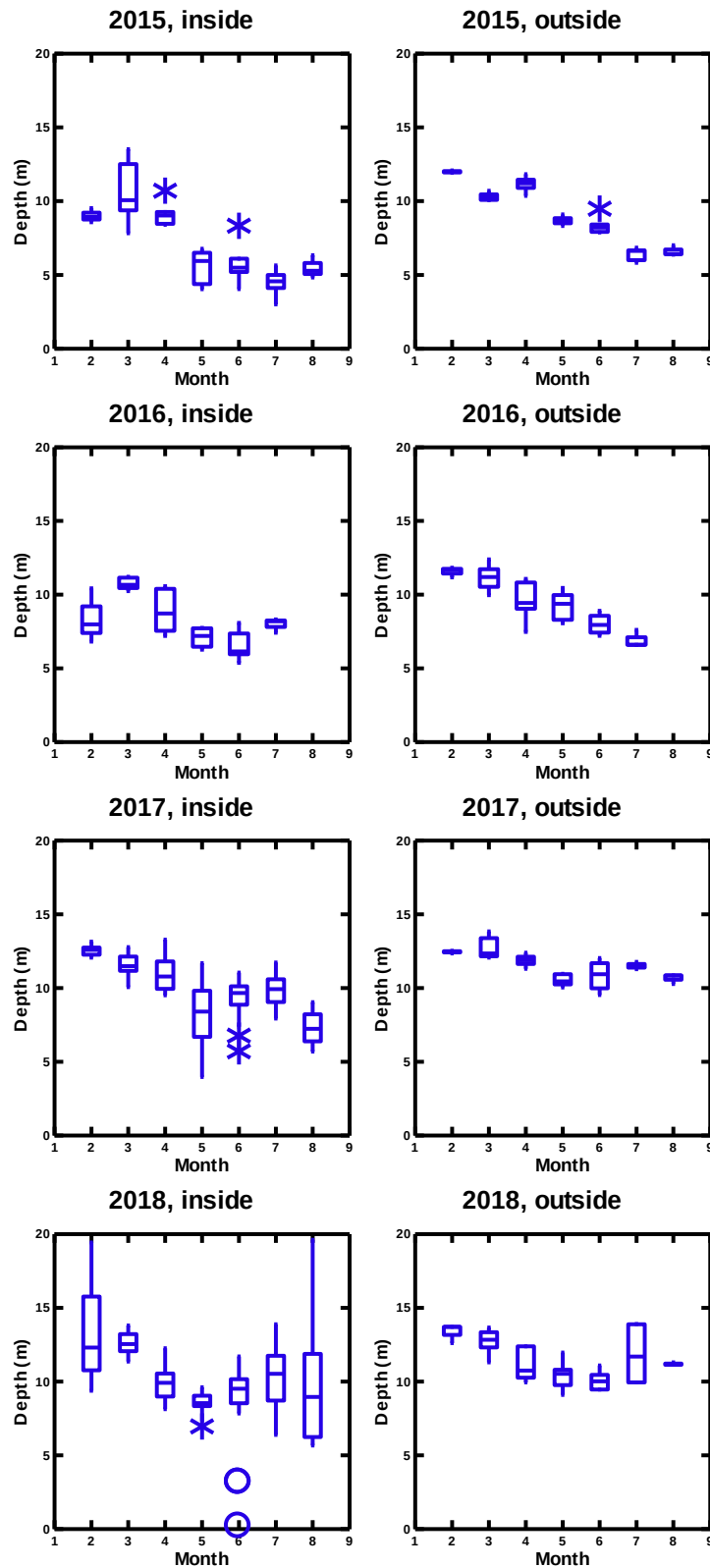


Figure 8. Boxplot of maximum water depth at Fir Island Farms beach seine sites by year, month, and spatial strata (inside, outside). Boxes show median, 25th and 75th percentiles. Whiskers show the 5th and 95th percentiles. Stars are observations that are still within the full distribution. Circles (if present) are outliers, i.e., observations outside the statistical distribution.

Water surface elevation

We report water surface elevation (WSE) fluctuation results for 2015 and 2016 measured upstream of the tide gate because of their importance to interpreting the fish assemblage, Chinook salmon, and salinity results. Obviously, after dike removal/breach restoration, both fish and saltwater would be expected to access ‘inside’ areas of Fir Island Farms. However, prior to that restoration, the tide gate was expected to prevent fish and salt water from entering the ‘inside’ areas of Fir Island Farms. Surprisingly, we observed high salinities in ‘inside’ areas in both pre- restoration years. We also heard the tide gate leaking during our beach seine sampling and photo documented the gate not closed on flooding tides (Figures 9 and 10). Thus, we examined WSE results for 2015 and 2016, measured upstream of the tide gate, to observe the degree of tidal influence on the ‘inside’ area of Fir Island Farms.

In 2015, daily high WSE averaged 3.87 ft (NAVD88) and fluctuated between 3.6 and 4.2 ft (NAVD88) tracking the spring/neap tide cycle (Figure 11). Daily low WSE in 2015 did not vary much, averaging 2.85 ft (NAVD88) and fluctuating between 2.78 to 2.94 ft. Overall, WSE fluctuation in 2015 was about 1 ft, but was as high as 1.4 ft and as low as 0.7 ft.

In 2016, WSE levels were higher than in 2015. Noteworthy is the WSE anomaly around March 10th. This reflects a strong winter storm, which allowed storm surge over the dikes in several places. After this storm event, daily high WSE varied by about 1ft and tracked the spring/neap tide cycle (Figure 11). Overall, WSE fluctuation in 2016 ranged from 1 to 1.5 ft.

The 2015 and 2016 WSE results, along with the more anecdotal evidence of ‘leaking tide gates’, suggest Fir Island Farms ‘inside’ habitat areas before restoration were subject to some tidal influence that could cause fish and local environmental results to differ from what was originally hypothesized. For example, a non-leaking traditional gravity-operated tide gate would be expected to exclude upstream access to smaller fish.



Figure 9. Fir Island Farms Tide gate open on flooding tide (October 26, 2015 at 10:40AM).



Figure 10. Fir Island Farms Tide gate open on flooding tide (October 26, 2015 at 10:40AM).

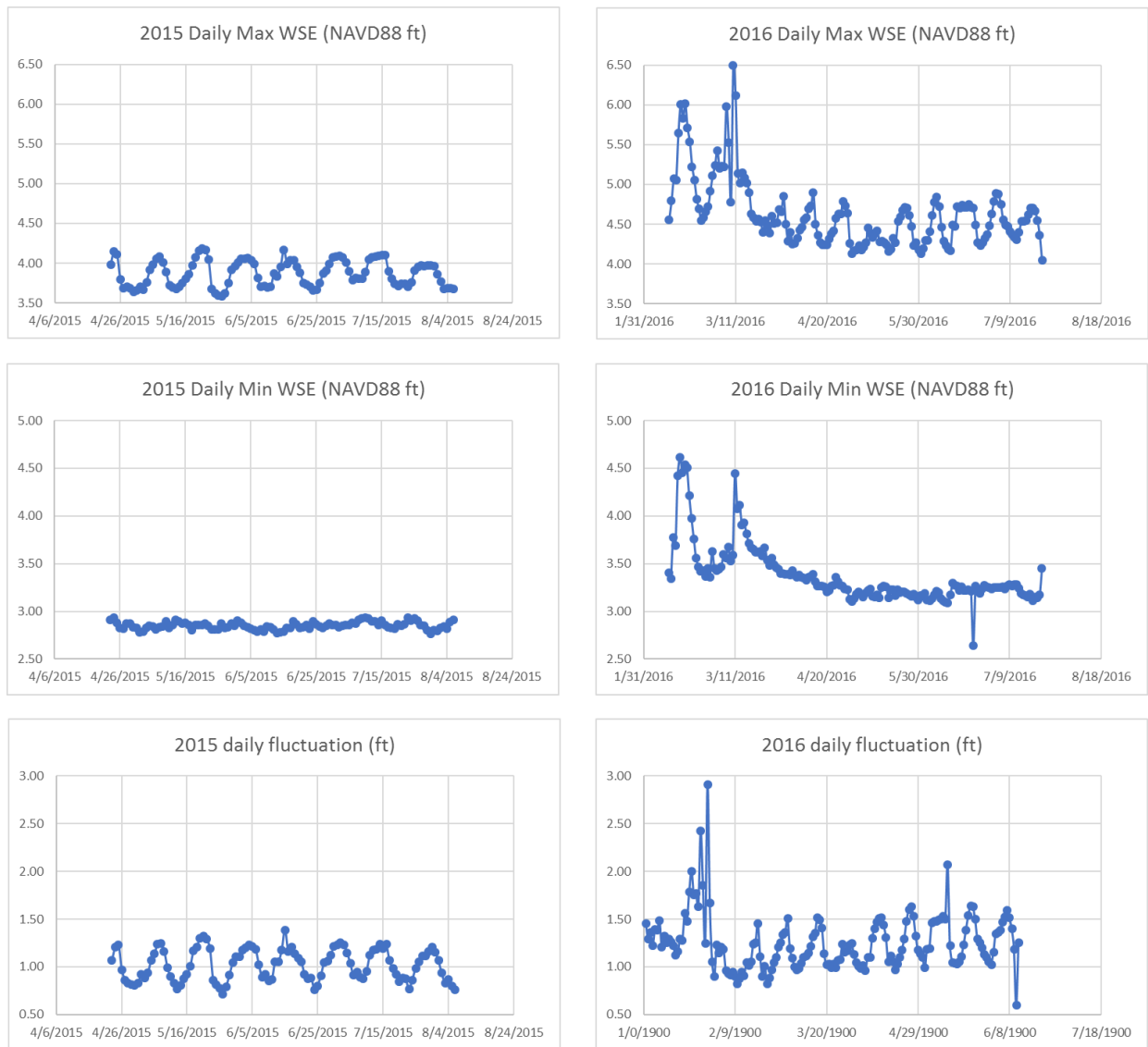


Figure 11. Daily WSE results for Fir Island Farms 'inside' habitat area in 2015 and 2016. Results are from WDFW level logger located just upstream of the tide gate.

Fish Assemblage:

Overall, the four years of beach seine sampling caught over 80,000 fish from 21 different species (Tables 3 and 4). Not surprisingly, Three-spine stickleback made up most of the catch in all years. Surprisingly, juvenile Chinook were caught upstream of the tide gate in 2015 and 2016 before restoration occurred confirming that the leaking tide gate did allow upstream fish passage. Four other salmon or estuarine species were documented upstream of the tide gate before restoration occurred: chum salmon, starry flounder, peamouth chub, and staghorn sculpin. After restoration, in 2017 and 2018, juvenile salmon and estuarine fish species catches and catch per unit effort increased upstream of the removed tide gate, while three-spine stickleback abundance declined. We also documented the presence of three non-native species: shad, yellow perch, and brown bullhead of which the latter two are known as freshwater fishes.

Table 3. Total catch by species at Fir Island Farms from 2015 through 2018. Mean catch per unit effort (beach seine set) is in parentheses.

Group	Species	Before Restoration				After Restoration				Grand Total
		2015		2016		2017		2018		
		inside	outside	inside	outside	inside	outside	inside	outside	
Salmon	Chinook salmon, natural origin (wild) unmarked subyearling, <i>Oncorhynchus tshawytscha</i>	14	71	63	101	1,749	293	714	52	3,057
	Chinook salmon, hatchery origin subyearlings, all marks combined	0	4	0	0	4	0	3	4	15
	Chum salmon, subyearling, <i>Oncorhynchus keta</i>	1	44	0	32	1,906	232	255	25	2,495
	Coho salmon, unmarked yearling <i>Oncorhynchus kisutch</i>	0	0	0	2	12	1	0	1	16
	Pink salmon, subyearling, <i>Oncorhynchus gorbuscha</i>	0	0	0	1	0	0	145	0	146
	Bull trout, all ages, <i>Salvelinus confluentus</i>	0	0	0	0	1	0	0	0	1
Flatfish	Starry flounder, <i>Platichthys stellatus</i>	229	45	8	50	1,589	41	1,300	83	3,345
	English sole, <i>Parophrys vetulus</i>	2	0	0	0	0	0	0	0	2
	Unknown flatfish post larval	0	0	0	0	2	0	0	0	2
Forage fish	Peamouth chub, <i>Mylocheilus caurinus</i>	0	1	201	95	1,586	5	688	15	2,591
	Surf smelt, <i>Hypomesus pretiosus</i>	0	22	0	11	6	109	137	18	303
	Pacific herring, <i>Clupea pallasii</i>	0	1	0	0	1	0	0	0	2
Sculpin	Pacific staghorn sculpin, <i>Leptocottus armatus</i>	53	11	30	96	2,734	13	1,019	15	3,971
	Prickly sculpin, <i>Cottus asper</i>	0	0	0	0	16	0	48	1	65
Common estuarine/nearshore	Three-spine stickleback, <i>Gasterosteus aculeatus</i>	29,940	688	6,994	361	12,860	296	6,244	49	57,432
	Shiner surf perch, <i>Cymatogaster aggregate</i>	0	803	7	382	3,823	62	2,205	50	7,332
	Arrow goby, <i>Clevelandia ios</i>	0	0	0	0	3	0	1	0	4
	Snake prickleback, <i>Lumpenus sagitta</i>	0	0	0	0	0	0	5	0	5
Native freshwater	Whitefish, all ages, <i>Prosopium williamsoni</i>	0	0	0	0	1	0	0	0	1
Non-native	American shad (non-native), <i>Alosa sapidissima</i>	0	1	0	0	1	0	3	0	5
	Brown bullhead, <i>Ictalurus nebulosus</i>	0	0	0	0	0	0	1	0	1
	Yellow perch, <i>Perca flavescens</i>	0	0	0	0	0	0	2	0	2
	Grand total	30,239	1,691	7,303	1,131	26,294	1,052	12,770	313	80,793

Table 4. Mean beach seine catch per unit effort by species at Fir Island Farms from 2015 through 2018.

Group	Species	Before Restoration				After Restoration			
		2015		2016		2017		2018	
		inside	outside	inside	outside	inside	outside	inside	outside
Salmon	Chinook salmon, natural origin (wild) unmarked subyearling, <i>Oncorhynchus tshawytscha</i>	0.389	1.919	2.100	3.367	8.060	8.618	2.845	1.444
	Chinook salmon, hatchery origin subyearlings, all marks combined	0.000	0.108	0.000	0.000	0.018	0.000	0.012	0.111
	Chum salmon, subyearling, <i>Oncorhynchus keta</i>	0.028	1.189	0.000	1.067	8.783	6.824	1.016	0.694
	Coho salmon, unmarked yearling <i>Oncorhynchus kisutch</i>	0.000	0.000	0.000	0.067	0.055	0.029	0.000	0.028
	Pink salmon, subyearling, <i>Oncorhynchus gorbuscha</i>	0.000	0.000	0.000	0.033	0.000	0.000	0.578	0.000
	Bull trout, all ages, <i>Salvelinus confluentus</i>	0.000	0.000	0.000	0.000	0.005	0.000	0.000	0.000
Flatfish	Starry flounder, <i>Platichthys stellatus</i>	6.361	1.216	0.267	1.667	7.323	1.206	5.179	2.306
	English sole, <i>Parophrys vetulus</i>	0.056	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Unknown flatfish post larval	0.000	0.000	0.000	0.000	0.009	0.000	0.000	0.000
Forage fish	Peamouth chub, <i>Mylocheilus caurinus</i>	0.000	0.027	6.700	3.167	7.309	0.147	2.741	0.417
	Surf smelt, <i>Hypomesus pretiosus</i>	0.000	0.595	0.000	0.367	0.028	3.206	0.546	0.500
	Pacific herring, <i>Clupea pallasii</i>	0.000	0.027	0.000	0.000	0.005	0.000	0.000	0.000
Sculpin	Pacific staghorn sculpin, <i>Leptocottus armatus</i>	1.472	0.297	1.000	3.200	12.599	0.382	4.060	0.417
	Prickly sculpin, <i>Cottus asper</i>	0.000	0.000	0.000	0.000	0.074	0.000	0.191	0.028
Common estuarine/nearshore	Three-spine stickleback, <i>Gasterosteus aculeatus</i>	831.667	18.595	233.133	12.033	59.263	8.706	24.876	1.361
	Shiner surf perch, <i>Cymatogaster aggregate</i>	0.000	21.703	0.233	12.733	17.618	1.824	8.785	1.389
	Arrow goby, <i>Clevelandia ios</i>	0.000	0.000	0.000	0.000	0.014	0.000	0.004	0.000
	Snake prickleback, <i>Lumpenus sagitta</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.000
Native freshwater	Whitefish, all ages, <i>Prosopium williamsoni</i>	0.000	0.000	0.000	0.000	0.005	0.000	0.000	0.000
Non-native	American shad (non-native), <i>Alosa sapidissima</i>	0.000	0.027	0.000	0.000	0.005	0.000	0.012	0.000
	Brown bullhead, <i>Ictalurus nebulosus</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.000
	Yellow perch, <i>Perca flavescens</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.000

Wild juvenile Chinook salmon

Density

Before/after restoration & within/adjacent to the restored sites

Graphical analysis: Surprisingly, the before restoration condition has significant numbers of juvenile Chinook within ‘inside’ habitat areas, i.e., upstream of a traditional, gravity operated, tide gate (Figure 12). However, as previously noted, the tide gate leaked, so juvenile Chinook were able to occupy the channels within the project area before restoration. Before restoration, lower densities of Chinook were upstream and the normal seasonal curve was shifted or truncated (3 months of presence rather than 6 or more months). After restoration, the density curve for ‘inside’ habitat matched ‘outside’ habitat (2017) or even had higher peak densities (2018).

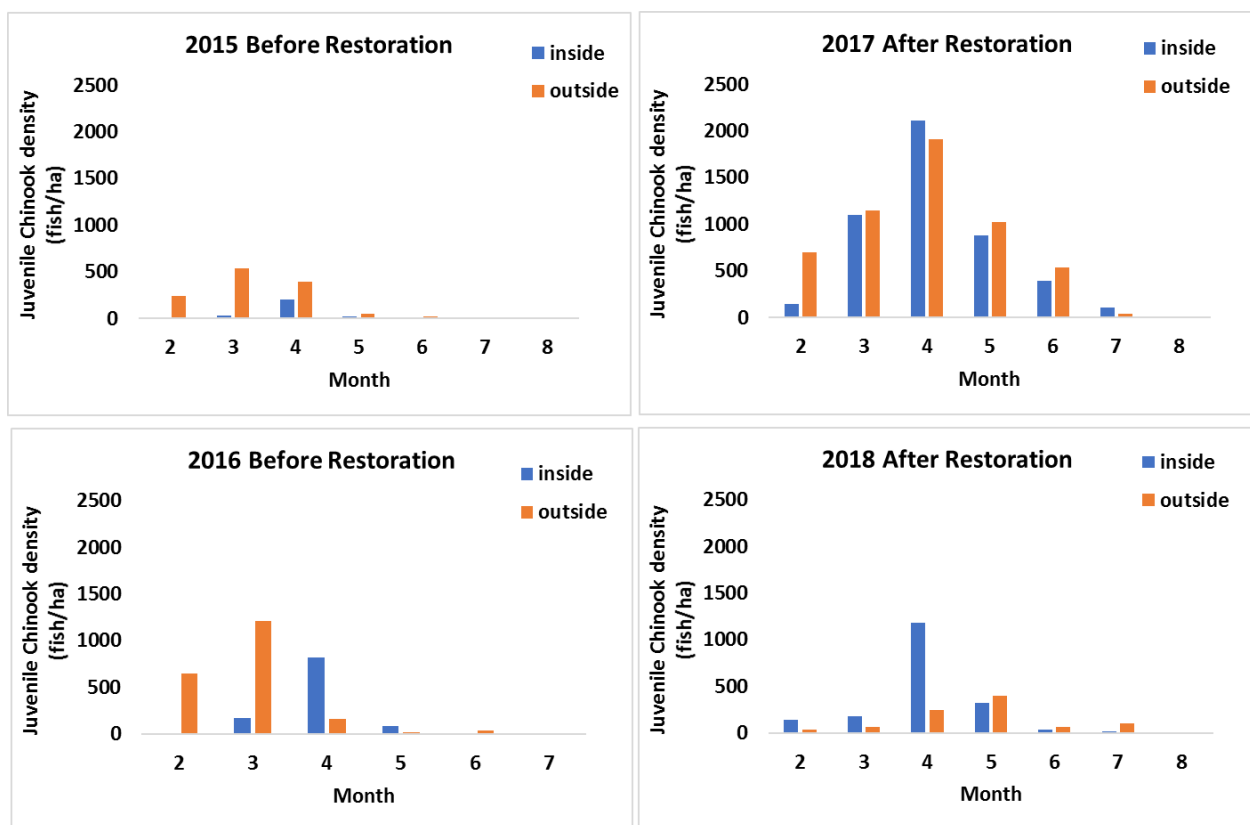


Figure 12. Juvenile wild Chinook salmon density by month and year for spatial strata: inside and outside of Fir Island Farms Restoration area.

Statistical analysis: We used ANOVA methodology to determine factor and covariate influences on wild juvenile Chinook densities. Chinook densities were averaged by week and spatial strata and log transformed ($\log x+1$). Factors included in each ANOVA were restoration (before or after), spatial (inside, outside) or year (2015, 2016, 2017, 2018), which is a replacement for the factor, restoration. Covariates included were week, salinity, temperature, DO, and depth.

The final model uses 90 records of Chinook density and has an R^2 of 0.165, but an overall significance of $p < 0.001$. No covariates were significant. Individually, only the factor ‘restoration’ was significant ($p = 0.01$) but the interaction of ‘spatial*restoration’ was significant ($p = 0.059$). Pairwise comparison revealed that Chinook densities were significantly higher ($p < 0.001$) in ‘inside’ areas after restoration than before restoration (Figure 13). The most important finding from this analysis is the detection of higher densities of Chinook inside the restored area after restoration, and at the same time no significant difference in Chinook densities immediately outside of the restored area. This suggests the restoration project not only had an influence on attracting fish into the newly restored habitat, but that it was not simply an attraction of fish that would otherwise just be rearing nearby. The result of higher Chinook density for ‘inside’ habitat after restoration is not surprising given the ‘inside’ area was blocked by a tide gate prior to restoration. However, the leaky tide gate complicated the density analysis by providing more than a few non-zero values for Chinook density prior to restoration, and thus confounded easy statistical detection of a density change.

In addition to localized factors, such as restoration, Chinook densities at Fir Island Farms may be influenced by variability in the number of juvenile Chinook salmon outmigrating from the Skagit River each year. Skagit River subyearling wild Chinook salmon outmigration estimates for 2015, 2016, and 2017 are 1.13, 3.09, and 3.07 million fish, respectively (J Anderson and C Kinsel, WDFW). Outmigration estimates for 2018 are not yet available.

More important to Fir Island Farms’ ecological success are the Chinook abundance results, because the restored state of Fir Island Farms has several magnitudes more habitat available to fish than what was available through a leaking tide gate. Even a low density of fish over a large area provides habitat for many individuals.

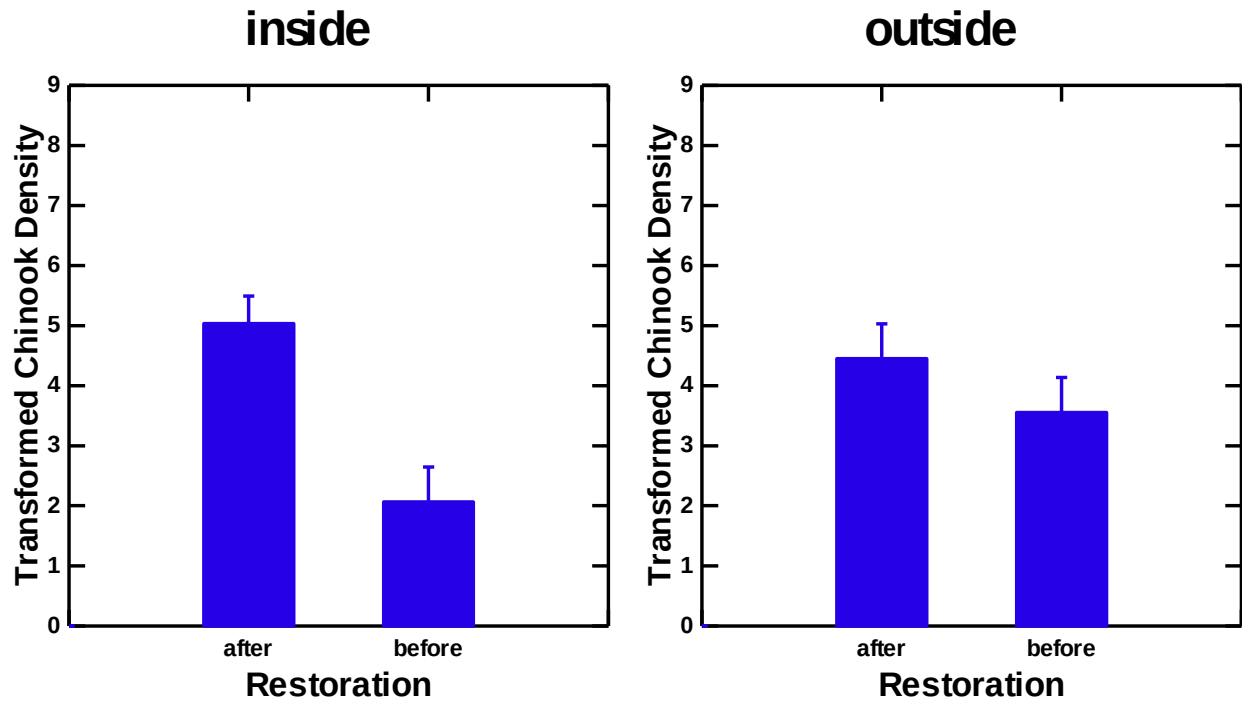


Figure 13. Wild juvenile Chinook density by factors: restoration (before, after) and spatial strata (inside, outside) for Fir Island Farms Restoration project, 2015-2018. Transformed Chinook densities are log transformed ($\log x+1$). Error bars are standard error.

Comparison with long term monitoring sites

To compare actual fish monitoring results at Fir Island Farms to the ten Skagit tidal delta long term monitoring sites, we calculated the season-long density of juvenile Chinook salmon and plotted them by landscape connectivity values at each site.

Landscape connectivity: Landscape connectivity, or large-scale connectivity, refers to the relative distances and pathways that salmon must travel to find habitat over a very large area. As this concept is applied in the Skagit River delta, landscape connectivity is a function of both the distance and complexity of the pathway that salmon must follow to specific habitat areas (e.g., candidate restoration sites). Connectivity decreases as complexity of the route the fish must swim increases and the distance the fish must swim increases. Within the delta, the complexity of the route fish must take to find habitat is measured by the distributary bifurcation order and distance traveled. Habitat that is less connected to the source of fish has lower densities of fish. Landscape connectivity differences within the Skagit delta are a strong predictor of seasonal juvenile Chinook salmon density explaining up to 89% of juvenile Chinook salmon seasonal density at a site (Beamer et al 2005; Beamer and Wolf 2016).

Landscape connectivity (LC) for each site is calculated:

$$LC = \frac{1}{\sum_{j=1}^{j_{end}} (O_j * D_j)}$$

where O_j = distributary channel order for channel segment j , D_j = distance along segment j of order O_j , j = count (1... j_{end}) of distributary channel segments, and j_{end} = total number of channel segments at destination or sample point. Methods are more completely described in Beamer and Wolf (2011).

Landscape connectivity was calculated to Fir Island Farms during its feasibility via three potential pathways: Browns Slough, Claude Davis Slough, and Dry Slough (Wolf 2010, shown as Appendix 1). Fir Island Farms in its restored state follows the Claude Davis Slough pathway so this result was used in the juvenile Chinook carrying capacity estimate and to compare monitored values of juvenile Chinook density at Fir Island Farms to ten long-term fish monitoring sites (Appendix 1, see Figure 2 and Table 2). Landscape connectivity for Fir Island Farms via Claude Davis Slough is 0.01904. We used landscape connectivity values from the NOAA/WRCO SRFB Skagit Hydrodynamic Model Project for the ten long term fish monitoring sites (Beamer et al. 2016). Reference site landscape connectivity values range from 0.0158 to 0.0881.

Seasonal Chinook density: To compare actual fish monitoring results at Fir Island Farms to the ten Skagit tidal delta long term monitoring sites, we calculated the season-long density of juvenile Chinook salmon for each site/year combination. This fish density statistic is termed *cumulative Chinook salmon density*. Cumulative Chinook salmon density was estimated for the periods

February 1 through August 15 for timing curves of juvenile Chinook salmon in Skagit River tidal delta habitat. Cumulative Chinook salmon density (C), (fish*days*ha⁻¹), was calculated as:

$$C = \sum_{m=F}^L D_m n_m$$

where D_m is the average monthly density, n_m is the number of days in the month, and F and L are the first and last months (m) sampled, respectively.

Cumulative Chinook salmon density for each monitoring site and year combination was divided by the average resident time (35 days) of individual juvenile Chinook salmon rearing in Skagit River tidal delta habitat (Beamer et al. 2000). This calculation procedure is an estimate of the population of juvenile Chinook salmon that used habitat at each monitoring site and year combination, standardized to a habitat area of one hectare.

Results: There was a positive relationship between seasonal wild juvenile Chinook salmon density and landscape connectivity for the long-term monitoring sites throughout the Skagit River delta during the years when Fir Island Farms monitoring occurred (Figure 14). Depending on the year, landscape connectivity explains 41% to 58% of the variation in seasonal juvenile Chinook salmon density at the Skagit River delta long-term monitoring sites. Before restoration at Fir Island Farms, juvenile Chinook density within the project area clustered well below (2015) or on the lower side (2016) of the scatter of the Skagit River long term monitoring sites (Figure 14, top and middle panels). After restoration at Fir Island Farms (2017), juvenile Chinook density within the project area clustered within the scatter of the Skagit River long term monitoring sites (Figure 14, bottom panel), suggesting that the restored habitat of Fir Island Farms is utilized by juvenile Chinook consistent with other areas within the Skagit tidal delta. Results for 2018 are not yet available, because data for the Skagit tidal delta long term monitoring sites have not been processed yet.

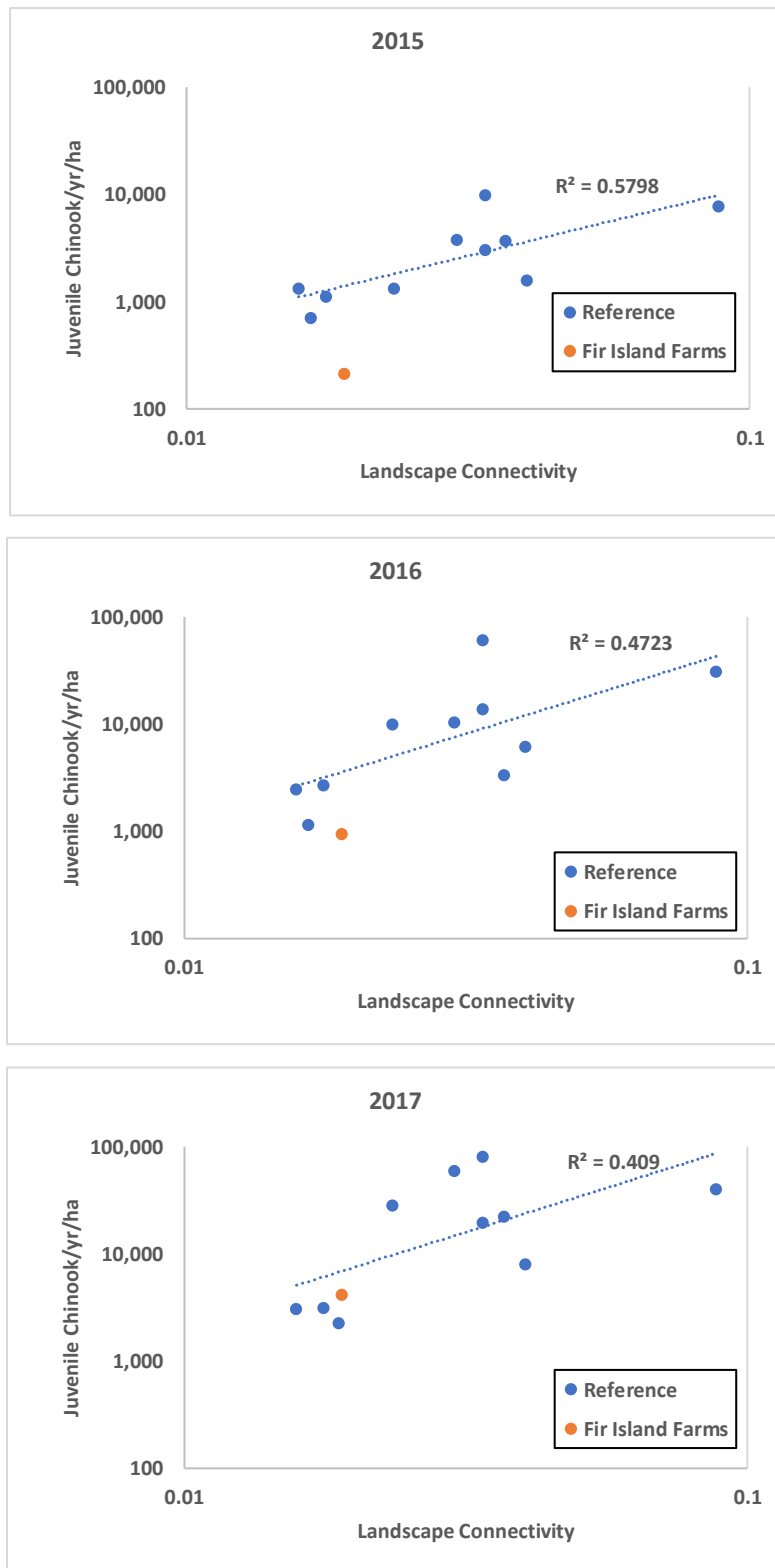


Figure 14. Relationship between landscape connectivity and seasonal Chinook salmon density for Skagit River tidal delta long-term monitoring sites and Fir Island Farms Restoration area, 2015 through 2017.

Abundance

In this section we report estimates of monitored juvenile Chinook abundance for the before- and after- restoration years within Fir Island Farms. We also compare the abundance estimates to predicted juvenile Chinook carrying capacity for the as-built condition of Fir Island Farms for predicted sustainable habitat.

Before/after restoration within the restored site

We estimated juvenile wild Chinook salmon abundance to determine the number of fish that reared in ‘inside’ habitat of the Fir Island Farms Restoration project for each year of monitoring. Fish abundance was calculated as fish density multiplied by the wetted area of ‘inside’ habitat during the time of sampling. Fish abundance was calculated for each beach seine set on each sampling date because wetted area and juvenile Chinook salmon catches varied by sampling date. Fir Island Farms ‘inside’ wetted habitat area after restoration varies by tidal stage. Thus, for each beach seine set the wetted area was estimated in order to estimate the fish population size using a WSE-to-wetted area relationship described in Appendix 2 of this report. Wetted area for ‘inside’ habitat of Fir Island Farms prior to dike breaching (2015 and 2016) was considered a constant value of 0.62 hectares because the water was always contained within the bankfull stage of channels. In 2017 and 2018, the average wetted area of the Fir Island Farms ‘inside’ habitat area during fish sampling was 20.3 and 16.7 ha, respectively. This is approximately a 30-fold increase in area from the pre-restoration years.

Results: Wild juvenile Chinook abundance for ‘inside’ habitat of Fir Island Farms before restoration in 2015 and 2016 was 118 and 566 fish per year, respectively (Table 5). After restoration, Chinook abundance in 2017 and 2018 are estimated at 50,522 and 11,124 fish per year, respectively. The large increase in juvenile Chinook abundance at Fir Island Farms after restoration is presumed to be due to the: (a) unobstructed fish access to habitat (i.e., no longer through a tide gate, even if it did leak) and (b) ~30-fold increase in wetted area available as rearing habitat.

In addition to localized factors, such as the restoration influence, Chinook abundance at Fir Island Farms may be influenced by variability in the number of juvenile Chinook salmon outmigrating from the Skagit River each year. Unfortunately, we are only able to account for the number of outmigrants for 3 of 4 years of monitoring. Skagit River subyearling wild Chinook salmon outmigration estimates for 2015, 2016, and 2017 are 1.13, 3.09, and 3.07 million fish, respectively (J Anderson and C Kinsel, WDFW). Outmigration estimates for 2018 are not yet available from WDFW. Nevertheless, years 2016 and 2017 make a good before- and after-restoration comparison, because in both years the number of outmigrants were slightly over 3 million wild Chinook subyearlings. Beamer et al. (2005) estimated the Skagit estuary reaches full carrying capacity for juvenile Chinook rearing at an outmigration of 5.1 million subyearlings annually. Thus, an outmigration of 3 million subyearlings equates to approximately 60% of carrying capacity.

Table 5. Population estimate of individual juvenile wild Chinook salmon by year that used habitat inside of the Fir Island Farms Restoration project.

Year	Seasonal Chinook abundance in fish-days Point estimate (upper & lower 95% CI)	Average Chinook delta residence period (days)	Juvenile Chinook population Point estimate (upper & lower 95% CI)
2015	4,122 (243-8,001)	35 ^a	118 (7-229)
2016	19,801 (5,909-33,692)		566 (169-963)
2017	1,768,608 (1,217,303-2,319,912)		50,532 (34,780-66,283)
2018	389,323 (245,477-533,169)		11,124 (7,014-15,233)

a – based on juvenile Skagit Chinook salmon otolith results reported in Beamer et al. (2000).

Comparison to wild juvenile Chinook carrying capacity prediction

Wild juvenile Chinook salmon abundance estimates (Table 5) can be compared to model-generated carrying capacity estimates for juvenile Chinook salmon for the Fir Island Farms as-built condition (Table 6).

Methods: Juvenile Chinook carrying capacity for the Fir Island Farms as-built condition was estimated using an empirical model developed for the Skagit Chinook Recovery Plan that predicts carrying capacity estimates for estuarine rearing habitat within the Skagit tidal delta based on channel area and landscape connectivity. Overall, the model explained 68% of the variation in seasonal Chinook density at six sites over eleven years. The landscape connectivity factor explained 37% of the variation while density dependence (outmigrants) explained the remaining 31%. The methods are described in Beamer et al. (2005) (pages 89-94). Juvenile Chinook salmon carrying capacity is based on two variables: 1) wetted area available to fish; and 2) landscape connectivity. Both variables are positively correlated with juvenile Chinook abundance (i.e., larger habitat areas and higher connectivity values result in higher estimates of juvenile Chinook carrying capacity).

Results: The predicted juvenile Chinook carrying capacity for the Fir Island Farms as-built tidal footprint is just over 21,000 juvenile Chinook per year (Table 6). The predicted carrying capacity for this project varies by tens of thousands of fish per year as a function of predicted habitat amount, from a low of 8,067 to a high of 50,034.

Fir Island Farms feasibility documents, summarized on WDFW's webpage,³ state: WDFW's preferred alternative will significantly contribute to the recovery of Skagit Chinook salmon by restoring 126 acres (50.9 hectares) of tidal marsh habitat, restoring 17.44 acres (7.06 hectares) of new tidal channel habitat, and producing an estimated 65,000 – 320,600 new Chinook smolts annually.

Juvenile Chinook carrying capacity estimates for Fir Island Farms depend on inputs for habitat area and landscape connectivity, well as the carrying capacity model used. Landscape connectivity inputs appear to be similar for the feasibility study and monitored the restored condition of Fir Island Farms. After restoration was completed at Fir Island Farms, we estimated low tide wetted area as 2.311 hectares (Appendix 2, Figure A1), bankfull wetted area as 7.108 hectares⁴ (Appendix 2, Figure A3), and the tidal footprint to be 53.073 hectares (Appendix 2, Figure A5). Thus, habitat areas measured after restoration are also similar to values predicted in the feasibility study. However, the sustainable amount of tidal channel at Fir Island Farms is predicted to decline from the 7+ hectares predicted in the feasibility study and observed after restoration for the 'bankfull' condition (Table 6. Also, see discussion in Appendix 3). A decline in habitat area would also reduce juvenile Chinook carrying capacity.

To estimate juvenile Chinook carrying capacity for Fir Island Farms, the feasibility study used two different models: the Skagit Chinook Plan Model (i.e., the same model we used for results in Table 6) and a new model called 'Reference Site Model.' The Reference Site Model was created out of concern that the Skagit Chinook Plan Model would significantly underestimate juvenile Chinook carrying capacity in areas like Fir Island Farms (Conner et al. 2011). However, the Skagit Chinook Plan Model prediction of 50,000-64,000 fish/yr for 5.52-7.108 hectares of habitat has a better fit to the monitored results for Chinook abundance after restoration at Fir Island Farms (Table 5). The 50,000 fish abundance estimate for Fir Island Farms in 2017 is consistent with what is expected on a 3 million fish outmigration for 7+ hectares of habitat. We suspect the 11,000 fish abundance estimate for 2018 coincides with a significantly smaller outmigration than in 2017.

³ https://wdfw.wa.gov/lands/wildlife_areas/skagit/final_restoration_study.php

⁴ The bankfull stage includes backwatered area at the site's downstream end near the old tide gate and in the SE corner along the levee.

Table 6. Summary of channel habitat area, landscape connectivity, and predicted Chinook carrying capacity for the as-built Fir Island Farms restoration area. The landscape connectivity estimate is from Appendix 1. Channel area estimates are from Appendix 3.

Predicted channel area (ha)		Landscape connectivity	Predicted juvenile Chinook carrying capacity (fish/yr)
Median	2.22	0.01904	20,122
Low 80% confidence limit	0.89		8,067
High 80% confidence limit	5.52		50,034
After restoration observed bankfull	7.108		64,428

Note: we did not include estimates for increased juvenile Chinook carrying capacity due to indirect (i.e., downstream of dikes) habitat formation. Based on our analysis, downstream benefits will likely be small (see discussion in Appendix 3).

Body size

Before/after restoration & within/adjacent to the restored sites

Interpreting changes of juvenile Chinook length pre- and post-restoration at Fir Island Farms is not as straightforward as the density and abundance results. Overall, we collected 1,908 observations of juvenile Chinook fork length to analyze body size changes pre- and post-restoration at Fir Island Farms (Figure 15). However, interpreting these data statistically is somewhat difficult because of several biological and sampling issues. The expected seasonal increase in fork length (Figure 15) as well as annual and seasonal variability in juvenile Chinook density (Figure 12), prey availability, and water temperature (Figure 3) all influence growth of juvenile Chinook through density dependent or bioenergetic processes. These issues make detecting changes in juvenile Chinook body size due strictly to restoration difficult. Additionally, the 1,908 sample collection is highly unbalanced seasonally (within- and across years) and spatially (inside/outside). Both issues causing unbalanced samples are logically expected because juvenile Chinook use estuarine habitat seasonally and few fish would be expected within Fir Island Farms prior to restoration. Thus, to improve temporal and spatial balance we averaged the 1,908 fish length dataset by sampling event (week) and spatial strata (inside/outside) which resulted in 304 observations of average Chinook length (Table 7). We then matched up the 304-observation dataset with covariate values linked to three influences on juvenile Chinook salmon body size: density dependence, bioenergetics, and season. Each covariate observation was averaged by sampling event (week) and spatial strata (inside/outside). We used log transformed Chinook density (LnDensity) for the density dependence covariate. We hypothesize density would be negatively correlated with fork length because crowded fish have reduced access to food through competition. We used log transformed water temperature (LnTemp) for the bioenergetics covariate. We hypothesize water temperature values spanning winter to summer would be positively correlated with fork length because assimilation of food into body tissue is optimal when water temperatures warm during spring/early summer. Also, food availability in estuarine habitats follows the spring bloom which is related to seasonal increases temperatures and daylight hours. For the expected seasonal increase in fish length we used week or month.

Finally, we used the covariate matched 304 record dataset to test over twenty candidate models in their ability to predict juvenile Chinook length using ANOVA methodology. We listed candidate models by three categories (Biological Only, Simple Restoration, Yearly Restoration) to select various model factors and covariates (Table 8). The Biological Only models use only numerical covariate inputs for the hypothesized biological relationships that influence fish size. These included covariates for density dependence (DD), bioenergetics (BE), and temporal (week or month) previously described. Week and month correlate positively with water temperature so no candidate model could include values for both. We used either temperature or one of the temporal covariates. The Simple Restoration models use factors for restoration effects (before/after = BA) and spatial effects (inside/outside = IO) plus covariates for biological influences on fish length. The Yearly Restoration models substitute 'year' for 'BA' to account for restoration effects but are otherwise the same as the simple restoration models in accounting for possible biological effects.

Results: All 14 models described in Table 8 significantly characterize juvenile Chinook length at Fir Island Farms but their levels of AIC support and their ability to predict juvenile Chinook length vary widely (Table 9). The candidate models order in five groups of AIC support, ranging from ‘very good’ to ‘poor’ with overall R^2 ranging from 0.04 to 0.71. Overall, the seasonal influence on juvenile Chinook length is statistically the strongest. The top candidate models (i.e., categories: very good and good) all include either ‘week’ or ‘month.’ Month or week alone explain 62% and 65% of the variation in average juvenile Chinook length, respectively.

Restoration and spatial influences – juvenile Chinook were smaller in the years after Fir Island Farms was restored than before, and fish were larger in the habitat located ‘inside’ than ‘outside.’ These results were detected in models with- and without the strong seasonal influence included.

Biological influences – our hypothesized density dependent and bioenergetic effects were supported. Together, density and temperature alone (Model 5) explains nearly half of the variation in juvenile Chinook length. The model coefficient for density was negative while the coefficient for temperature was positive.

Model 11 is the model with highest AIC support, explaining 71% of the variation in Chinook length in our dataset. Model 11 finds fish are always larger, as a function of time, in habitat associated inside of Fir Island Farms than outside, but the difference is dampened after restoration (Figure 16). This is possibly due to confounding effects of density dependence and/or bioenergetics as illustrated by Model 5 (Figure 17 and Table 10). Model 5 is not particularly useful as a prediction tool for juvenile Chinook length *per se*, but it is useful to illustrate the effects of varying temperature and density on juvenile Chinook length. These variables are not only influenced by localized forces related to restoration, but are also influenced by external forces, such as warm/cold years or high/low outmigrant juvenile Chinook populations. Thus, it is not necessarily surprising to find juvenile Chinook length decreased after restoration at Fir Island Farms after considering the nuances of the biological relationships and annual variability in forcing factors external to Fir Island Farms. In summary, prior to restoration the few juvenile Chinook that could access the project site grew to large size because of low competition for food. After restoration the size difference between fish in the restoration site and those in the adjacent reference sites decreased, because many more fish could access the restored site, so that competition for food increased. The net result is that fish are not larger following restoration, but more fish have access to additional rearing habitat.

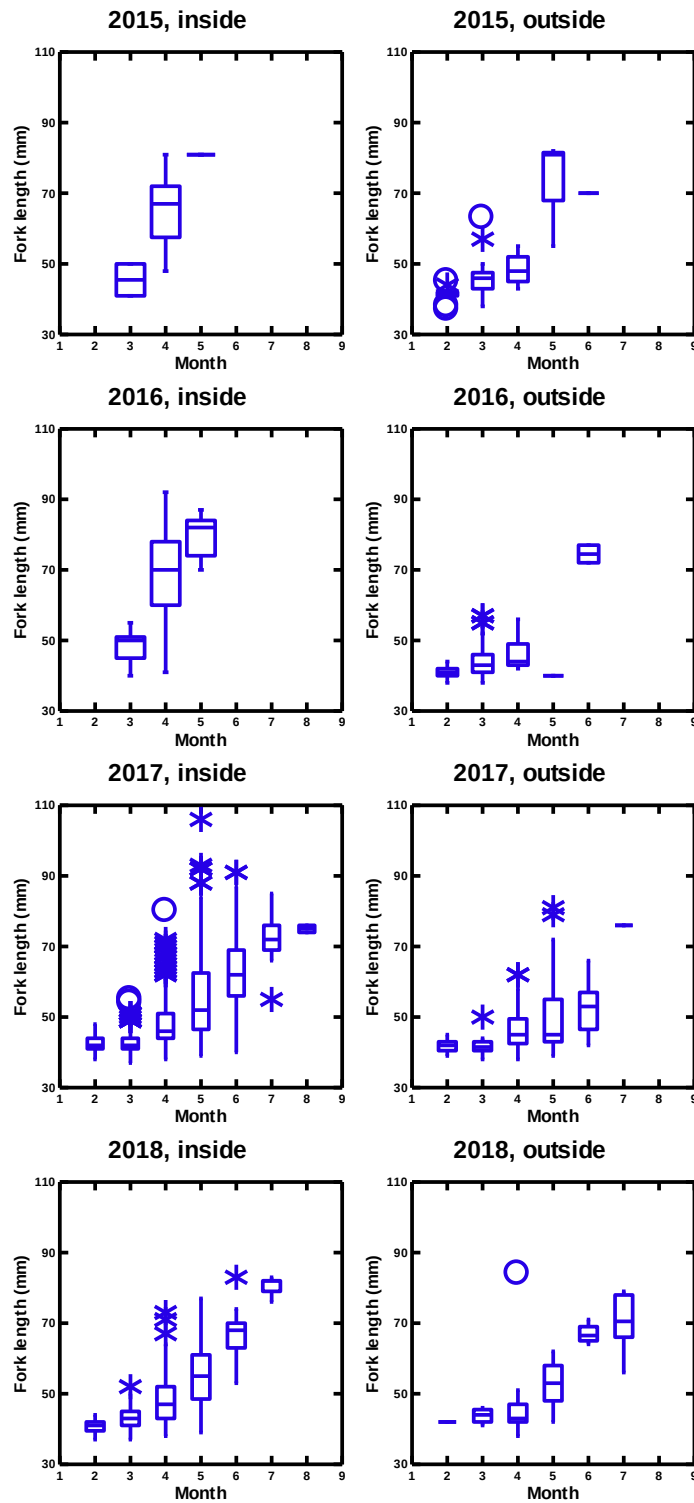


Figure 15. Boxplot of wild juvenile Chinook fork length at Fir Island Farms beach seine sites by year, month, and spatial strata (inside, outside). Boxes show median, 25th and 75th percentiles. Whiskers show the 5th and 95th percentiles. Stars are observations that are still within the full distribution. Circles (if present) are outliers, i.e., observations outside the statistical distribution.

Table 7. Count of average wild juvenile Chinook length samples by year, month and spatial strata.

Restoration	Year	Month	Spatial	
			inside	outside
Before	2015	2		3
		3	2	6
		4	4	5
		5	1	3
		6		1
		total	7	18
	2016	2		2
		3	3	6
		4	6	4
		5	2	1
		6		2
		total	11	15
After	2017	2	10	1
		3	28	2
		4	32	5
		5	18	4
		6	32	5
		7	9	1
		8	2	
		total	131	18
	2018	2	7	1
		3	14	2
		4	27	4
		5	25	5
		6	12	2
		7	3	2
		total	88	16

Table 8. Candidate models for predicting juvenile Chinook length (log transformed) using 304 records of average length. Models were only listed where all covariates are significant ($p < 0.05$) and at least one factor or interaction of interest is significant ($p < 0.05$). Model categories and components are explained in the text. The presence of an 'x' means that factor or covariate was included in the model.

Model category	Model components	Model #	Factors			Covariates			
			restoration	spatial	year	LnDensity	LnTemp	week	month
Biological Only	DD	Model 1				x			
	BE	Model 2					x		
	temporal 1	Model 3							x
	temporal 2	Model 4						x	
	DD/BE	Model 5				x	x		
	DD/temporal 1	Model 7				x			x
Simple Restoration	BA/IO only	Model 8	x	x					
	BA/IO + Model 5	Model 9	x	x		x	x		
	BA/IO + Model 7	Model 10	x	x		x			x
	BA/IO + Model 4	Model 11	x	x				x	
Yearly Restoration	Yr/IO	Model 14		x	x				
	Yr/IO + Model 7	Model 15		x	x	x			x
	Yr/IO + Model 3	Model 16		x	x				x
	Yr/IO + Model 4	Model 19		x	x			x	

Table 9. Performance of juvenile Chinook length models shown in Table 8. Only models are listed where all covariates are significant ($p < 0.05$) and at least one factor or interaction of interest is significant ($p < 0.05$).

Model #	R ²	First order autocorrelation	AIC (corrected)	Delta AIC	support tier
Model 11	0.706	0.002	-456.567	0	very good
Model 19	0.713	-0.018	-455.189	1.378	very good
Model 10	0.690	-0.027	-438.488	18.079	good
Model 15	0.696	-0.041	-435.666	20.901	good
Model 16	0.692	-0.047	-434.044	22.523	good
Model 4	0.650	0.132	-409.268	47.299	modest
Model 7	0.626	0.115	-389.23	67.337	modest
Model 3	0.618	0.118	-383.183	73.384	modest
Model 9	0.528	0.095	-311.749	144.818	fair
Model 5	0.484	0.154	-293.182	163.385	fair
Model 2	0.470	0.146	-284.904	171.663	fair
Model 1	0.048	0.110	-105.305	351.262	poor
Model 8	0.037	0.094	-97.809	358.758	poor
Model 14	0.046	0.089	-92.132	364.435	poor

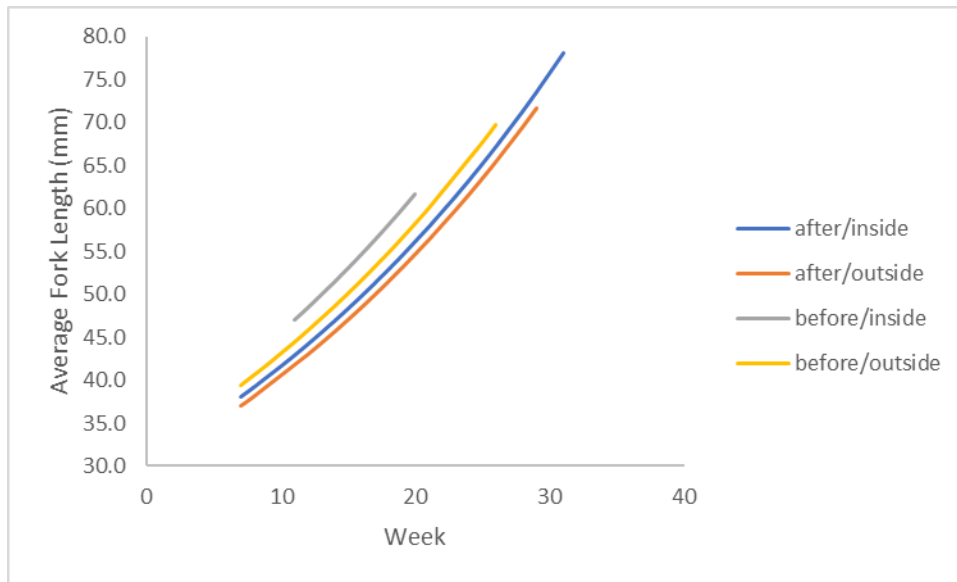


Figure 16. Juvenile Chinook length predictions from Model 11.

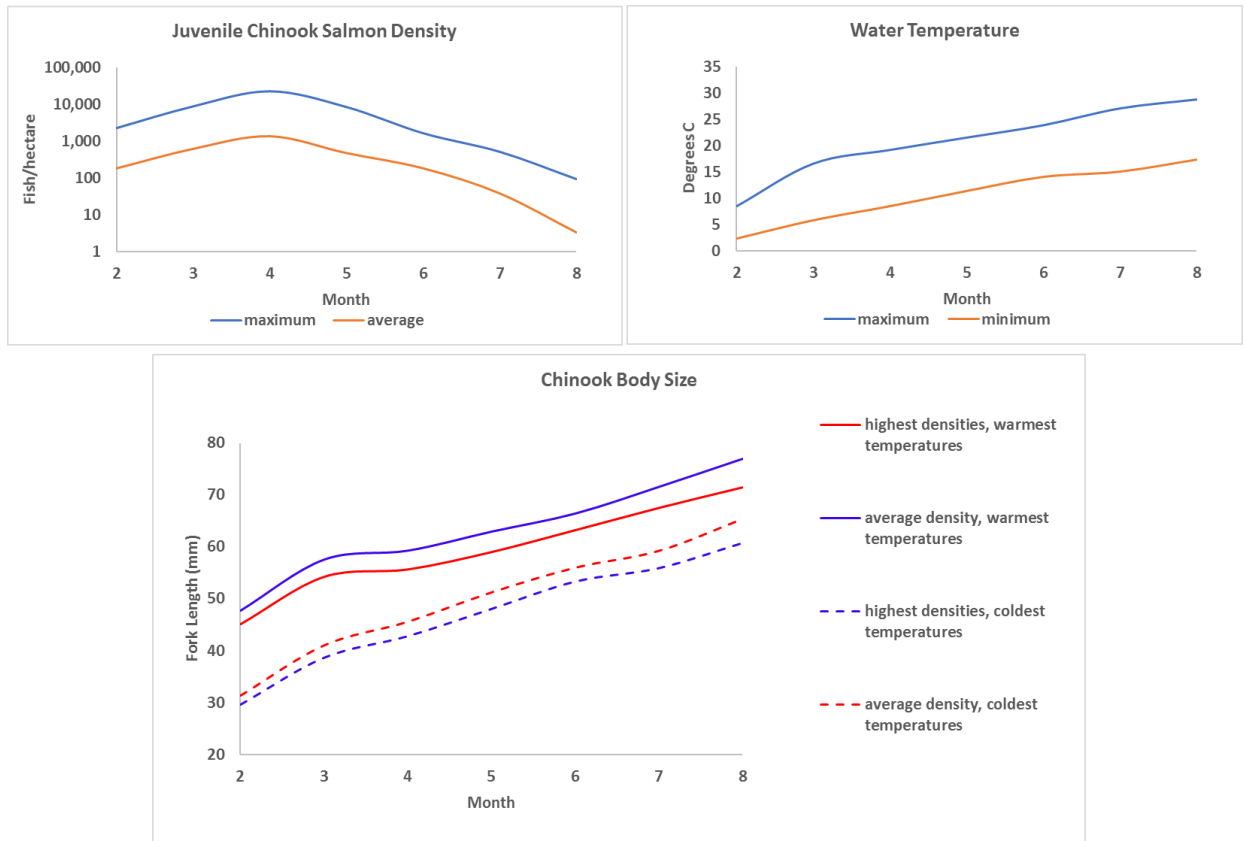


Figure 17. Model 5 scenario inputs and juvenile Chinook length predictions. The top left panel is a plot of the highest and average monthly juvenile Chinook densities in the Fir Island Farms dataset. The top right panel is a plot of maximum and minimum water temperature in the Fir Island Farms dataset. The bottom panel is predicted monthly juvenile Chinook length based on four scenarios using a combination of density and temperature from the top graph panels.

Table 10. Juvenile Chinook length predictions from Model 5.

Scenario	February	August	Length change (mm)	Growth (mm/month)
highest densities, warmest temperatures	45.0	71.5	26.4	4.4
average density, warmest temperatures	47.6	76.9	29.3	4.9
highest densities, coldest temperatures	29.6	60.8	31.2	5.2
average density, coldest temperatures	31.3	65.4	34.1	5.7
caused by differing density scenarios			2.9	0.5
caused by differing temperature scenarios			4.8	0.8

Recommendations for future monitoring

Fish respond to changes in habitat conditions which are influenced by landscape controls and natural processes (Beechie et al 2003; 2010). Understanding fish response to habitat restoration will likely require multiple years of monitoring coupled with on-site monitoring of habitat conditions while accounting for extrinsic factors such as varying fish population size, and seasonal and year differences in the environmental conditions (e.g. salinity, temperature, and flow). Initial restoration effectiveness monitoring is extremely useful but potentially not conclusive in estimating sustainable site performance if habitat conditions are expected to change significantly over time. Thus, we suggest periodic monitoring of habitat (channels, hydrology, vegetation) coupled with fish monitoring to determine the trajectory of fish response to habitat changes as they move toward their sustainable equilibrium conditions.

The frequency of monitoring can be determined based on the expected rate of change in habitat trajectory. Specifically, future predictions of channel allometry suggests tidal channel area at Fir Island Farms will decline from the 7+ hectares predicted in the feasibility study and observed after restoration for the ‘bankfull’ condition to a sustainable equilibrium amount of 2.22 hectares (0.89-5.52 hectares 80% confidence interval) (Table 6; Appendix 3, Table 1). If channel area declines, we hypothesize that juvenile Chinook abundance will also decline.

Initial post-restoration monitoring of Fir Island Farms vegetation found the site sparsely vegetated and dominated by non-native species two years after restoration (Hood 2018a, 2018b). Seasonal growth rates of juvenile Chinook salmon as indicated by changes in fork length frequency suggests that spatial and temporal heterogeneity in water temperature, prey availability and quality, and density dependent processes may act synergistically to influence growth of juvenile Chinook within a restored site. Specifically, marsh vegetation is known to secondarily produce highly nutritious prey targeted by juvenile salmon (e.g., Congleton 1978). Therefore, vegetation monitoring can be useful in inferring changes in salmon habitat productivity when coupled with monitoring of seasonal changes in juvenile salmon growth rates. A fundamental question for Fir Island Farms is whether the magnitude of the effects of density dependent processes regulating habitat use by juvenile Chinook salmon will decline as the restored habitat becomes more naturally vegetated and (presumably) on-site prey production increases? Furthermore, will the productivity of juvenile Chinook using the site increase as the site’s vegetation matures?

Finally, it is important to consider overall site differences of Fir Island Farms compared to other monitored restoration sites. For example, Fir Island Farms is well drained at low tide relative to other restored areas in the Skagit tidal delta where large wetted impounded areas remained at low tide (e.g., Wiley Slough, Fisher Slough). Sites with large impoundments may initially benefit from a pulse of detritus-based productivity immediately following restoration. Conversely, for Fir Island Farms and other similar sites, where there may not be a large detritus-base pulse, productivity may be more influenced by the development of the new marsh. Because these site differences may create different trajectories of site productivity, it is important to compare the performance of

multiple restored sites with differing allometric characteristics to better determine which site characteristics predict the long-term performance of restoration projects over time.

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Appendix 1. Fir Island Farms Estuary Restoration Project: Landscape Connectivity Calculation

Date: June 2, 2010

By: Karen Wolf, Skagit River System Cooperative

Purpose and Calculation Methods:

Within the delta and nearshore ecosystems of the Skagit River, Beamer et al. (2005) used habitat connectivity as an attribute to help predict the use of specific habitats for Chinook salmon recovery planning.

Landscape connectivity was defined as a function of both the length and the complexity of the pathway that juvenile Chinook salmon must follow to certain types of habitats, like blind tidal channels in the Skagit delta or pocket estuaries in adjacent nearshore areas. Habitat connectivity decreases as the complexity of the route fish must swim increases and as the distance the fish must swim increases. Within the Skagit delta, the complexity of the route fish must take to find key habitat was measured by the delta distributary channel bifurcation order and distance traveled. Beamer et al. (2005) show results from 2003, which had an outmigration population size of 5,500,000 juvenile Chinook salmon. In this year, landscape connectivity explained 68% of the variation in seasonal density of Chinook salmon at monitored sites within the Skagit estuary (see pages 20-21 of Beamer et al. 2005).

An ArcMap data layer, *fish_direction*, was created in GIS to calculate landscape connectivity values for specific places within the Skagit tidal delta or pocket estuaries within adjacent nearshore areas (e.g., Skagit Bay or Padilla Bay). *Fish_direction* reflects the pathways juvenile Chinook salmon are expected to move through the delta channel network and along the nearshore to find and colonize habitat. It includes quantification of 'Bi' (index bifurcation order) by creating GIS-based rules for the methods described in Appendix D.V, page 79 of Beamer et al. (2005). Pathway location and direction outside of the tidal delta is based on drift buoy results (Appendix D.VI, page 81 in Beamer et al. 2005) and low tide channel locations visible on orthophotos. The following attributes are included in the *fish_direction* GIS theme and are included in tables below for each Landscape Connectivity calculation.

Definitions of Table Headings

AssocPoly	Polynome from <i>tidelta</i> theme that fish direction arc is representing (if any)
Bi	Index bifurcation order
Length_km	Length of arc in kilometers
Km_x_bi	Kilometer length multiplied by Bi
Sum	Sum of all Km_x_bi values for a specific pathway
Landscape Connectivity	1/Sum

Results:

The Fir Island Farms Project footprint was provided by Bob Warinner (WDFW).

I calculated three different values of Landscape Connectivity based on three potential pathways that juvenile Chinook salmon might take to find the site.

These pathways are via: Browns Slough (Figure 1, Table 1), Davis Slough (Figure 2, Table 2), and Dry Slough (Figure 3, Table 3).

Reference

Beamer, E, A McBride, C Greene, R Henderson, G Hood, K Wolf, K Larsen, C Rice, and K Fresh. 2005. Delta and nearshore restoration for the recovery of wild Skagit River Chinook salmon: linking estuary restoration to wild Chinook salmon populations. Appendix to the Skagit Chinook Recovery Plan. Available at www.skagitcoop.org/.

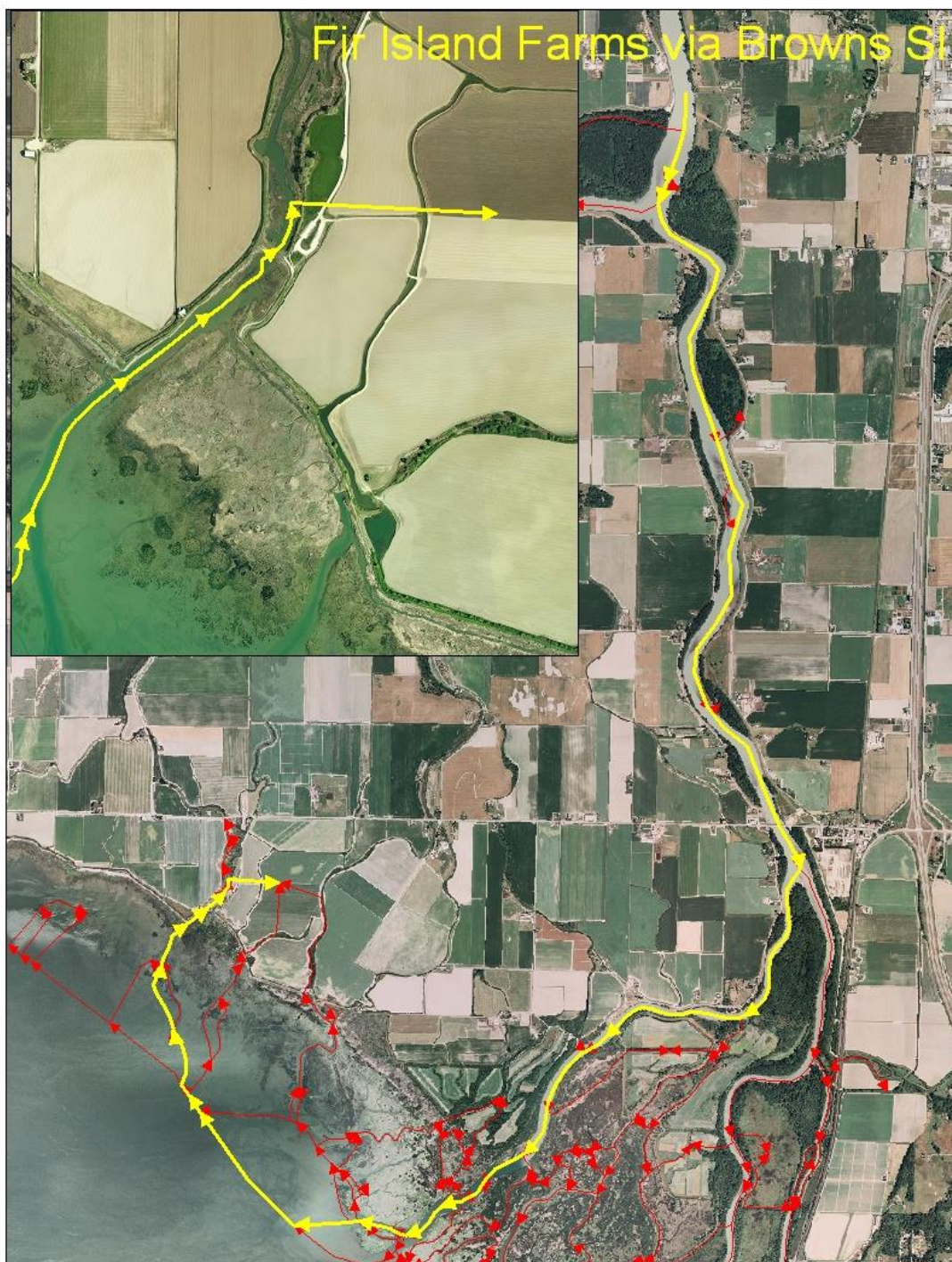


Figure 1. Pathway used to calculate Landscape Connectivity to Fir Island Farms Restoration Project via Browns Slough. Red and yellow arcs are from the GIS theme *fish_pathway*. Yellow arcs show the pathway chosen for calculating Landscape Connectivity to this site.

Table 1. Worksheet showing calculation of Landscape Connectivity to Fir Island Farms Restoration Project via the Browns Slough pathway.

AssocPoly	Comments	Bi	Length_km	km_x_bi
282		2	6.31612	12.63223
376		3	1.40477	4.21432
378		3	1.27704	3.83112
379		3	1.26078	3.78234
380		3	0.84745	2.54234
377		3	0.39639	1.18917
0		5	0.46167	2.30833
19		6	0.62397	3.74384
396		5	0.21863	1.09313
469		5	0.35162	1.75810
468		5	0.05392	0.26959
0		4	1.25725	5.02900
0		5	0.49378	2.46890
396		5	0.20521	1.02603
0		4	0.16446	0.65785
0		4	0.10664	0.42654
0	to Fir Is Farms via Browns Sl	6	0.43279	2.59674
244		5	0.10298	0.51491
23		4	0.41881	1.67524
23		4	0.06742	0.26969
281		1	0.78573	0.78573
281		1	0.18539	0.18539
Sum				53.00055
Landscape Connectivity				0.01887

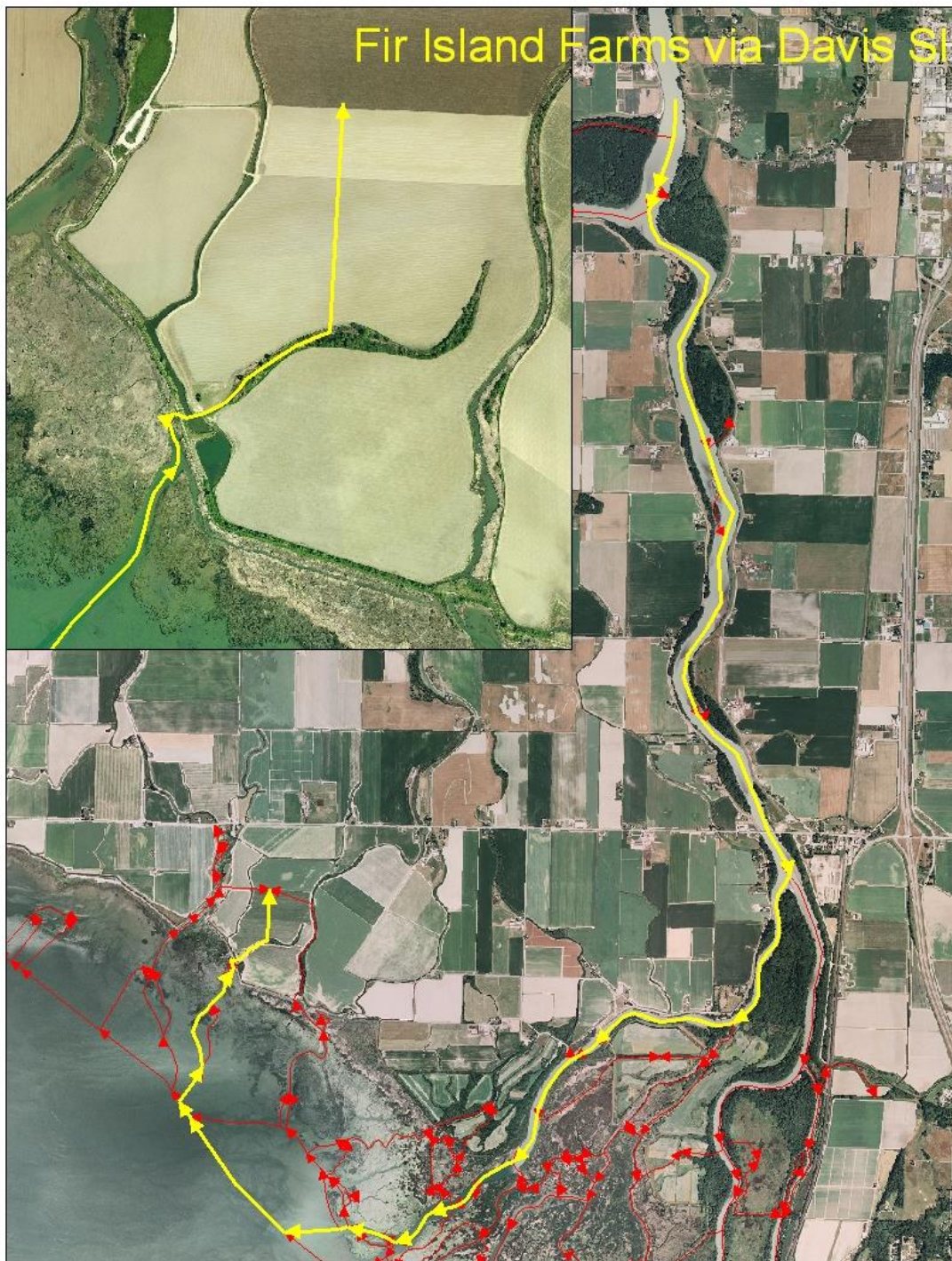


Figure 2. Pathway used to calculate Landscape Connectivity to Fir Island Farms Restoration Project via Davis Slough. Red and yellow arcs are from the GIS theme *fish_pathway*. Yellow arcs show the pathway chosen for calculating Landscape Connectivity to this site.

Table 2. Worksheet showing calculation of Landscape Connectivity to Fir Island Farms Restoration Project via the Davis Slough pathway.

AssocPoly	Comments	Bi	Length_km	km_x_bi
282		2	6.31612	12.63223
376		3	1.40477	4.21432
378		3	1.27704	3.83112
379		3	1.26078	3.78234
380		3	0.84745	2.54234
377		3	0.39639	1.18917
0		5	0.46167	2.30833
397		6	0.10594	0.63562
398		6	0.93436	5.60619
0		4	1.25725	5.02900
0		5	0.34916	1.74582
0		4	0.16446	0.65785
0	to Fir Is Farms via Davis SI	7	0.77689	5.43824
23		4	0.41881	1.67524
23		4	0.06742	0.26969
281		1	0.78573	0.78573
281		1	0.18539	0.18539
Sum				52.52862
Landscape Connectivity				0.01904

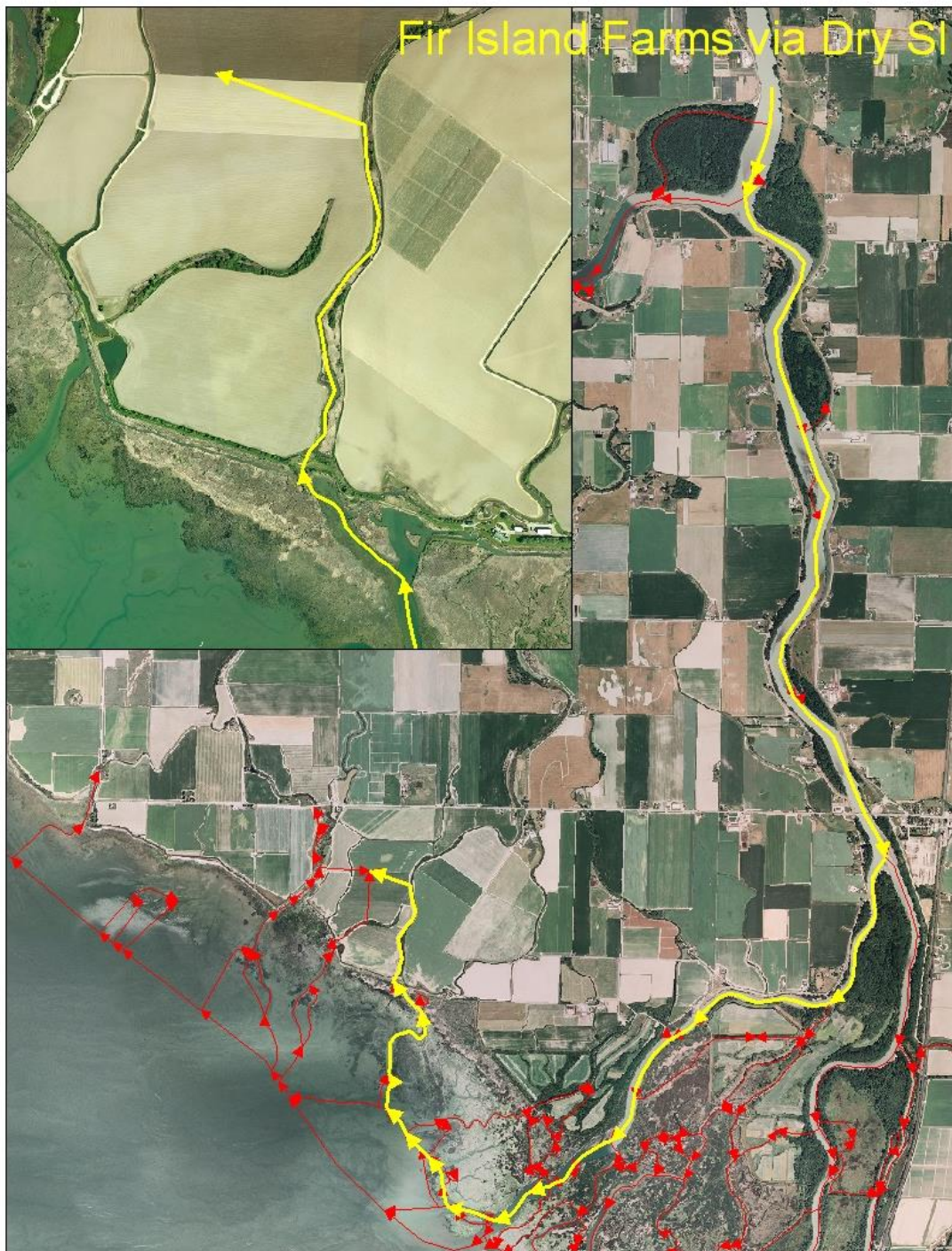


Figure 3. Pathway used to calculate Landscape Connectivity to Fir Island Farms Restoration Project via Dry Slough. Red and yellow arcs are from the GIS theme *fish_pathway*. Yellow arcs show the pathway chosen for calculating Landscape Connectivity.

Table 3. Worksheet showing calculation of Landscape Connectivity to Fir Island Farms Restoration Project via the Dry Slough pathway.

AssocPoly	Comments	Bi	Length_km	km_x_bi
282		2	6.31612	12.63223
376		3	1.40477	4.21432
378		3	1.27704	3.83112
379		3	1.26078	3.78234
380		3	0.84745	2.54234
377		3	0.39639	1.18917
155		6	0.31320	1.87918
198		8	0.36336	2.90688
402		6	0.82004	4.92025
158		6	0.46078	2.76470
0		7	0.07546	0.52824
0		5	0.18821	0.94107
0		5	0.26323	1.31613
0	to Fir Is Farms via Dry Sl	9	1.25075	11.25675
23		4	0.41881	1.67524
158		6	0.01766	0.10595
158		6	0.01766	0.10595
281		1	0.78573	0.78573
281		1	0.18539	0.18539
Sum				57.56299
Landscape Connectivity				0.01737

Appendix 2. Post-restoration relationship between water surface elevation and wetted area

For each fish sampling day, the wetted area was estimated in order to estimate the fish population size that used the restored FIF area over the monitoring season. Wetted area was calculated using water surface elevation (WSE) during the time of fish sampling. Thus, a WSE-to-wetted area relationship was developed for the FIF dike setback restoration area (Figure A1).

Initially, the wetted area was to be determined by digitizing elevation polygons from a high-resolution surface TIN (triangulated irregular network) to be provided by WDFW for the FIF As-Built (i.e., dike setback) condition. Unfortunately, WDFW was unable to provide an as-built TIN of the FIF restoration project area. Thus, we used data from five sources to digitize wetted area polygons representing varying WSE levels based on five data sources:

1. project design drawing elevations which are assumed to be as-built conditions,
2. the Pictometry orthophoto (taken May 21, 2017),
3. a Google Earth photo (taken July 24, 2017),
4. 2012 LiDAR (representing ‘before restoration’ conditions), and
5. field notes describing flooded extent collected during the time of fish sampling.

We used water pressure loggers to measure WSE at two locations within the Fir Island Farms dike setback area during 2017 in order to correlate wetted area polygon results to measured WSE (see Table below). Polygons were digitized on a Wacom DTU-2231 Interactive Pen Display tablet at a scale generally between 1:100 and 1:200.

WSE (NAVD88ft)	Wetted Area (ha)	photo figure #	Data Source
2.97	2.311	A2	Low tide condition (Google Earth, July 24, 2017)
5.00	7.108	A3	Bankfull channel condition (channel polygons only (Pictometry Orthophoto, May 21, 2017)
6.01	27.682	A4	Wetted area showing on the Pictometry Orthophoto, May 21, 2017)
10.00	53.073	A5	Fully flooded condition WSE to toe of dike (Pictometry 2017)

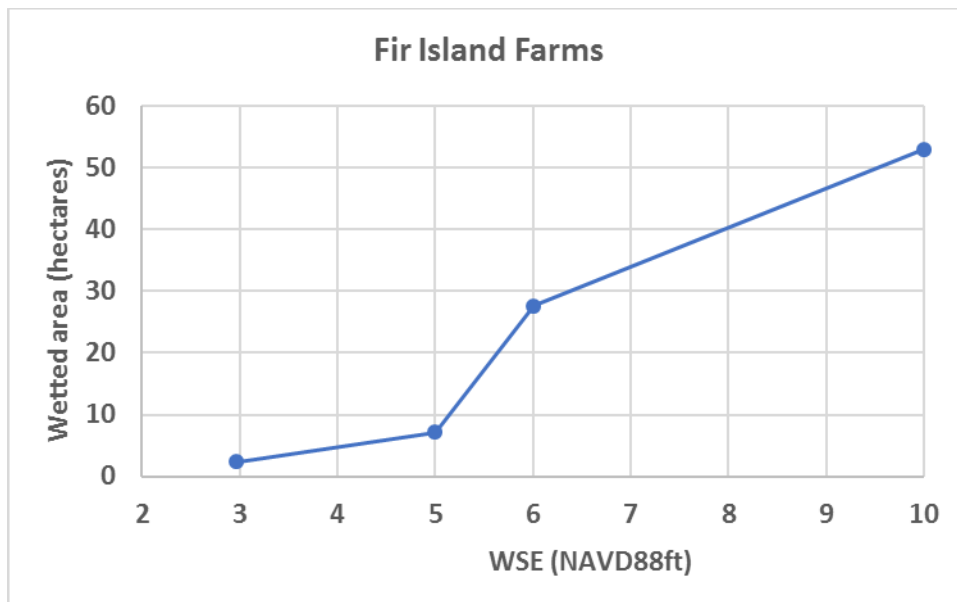


Figure A1.



Figure A2. **FIF during low tide conditions. The polygon was digitized over a background photo** is from Google Earth, taken July 24, 2017 at 1:30 pm PDT which coincides to a WSE on the Upper FIF gage of 2.97 ft NAVD88. The polygon was then displayed on the 2017 pictometry photo. We figured the time stamp out by using an online sun angle calculator compared to shadow positions visible in the photo on trees and buildings (located just SE of the FIF project area). Low water conditions within the FIF area is influenced by a sill located seaward of the project area. WSE doesn't go much lower than 2.56 ft NAVD88 because of this sill.

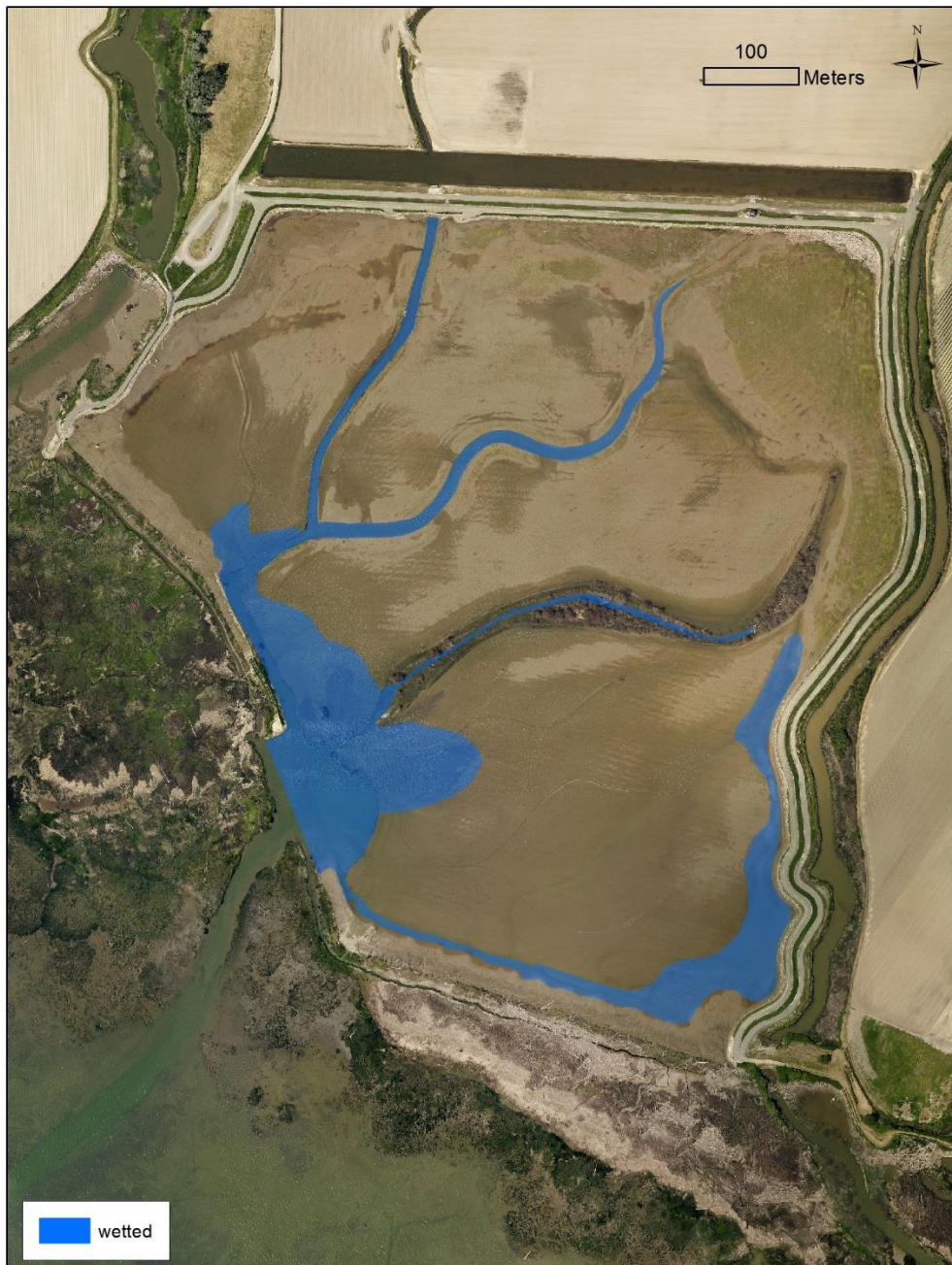


Figure A3. Fir Island Farms at a WSE of 5.0 ft NAVD88. This elevation is bank full of the channels



Figure A4. FIF during high tide conditions on May 21, 2017. The background photo was taken at approximately 2:45pm PDT which coincides to a WSE on the Upper FIF gage of 6.01 ft NAVD88. We figured the time stamp out by using an online sun angle calculator compared to shadow positions visible in the photo on trees and buildings (located just SE of the FIF project area).



Figure A5. Fir Island Farms at fully flooded perimeter to the toe of the dike which is at 10.0 ft NAVD88

Appendix 3. Fir Island Farms tidal channel habitat prediction

Methods

Sustainable tidal channel surface area and count were predicted for the as-built Fir Island Farms restored area using an allometric model that links marsh area to channel geometry (Hood 2007, Hood 2015). This is essentially an empirical regression model, i.e., patterns in reference marshes were used to predict outcomes in restoration marshes. The simplest form of the model finds that marsh area alone is sufficient to predict channel metrics (Hood 2007). While, more recent work finds that there is geographic variation in tidal channel allometry, and that tide range, storm wave fetch, and sediment supply also affect channel geometry in predictable ways to explain that geographic variation throughout Puget Sound (Hood 2015), the FIF area is relatively close to the South Fork Skagit Delta, so the simplest form of the South Fork model was deemed sufficient to provide a reference system for FIF.

Tidal marsh restoration through dike breaching or removal can have direct effects on channel network geometry in the restored site, as well as indirect effects on the channel network of the existing adjacent tidal marsh (Hood 2004). Restoration of upstream tidal prism via new tidal channels or restored tidal marsh surface drainage area will typically increase the width and surface area of downstream tidal channels in existing adjacent downstream marsh as the channels adjust (erode) to accommodate the increased tidal prism contributed by the newly restored site. Channel length is less likely to be increased unless new tidal channels develop in the downstream marsh. This indirect effect is expressed in the empirical allometric model as a non-linear effect of marsh area on tidal channel surface area and length. For example, one 100-acre marsh site typically has more tidal channel area and length than do two 50-acre sites, which typically have more channel area and length than four 25-acre sites, and so on. Restoring a site adjacent to existing tidal marsh produces more tidal channel than one would calculate separately for the restored site and the adjacent existing marsh, i.e., the whole is greater than the sum of its parts.

To calculate the likely indirect (i.e., off-site) effects of site restoration on existing, adjacent, downstream tidal marshes, the allometric model was applied to the sum of the surface areas of the restoration site and the adjacent downstream tidal marsh to generate channel geometry predictions for both sites as a collective unit. Then the allometric model was applied only to the restoration site and the result subtracted from the prediction for the collective site and adjacent off-site area. This produced an estimate of the channel surface area and length in the adjacent downstream marsh that would result from the indirect effect of project site restoration. This estimate can be compared to the currently existing amount of tidal channel area and length to see if a significant increase would be likely in the adjacent downstream marsh. In some cases, the existing adjacent marsh already has an unusually large number and size of tidal channels so that the prediction can be less than existing. This is a circumstance which prevents confident estimation of off-site effects of restoration. In most cases the predicted channel area and length is greater than the existing amount so that confidence in an off-site effect is greater.

Results

Fir Island Farms is located on the bayfront between the outlets of Browns and Dry Sloughs on Fir Island. The site is bordered by adjacent existing tidal marsh to the south (Figure 1), so downstream effects of site restoration were considered for the adjacent marsh. The reference system for allometric prediction (Table 1) consisted of the Skagit South Fork tidal marshes, due to the project site's proximity to the South Fork marshes and relatively similar exposure to Skagit Bay fetch.

Table 1. Allometric predictions of tidal channel area for FIF, with 80% confidence limits of the prediction in parentheses. Row labeled "Total – Upstr" shows the difference between upstream project site plus downstream existing marsh ("Total") predictions and project site only ("Upstr") predictions (i.e., indirect or downstream effects of project site restoration), with currently observed channel metrics in the existing downstream marsh shown in brackets for comparison with indirect effects predictions.

Site	Site area (ha)	Predicted channel area (ha)	Predicted channel outlet (count)
FIF restored area	53.073	2.22 (0.89 – 5.52)	22 (11-46)
FIF + dwnstr	83.096	4.39 (1.75 – 11.01)	na
Total - Upstr	30.023	2.17 [0.20]	na

Downstream effects on tidal channel development may be limited for the FIF restoration project and overestimated by our model, because the restoration site has only one outlet—to a large, pre-existing tidal channel that served as a drainage outlet for the site when it was farmed, and which conveyed and still conveys significant drainage from other farmlands on Fir Island. The restoration site is subsided relative to adjacent tidal marsh, so most of its tidal prism must drain through this single outlet. Thus, the outlet channel may deepen and widen given the newly reintroduced tidal prism, but other tidal channels outside of the project footprint will receive little additional tidal prism and so are unlikely to respond much to the nearby restoration. A single outlet channel for a 53 hectare tidal footprint is much lower than the median value of 22 channels (Table 1).

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Figure 1. Fir Island Farms restoration project site (red outline) and adjacent downstream marshes (yellow outline). The western downstream marsh boundary is formed by Browns Slough. The eastern boundary runs from the southeast corner of the restoration site to Skagit Bay, perpendicular to the shoreline.