Evaluating the role(s) of the Butte sink and Sutter Bypass for Butte Creek spring-run Chinook Salmon and other Central Valley juvenile salmonid populations - 2019 study year

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SUMMARY

California's Central Valley (CCV) Chinook Salmon stock has declined substantially since the mid-1800s with the spring, winter and late-fall runs listed as threatened or endangered, and the fall run heavily supplemented by hatcheries. As the largest population of CCV wild spring-run Chinook, Butte Creek fish are an important source for promoting life history diversity in the CCV Chinook Salmon community. This ESA listed population has been a relatively successful and stable population compared to other threatened Central Valley spring-run Chinook Salmon populations (i.e. Mill, Deer and Battle Creek). The Butte Sink and Sutter Bypass have been suggested to play an important role in their success by providing juvenile salmon a rich floodplain rearing habitat before their out-migration to the Pacific Ocean.

This project had several purposes. The first one was to quantify the differences in growth between the Butte Sink, Sutter Bypass, and adjacent Sacramento and Feather River habitats, for Butte Creek juvenile Chinook Salmon and other CCV Chinook Salmon populations that could potentially access those habitats. The second goal was to better understand the complex hydrology of the lower Butte Creek watershed during baseline and flooding conditions, and to characterize the food web composition and its dynamics through time. And the third goal was to identify which runs of Chinook Salmon were accessing the Butte Sink and Sutter Bypass, when the weirs overtopped and Sacramento River water mixed with Butte Creek water.

The key findings were that off-channel habitats within the Butte Sink and Sutter Bypass supported high growth rates for juvenile salmon. Both the Sacramento River and Feather River supported lower growth rates compared to the off-channel habitats of the Butte Sink and Sutter Bypass. Both managed wetlands and flooded agricultural habitats within the Butte Sink and the Sutter Bypass provided high growth rates. The abundance of zooplankton was much higher on the off-channel Butte Sink and Sutter Bypass locations and functioned as a food resource for the juvenile salmon. All four runs of Chinook Salmon were captured in either the Butte Sink or Sutter Bypass, highlighting the potential importance of these habitats for all four runs of Central Valley Chinook Salmon.

INTRODUCTION

The California Central Valley (CCV) supports four runs of Chinook Salmon that are named according to the season in which the adults return to freshwater: fall-, late-fall-, winter-, and spring-run. Prior to Euro-American settlement, an estimated 1-2 million wild Chinook Salmon would return to the CCV rivers each year (Yoshiyama et al. 1998), achieving this abundance in large part because they had access to vast and diverse natural freshwater habitats, from which this unique diversity of Chinook Salmon life history strategies emerged.

Central Valley rivers once carried runoff from large winter storms and spring snowmelt onto low-lying floodplains, slowing and spreading water into complex mosaics of riparian forest and wetlands. Large flood basins, floodplains, and tidal wetlands were often inundated for long periods in most years providing food rich rearing habitat that was essential to support the large salmon populations. Those highly productive floodplain waters provided ideal conditions for juvenile salmon to feed and grow before migrating to the ocean (Welcomme 1979, Ribiero et al. 2004). Over the last century and a half, however, floodplain habitats have been diminished by 95% since pre-settlement levels (Hanak et al. 2011). Valued for their rich soils, most of the Central Valley's floodplains have been converted to agriculture and have been disconnected from their rivers by levees and dykes (Speir et al. 2015). Flow alteration, especially the reduction of large flow events, from large upstream dams and water diversions, has also limited the inundation duration and extent of remnant floodplain habitats. The loss of floodplain habitat, along with other limiting factors such as the loss of spawning habitat and the degradation of remaining migratory corridors have taken a toll on CCV Chinook Salmon. Currently the fall- and late fall-run are listed as "Species of Concern", fall-run is also heavily supplemented by hatcheries, spring-run is listed as threatened, and winter-run is listed as endangered under the Endangered Species Act (Williams 2006).

In order to control high flows that would otherwise inundate farmland and cities, the Sacramento Flood Control Project was created in 1911 and adopted by Congress in the Flood Control Act of 1917 (Kelley 1989). The Project was designed to passively spill water from the Sacramento River and tributaries through a system of weirs into a series of flood bypasses. The system of bypasses was designed to divert floodwaters from the main river channels and eventually convey the floodwaters into the Sacramento-San Joaquin Delta. The Sutter Basin is the uppermost flood bypass in the Sacramento Valley, encompassing approximately 14,000 hectares from the Butte Sink in the north to the confluence of the Sutter Bypass with the Feather and Sacramento Rivers near Verona in the south. In late winter and spring, Sacramento River water can flow into the Butte Sink and the Sutter Bypass via Moulton, Colusa, and/or Tisdale weirs. In addition, the upper Butte Creek watershed connects to the Butte Sink just north of the Sutter Buttes. The low lying topography of the Butte Sink and Sutter Bypass and the design of the weir infrastructure connected to the Sacramento River means that the Sutter Bypass floods nearly every year and is a crucial piece of the Central Valley Project relieving pressure on the levees of the Sacramento and Feather Rivers (CVFMPP 2010). The frequent inundation allows for off-channel ecosystem processes to persist in the current altered hydrologic landscape. These processes provide ecosystem services such as groundwater recharge, food web production, and off-channel habitat for aquatic species (Sommer et al. 2001, Grozholtz and Gallo 2006, Opperman et al. 2009).

Butte Sink and Sutter Bypass provide important rearing habitat for Butte Creek spring-run Chinook Salmon population, especially in years of extensive winter and spring flooding (Ward and Mc Reynolds 2004, Johnson and Lindley 2016). This ESA listed population has been a relatively successful and stable population compared to other threatened spring-run Chinook Salmon populations (i.e. Mill, Deer and Battle Creek; Azat et al. 2017). Recapture data of coded wire tagged (CWT) Butte Creek fry suggest that large numbers of spring-run juveniles reside for extended periods in the Butte Sink and Sutter Bypass before continuing their migration to the ocean (Ward and McReynolds 2004).

This project presents a unique opportunity to investigate the potential ecosystem benefits of one of the last ephemeral floodplain habitats found in the Sacramento Valley for the remaining populations of Chinook Salmon from the Sacramento River and its tributaries. This project focused on measuring the water quality, food web, and resulting performance of juvenile Chinook Salmon in the Sutter Basin and adjacent locations in the Sacramento and Feather Rivers. These findings will help inform water managers and habitat restoration and reconciliation efforts for Chinook Salmon in CCV.

OBJECTIVES

The purpose of this study was to quantify the benefits of the Butte Sink and Sutter Bypass for juvenile Chinook Salmon compared to adjacent river channel habitats. Future management actions can utilize this information to maximize benefits to juvenile salmon and help enhance the abundance of Chinook Salmon populations in the CCV. Consequently, it is crucial to first have a better understanding of what mechanisms and locations create high quality habitat for juvenile salmon. To do this, we developed this study that aimed at answering the following questions:

1) How does the hydrology of the Butte Sink and the Sutter Bypass (see Figure 1 for region's delineation) affect juvenile Chinook Salmon?
2) What are the growth benefits to juvenile Chinook Salmon rearing in Butte Sink and Sutter Bypass in comparison to adjacent channelized rivers habitats?
3) What runs of Chinook Salmon utilize the Butte Sink and Sutter Bypass?

MATERIALS AND METHODS

Site locations

13 locations were selected for the study across 5 regions: 1) Butte Sink: North of Colusa weir, 2) Upper Bypass: Colusa weir to Tisdale weir, 3) Lower Bypass: Tisdale weir south to Sacramento River, 4) Sacramento River, and 5) Feather River (Table 1, Figure 1). Three different habitat types were identified; channel, off-channel wetland, and off-channel agricultural substrate. Some regions, such as the Butte Sink and Sutter Bypass, had several habitat types considered, while others, such as the Sacramento and Feather River, were only characterized by one type of habitat.

Table 1. Cage site locations across the different regions, and associated data collection.

Region	Location	Habitat type	Growth Cage Number	Gut Content Cage	Dissolved oxygen	Water quality	Lower trophic
Butte Sink	BSW1	Wetland	2		YES	YES	YES
	BSW2	Wetland	2	YES	YES	YES	YES
	BSC1	Channel	2			YES	YES
Upper Bypass	UBA1	Agriculture	2			YES	YES
	UBW1	Wetland	2	YES	YES	YES	YES
Lower Bypass	LBW1	Wetland	2	YES	YES	YES	YES
	LBA1	Agriculture	2			YES	YES

	LBA2	Agriculture	2			YES	YES
Sacramento River	SRC1	Channel	2		YES	YES	YES
	SRC2	Channel	2	YES		YES	YES
	SRC3	Channel	2			YES	YES
	SRC4	Channel	2			YES	YES
Feather River	FRC1	Channel	2	YES	YES	YES	YES

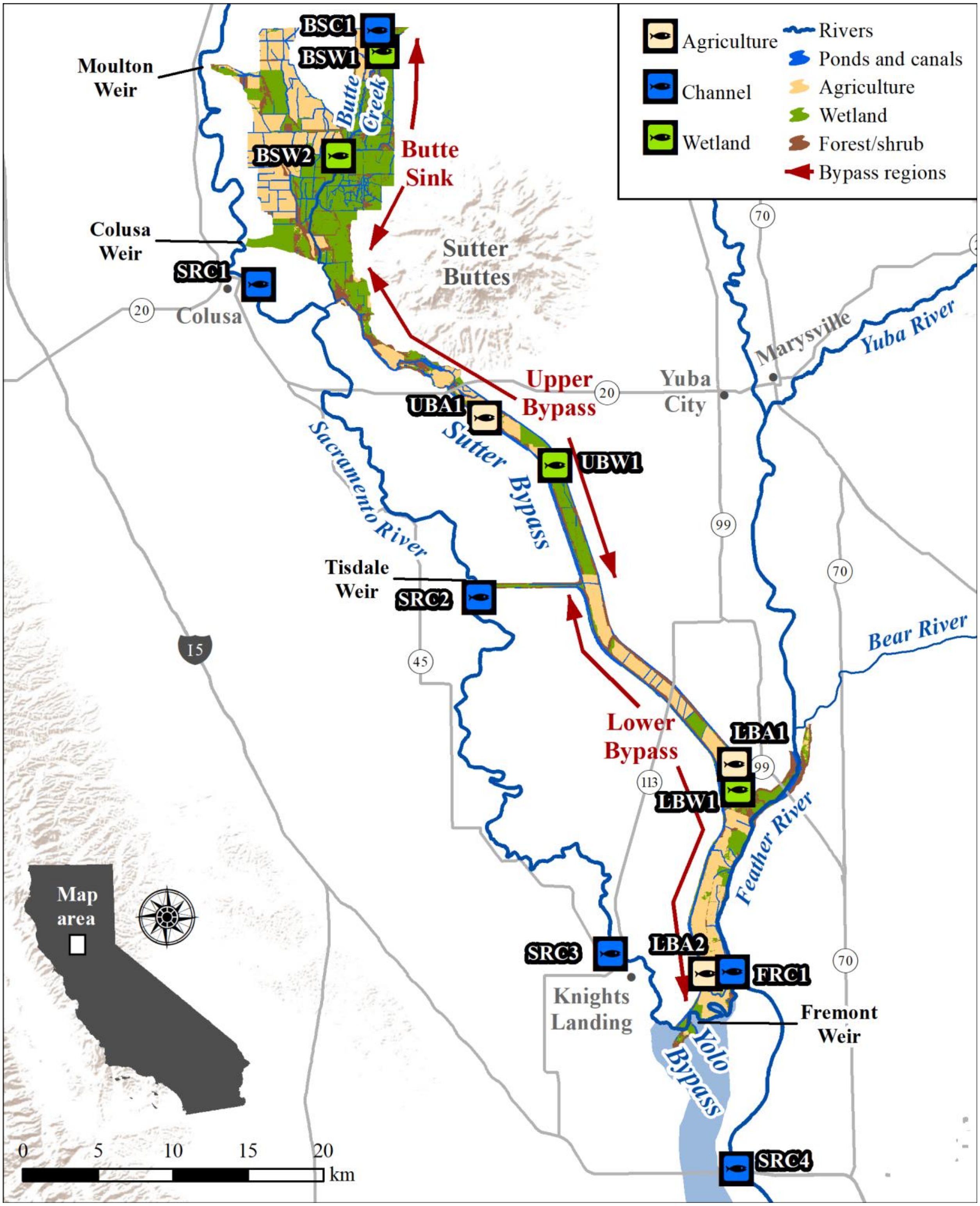

Figure 1. Study area map with the different regions considered and the fish cage locations. The Butte Creek watershed is separated in three regions: 1) Butte Sink: North of Colusa weir, 2) Upper Bypass: Colusa weir to Tisdale weir, 3) Lower Bypass: Tisdale weir south to Sacramento River.

Hydrology

River flow data for the three main inputs; Sacramento River, Feather River, and Butte Creek, including the Butte Sink and Sutter Bypass was downloaded from the California Data Exchange Center (CDEC, http://cdec.water.ca.gov/). Sacramento River flow data came from the Sacramento River at Butte City (BTC) gaging station. Feather River flow came from the Feather River at Boyd's Landing above Star Bend (FSB) station. Butte Creek flow data was obtained from the Butte Creek at Durham (BCD) station. Input to the Sutter Bypass from the Sacramento River at the three passive weirs was obtained from Sacramento River at Moulton Weir (MLW), Sacramento River at Colusa Weir (CLW), and Sacramento River at Tisdale Weir (TIS). Sutter Bypass flow was obtained from the Butte Slough near Meridian (BSL) gage.

A rating curve was developed between the quantity of area inundated in the Sutter Bypass, which extends from Pass Road in the north to the Sacramento River in the south. Area inundated was estimated using a normalized difference water index (NDWI, Eq. 1) on Landsat 8 band remotely sensed data collected from USGS EROS website. Six dates were chosen from the period of record, 2013-2019, which spanned the range of flooded conditions and satisfied the <5% maximum cloud cover criteria. The relationship between river stage at BSL and the proportion of inundated area in the Sutter Bypass was modeled using a linear model (Eq. 2).

$$NDWI = \frac{green-NIR}{green+NIR} \qquad \text{Eq. 1}$$

$$Y = B_0 + B_1X \qquad \text{Eq. 2}$$

with Y = proportion of inundated area, and X = river stage.

Water quality sampling

Water quality sampling was performed from 1/7/2019 to 4/29/2019. Continuous water temperature (°C) was collected at all sites, and continuous dissolved oxygen (mg/L, DO) was collected at a subset of 6 sites (one site per region, see Table 1) using submersible Onset U26 loggers continuously recording at a 15-minute interval and suspended approximately 0.5 meters below the water surface.

Point water quality data was also collected weekly at all sites with a YSI Exo2 multi parameter sonde. The parameters collected were: temperature (°C), dissolved oxygen percent saturation (%), dissolved oxygen concentration (mg/L), turbidity (NTU), chlorophyll-a concentration (µg/L), blue-green algae concentration (µg/L), electrical conductivity (µg/cm), salinity (PSU), and pH.

Additionally, water grab samples with 125mL bottles were used for laboratory water chemistry analysis. The parameters analyzed included total nitrogen (ppm), ammonium (NH_4; ppm, nitrate (NO_3; ppm), total phosphorus (TP; ppm), phosphate (PO_4; ppm), and dissolved organic carbon (DOC; ppm). Chlorophyll-a (ppb) and pheophytin α (ppb) was sampled with water grab samples in 1L bottles, filtered and analyzed at UC Davis.

Zooplankton sampling

Zooplankton was sampled weekly, at all sites, from 1/7/2019 to 4/29/2019, using a 30 cm diameter 150 µm mesh zooplankton net thrown five meters and retrieved through the water column four times from the stream bank. To account for differences in sampled volume due to variable water velocities, a flow meter attached to the zooplankton net was used to estimate the volume of water sampled. All samples were preserved in a solution of 95% ethanol.

Zooplankton subsampling was necessary due to the high density of invertebrates within the samples. Samples were rinsed through a 150 µm mesh and then emptied into a beaker. The beaker was filled to a known volume to dilute the sample, depending on the density of individuals within the sample, and then sub-sampled with a 1mL large bore pipette. If densities were still too great for enumeration the sample was split using a Folsom splitter or a colander before sub-sampling with the bore pipette. The dilution volume, number of splits, and number of aliquots removed was recorded and used to obtain total estimates of invertebrates which were divided by the total volume sampled to estimate density. Zooplankton samples were sorted into two groups of one hundred. One group was for the taxonomic group with the highest amount of individuals counted. A second group was for the total individual counts of each of the other taxonomic groups added up such that they met or exceeded a hundred in their total numerical count. If a hundred counts of the single highest taxonomic group was reached, but not a hundred of the remaining total individuals, then in the following aliquots the highest taxonomic group was not counted. Invertebrates were identified with the aid of a dissecting microscope at 4x magnification to the lowest taxonomic level possible using keys from "Ecology and Classification of North American Freshwater Invertebrates" (Thorp and Covich 2009), "Recent Freshwater Ostracods of the World" (Karanovic 2012), and "An Introduction to the Aquatic Insects of North America" (Merritt et al. 1996). Copepods were only identified to family. Terrestrial invertebrates were rare and not included in final counts.

Caged salmon experiment

The cage experiment was implemented from 2/19/2019 to 4/3/2019 (i.e. 42 or 43 days per cage) to study site-specific juvenile Chinook Salmon growth rates in the winter months, which corresponds to their peak rearing time period in the CCV (Williams 2006). Cages were utilized to maintain fish within a specific habitat for the duration of the study. Each site had two 2’x2’x4’ floating cages constructed with 1” pvc pipe frames enclosed with 1⁄4” plastic mesh material. This cage design has been used extensively for similar studies throughout the CCV. The cages allowed for re-measurement of fish at a specific location as well as allowing for food resources to enter the cage that are of a suitable size for juvenile salmon.

Each cage was stocked with 5 individually PIT tagged juvenile fall-run Chinook Salmon sourced from the Feather River Hatchery. The caged salmon were measured for fork length (FL) to the nearest millimeter and weighed to the nearest 1/100th of a gram (g) with an Ohaus Scout Pro scale, at a two-week interval (week 2: 3/4/2019-3/6/2019, week 4: 3/18/2019 - 3/21/2019, week 6: 4/1/2019 - 4/3/2019). The only exception to the two-week interval was during week 2 at BSW2 which was delayed a week until 3/12/2019.

One site per region had an additional double sized cage (2’x4’x4’) with 15 fish each. Three fish were randomly sampled and euthanized per week to look at gut contents over the course of the experiment (Table 2). Additionally, at the end of the 6 weeks, all remaining caged fish were euthanized and were used for gut contents.

Table 2. Number of salmon lethally sampled at each sampling date and for each site location. Numbers in parentheses denotes “placebo” fish stocked in weeks 2 or 4, to keep the same number of fish per cage over the course of the experiment. Asterisk denotes fish stocked in week 1 at Feather River to replenish 2 cages (1 growth and 1 gut content) which were beached during the descending hydrograph.

Region	**Location**	**Week 1 (2/25 - 2/26)**	**Week 2 (3/4 - 3/6)**	**Week 3 (3/11 - 3/12)**	**Week 4 (3/18 - 3/21)**	**Week 5 (3/25 - 3/26)**	**Week 6 (4/1 - 4/3)**	**Total**
Butte Sink	BSW1						7 (3)	10 (3)
	BSW2	3		3	3	2	10 (4)	21 (4)
	BSC1		1				10 (4)	11 (4)
Upper Bypass	UBA1						10 (3)	10 (3)
	UBW1	3	3		3	4	10 (2)	23 (2)
Lower Bypass	LBW1	3	3	2	1	1	10 (2)	20 (2)
	LBA1						10 (1)	10 (1)
	LBA2						10 (6)	10 (6)
Sacramento River	SRC1						9 (7)	9 (7)
	SRC2	3	3	3	3	3	10 (4)	10 (4)
	SRC3						8 (2)	8 (2)
	SRC4						10	10
Feather River	FRC1	1	3*	3*	2*	1*	9 (4*, 1)	20 (13*, 1)

Salmon diet

Stomach contents from euthanized caged salmon and collected fall-run Chinook Salmon (allowed under CDFW permit SC-13029) were identified to their lowest possible taxonomic group with the aid of a dissecting microscope at 4x magnification. Due to the partially decomposed nature of stomach contents, individuals were identified to their lowest taxonomic level. Cladocerans and amphipods were size classed into being smaller than or larger than 1.5 millimeters. The same taxonomic keys from the zooplankton identification were used to identify the stomach contents as well.

Growth estimation and modelling

We used individual fork length and weight measurements performed at week 0, 2, 4 and 6 to estimate a site-specific mean daily growth rate during the two-week intervals (expressed in millimeters per day (mm/day), and grams per day (g/day)), as well as a site-specific daily growth rate averaged for the entire length of the experiment (i.e. 6 weeks).

To explore the potential impact of cage location on fish growth rate we assessed whether there were statistically significant differences in the 6-weeks averaged mean daily FL growth rates among 1) region, and 2) habitat type (using “aov” and “anova” functions in R; see Table 1 for a list of regions and habitat types). A Tukey test (“TukeyHSD” function in R) was then used to perform a pairwise comparison of regional and habitat-specific FL growth rates.

Additionally, we developed various mixed effect growth models (Eq.3, Zuur et al. 2009, 2013) to investigate the influence of various biological and environmental factors on the site-specific mean daily fish FL growth rates. Particularly we looked at the influence of zooplankton density (Zoop; per m^3), chlorophyll-a concentration (CHL), Blue-Green-Algae (BGA), pH, turbidity (Turb), water temperature (Temp), and electrical conductance (SPC). Based on preliminary data exploration we decided to use the logarithm of the zooplankton density in this analysis (log Zoop). For each factor, we used the mean value averaged over the week when fish sizes were collected (i.e. at week 2, 4 and 6 of the experiment). Prior to fitting the models to the growth data, all the factors were also standardized. Cage location attributes (i.e. region or habitat type) were used as a random effect in the model to describe their influence on fish growth rate (Eq. 3). The coefficients of each model were estimated using the function “lmer” from the R package “lme4” (version 3.1.1., R Development Core Team 2013). Finally, we used Akaike's

Information Criterion corrected for small sample sizes (AICc) for model selection (Akaike 1973; Burnham and Anderson 2002).

$$\begin{aligned} Growth\ Rate &= Fixed\ effect + Random\ effect \\ Fixed\ effect &= B_0 + B_i X_i \\ Random\ effect &= loc + a + eps \end{aligned} \qquad \text{Eq. 3}$$

With X_i = ith fixed effect factor, a = random effect intercept, eps = random effect error, and loc = cage location factor.

Wild fish sampling

Wild fish were captured using either a seine or fyke nets set during flood events in the Sutter Bypass and Butte Sink (Figure 18). This sampling was conducted when the Sacramento River flowed over flood weirs into the Sutter Bypass starting in January and continuing until flood waters receded in May. Fish were identified to species and measured for fork length to the nearest mm. Chinook Salmon were also weighed to the nearest 0.01 g, and a subsample of 75 fall-run sized salmon were lethally sampled following the guidelines of our scientific collecting permit (CDFW permit SC-13029). Length-At-Date criteria (Greene 1992) was used as a proxy for Chinook Salmon run identification until submitted genetic fin clips are analyzed at the NOAA Southwest Fisheries Science Center in Santa Cruz.

RESULTS

Hydrology

The 2019 water year was above normal with an extraordinary number of cold weather systems during February and March which led to a substantial snowpack (http://cdec.water.ca.gov/). There were numerous weir overtopping events in the Sutter Bypass at all three weirs (Moulton, Colusa and Tisdale, Figure 2). Flashy tributary flooding dominated the early season hydrograph while increased reservoir releases from Keswick sustained significant flooding events during March into April. During the sampling season the maximum observed flow in the Sacramento River, Feather River, and Butte Creek reached 90,996, 38,340, and 10,622 cfs respectively, while minimum flows were 5,407, 2,573, and 67 cfs.

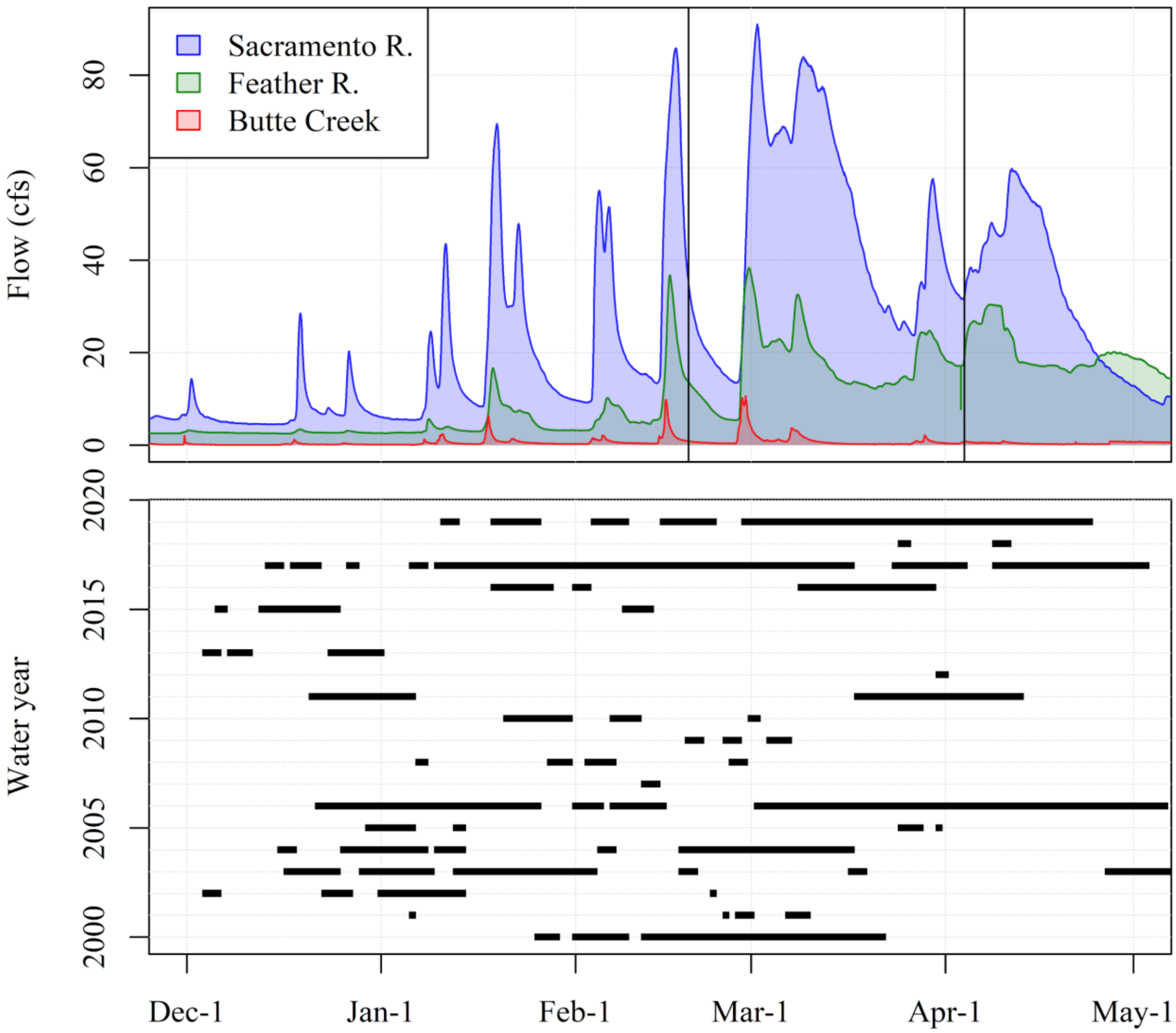

Figure 2. Top panel: hydrograph of the Sacramento River at Butte City (BTC), Feather River at Boyd's Landing above Star Bend (FSB), and Butte Creek flow at Durham (BCD) stations. Bottom panel: historical Tisdale Weir overtopping during December to May of each year 2000 to 2019. The vertical black lines in the top panel show the cage experiment time window.

The stage-inundation rating curve (figure 3.A) allowed us to back calculate the quantity of inundated area for the historical stage record at BSL. From the historical stage data at BSL, we calculated a stage duration curve (figure 3.B) which displays the probability with which a certain stage value at BSL will be exceeded. For instance, at a stage of 45 feet at BSL the inundated area in the Sutter Bypass is approximately 30% (Figure 3.A), and the probability of exceeding a stage of 45 feet is approximately 0.45 (Figure 3.B).

In 2019, stages at BSL varied between 41.23 ft and 55.97 ft with an average of 49.35ft, during the sampling season. Figure 4 illustrates the amount of inundated area in the Sutter Bypass for different BSL stages comprised between 41 and 53 ft.

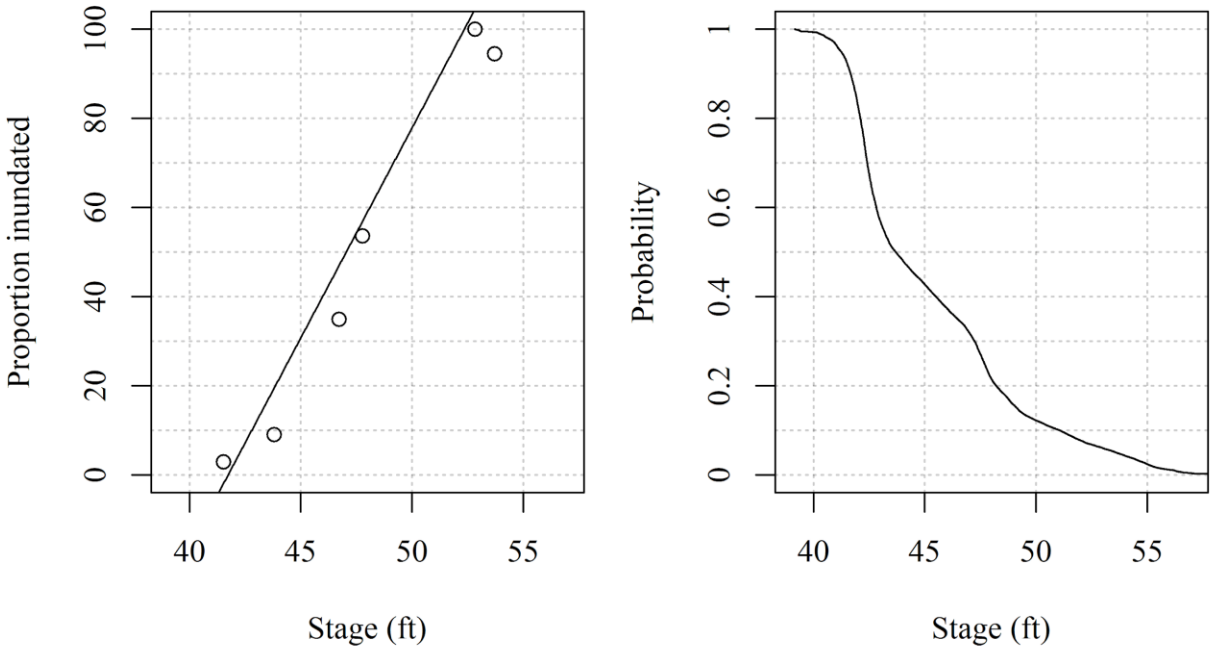

Figure 3. A. Stage-inundation rating curve, the line shows the linear model in Equation 2. B. Stage duration curve, showing the probability of exceeding a given stage.

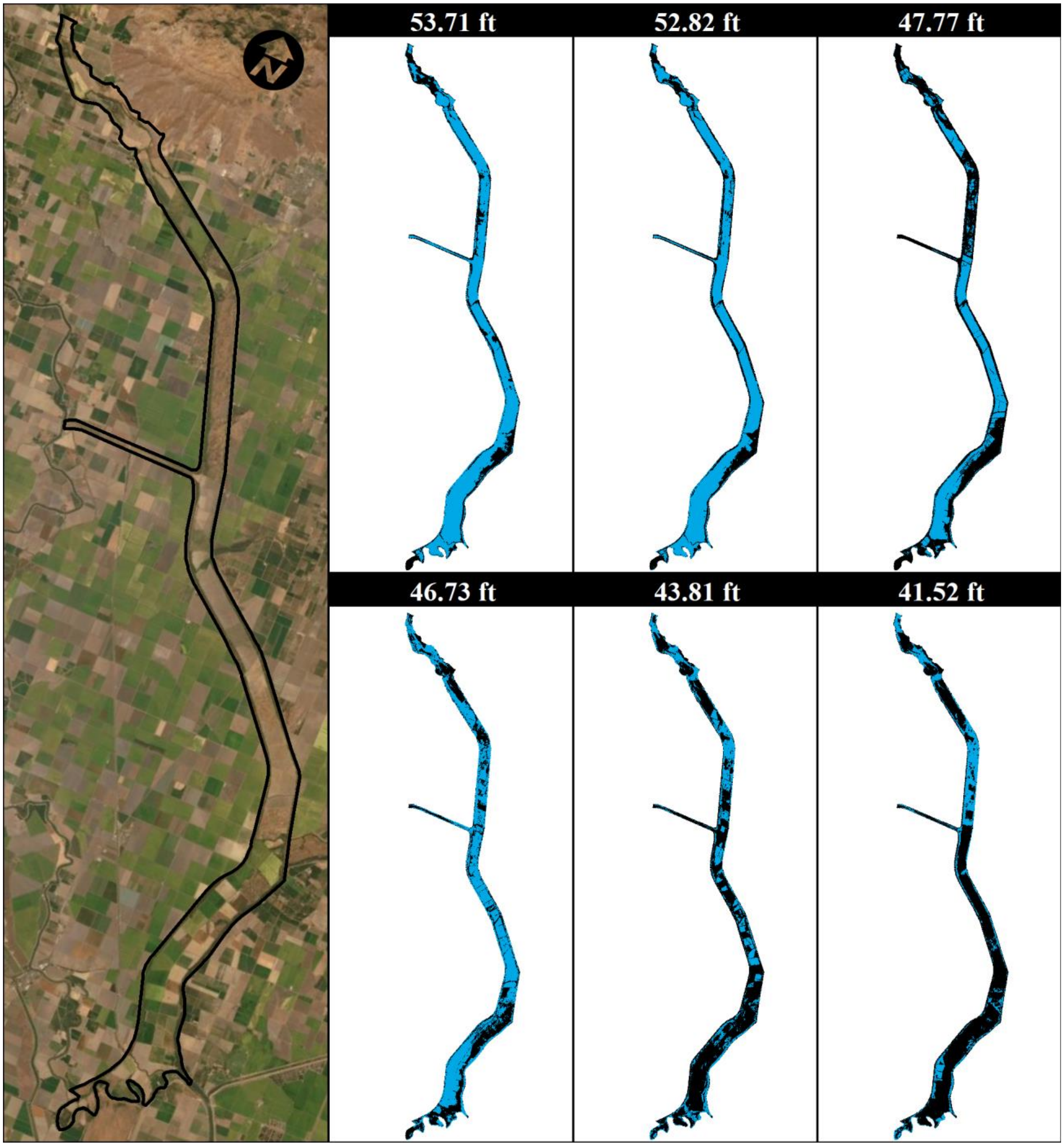

Figure 4. Map of the amount of inundated areas (blue) along the Sutter Bypass, for varying stages (53.71 ft, 52.82 ft, 47.77 ft, 46.73 ft, 43.81 ft and 41.52 ft) measured at BSL.

Water quality

Dissolved oxygen levels were generally high with little fluctuation in the river channel locations (i.e. Butte Creek, Feather River and Sacramento River). Wetland and agricultural habitats showed a larger range of dissolved oxygen, with some periods of low dissolved oxygen when flood waters receded and temperatures increased later in the season (Figure 5). Overall, water temperature increased throughout the course of the experiment, but a more pronounced increase was observed in wetland and agriculture sites of the Butte Sink and Sutter Bypass regions, where water surface area and residence time was larger (Figure 5).

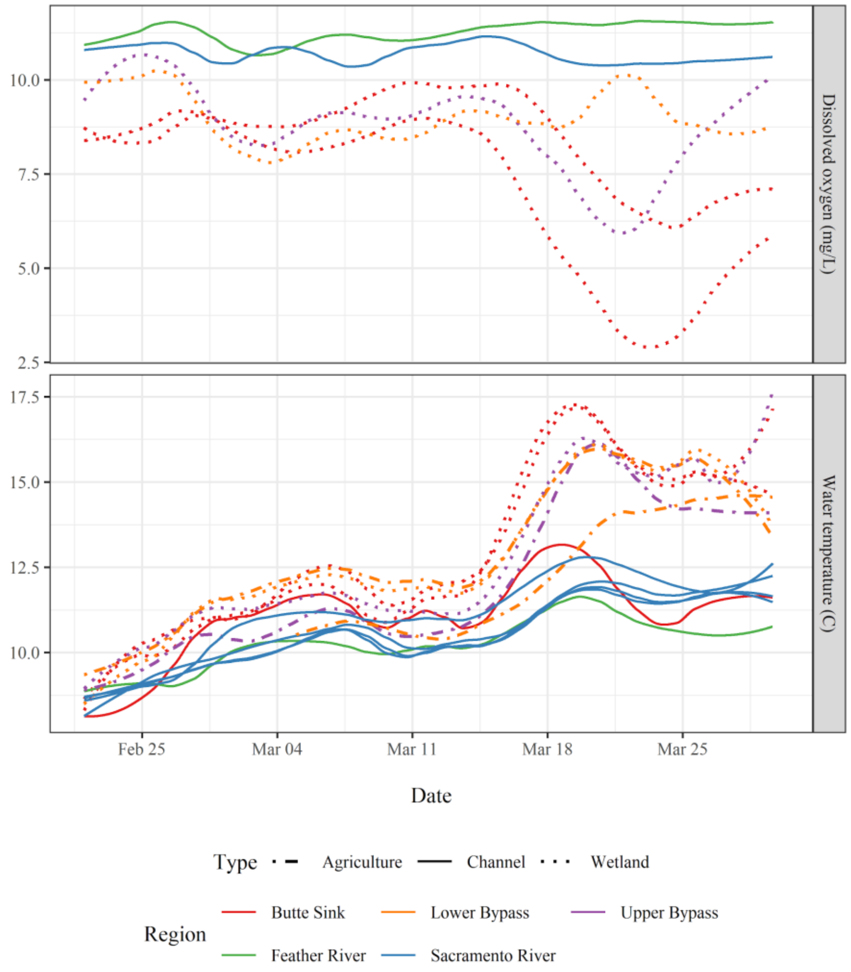

Figure 5. Dissolved oxygen (DO, in mg/L) and water temperature (°C) time series at the various cage locations.

In the Butte Sink, wetland specific conductivity was similar to channel conductivity during high flow events but diverged under lower flows when the wetlands were contained (Figure 6). During these containment periods, conductivity increased due to longer residence time during which evaporation concentrates solubles. Conductivity in certain flow and habitat conditions can be used to indicate residence time differences in the habitats with the same water source. Salinity followed the same pattern than conductivity (Figure 6).

Turbidity increased during storm events in the Sacramento River and Sutter Bypass. In March, due to reservoir releases the flow was high but the high turbidity related to storm events was not apparent (Figure 6). Chlorophyll-a levels remained at relatively low concentrations in the channel sites for the duration of the study. Chlorophyll-a concentrations were generally higher in off-channel habitats except during high flow events when concentrations were similar to the riverine habitats. The general pattern of chlorophyll-a in off-channel habitats was lower concentration during high flow events, increasing concentration during the descending limb of the hydrograph, and a subsequent decrease during full containment presumably due to grazing by secondary producers (i.e. zooplankton). BGA followed the same pattern as chlorophyll-a concentration (Figure 6).

Dissolved organic carbon concentrations in wetlands diverged the most from channel habitats during containment (Figure 7). This was observed most prominently in the Butte Sink region due to containment being achieved sooner than the Sutter Bypass which remained under flooding conditions for nearly the entire experiment. Furthermore, agriculture substrates did not see the same increases in DOC as wetlands. This is likely due to decomposition of standing vegetation in the wetlands versus the agricultural fields where rice straw or other vegetation was removed following harvest to prepare for the next growing season.

Another distinctive trend in the wetland habitats was near complete depletion of nitrate following containment (Figure 7). The wetlands appear to be nitrate limited. Phosphate in wetlands diverged in the opposite direction from nitrate (Figure 7), which is likely due to the lack of growth of new primary producers including phytoplankton, algae, and rooted macrophytes. Generally, as nitrate uptake is reduced, the phosphate concentration increases due to the decreased uptake by primary producers that are under the nitrate limitation.

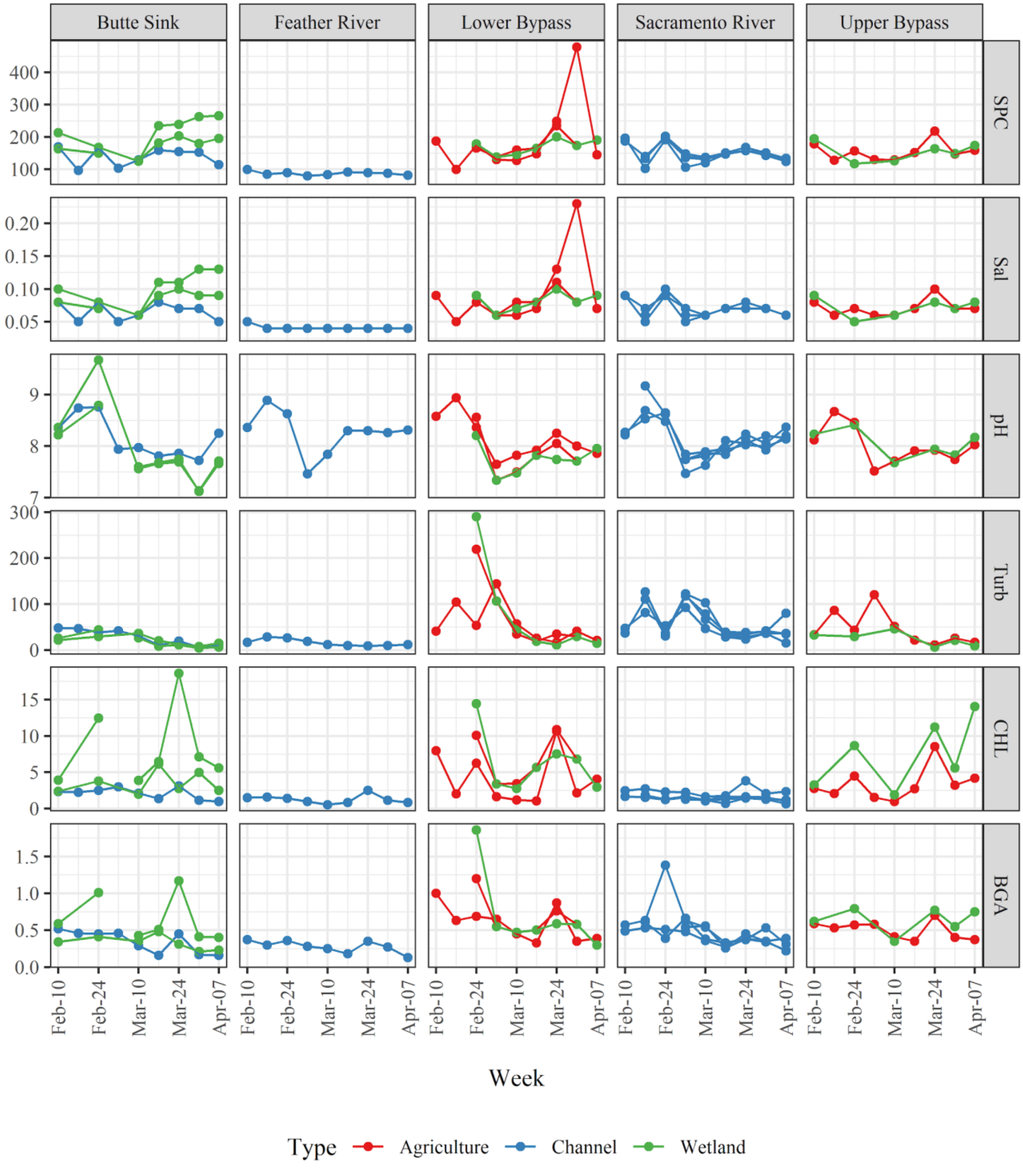

Figure 6. Physical water quality parameter time series at the various cage locations.

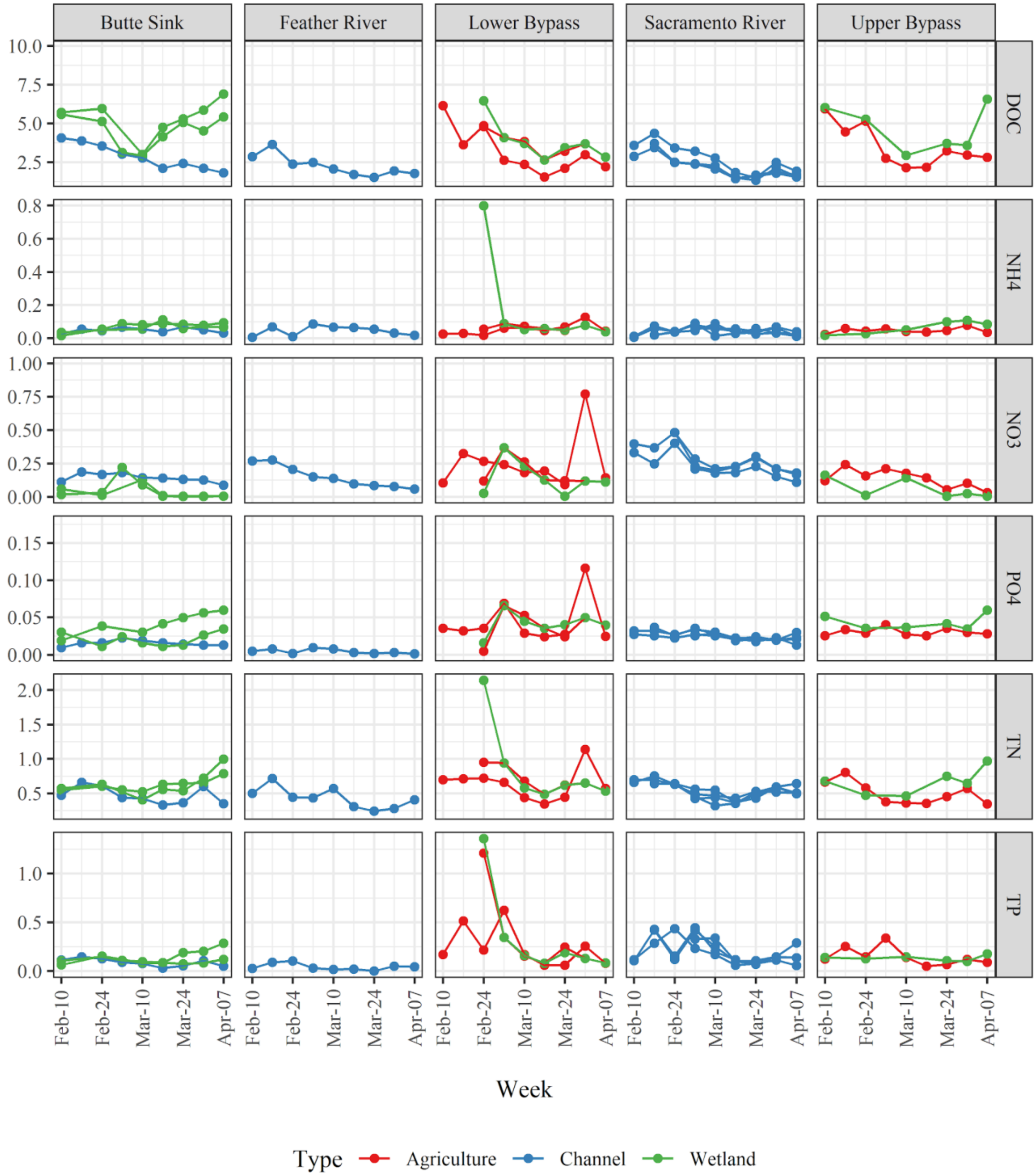

Figure 7. Nutrient loading time series at the various cage locations.

Zooplankton

The largest flood event of the 2019 season in the Butte Sink and Sutter Bypass peaked in the first two weeks of March. This flood event corresponded to lower zooplankton abundances observed at the beginning of the cage experiment in every region besides the Sacramento River. As the floodwaters receded in the last two weeks of March and water residence time increased in off-channel habitats, primary productivity and zooplankton abundance increased. By the end of the sampling season the highest zooplankton density was observed in the Butte Sink region. Zooplankton density was also relatively high in the Lower and Upper Bypass regions, the main difference between the two regions being that in the Upper Bypass overbank flow was contained earlier providing longer residence time for the lower trophic food web to develop. On the contrary, zooplankton densities in the Sacramento and Feather River sites remained much lower than in the other regions throughout the study period (Figure 8).

Copepod and cladoceran species dominated the zooplankton samples during the entire sampling period. Additionally, higher densities of rotifera started to show up in Feather River samples at the end of the cage experiment. Diptera and ostracoda species were also found in very small density throughout the sampling period, in each region (Figure 9).

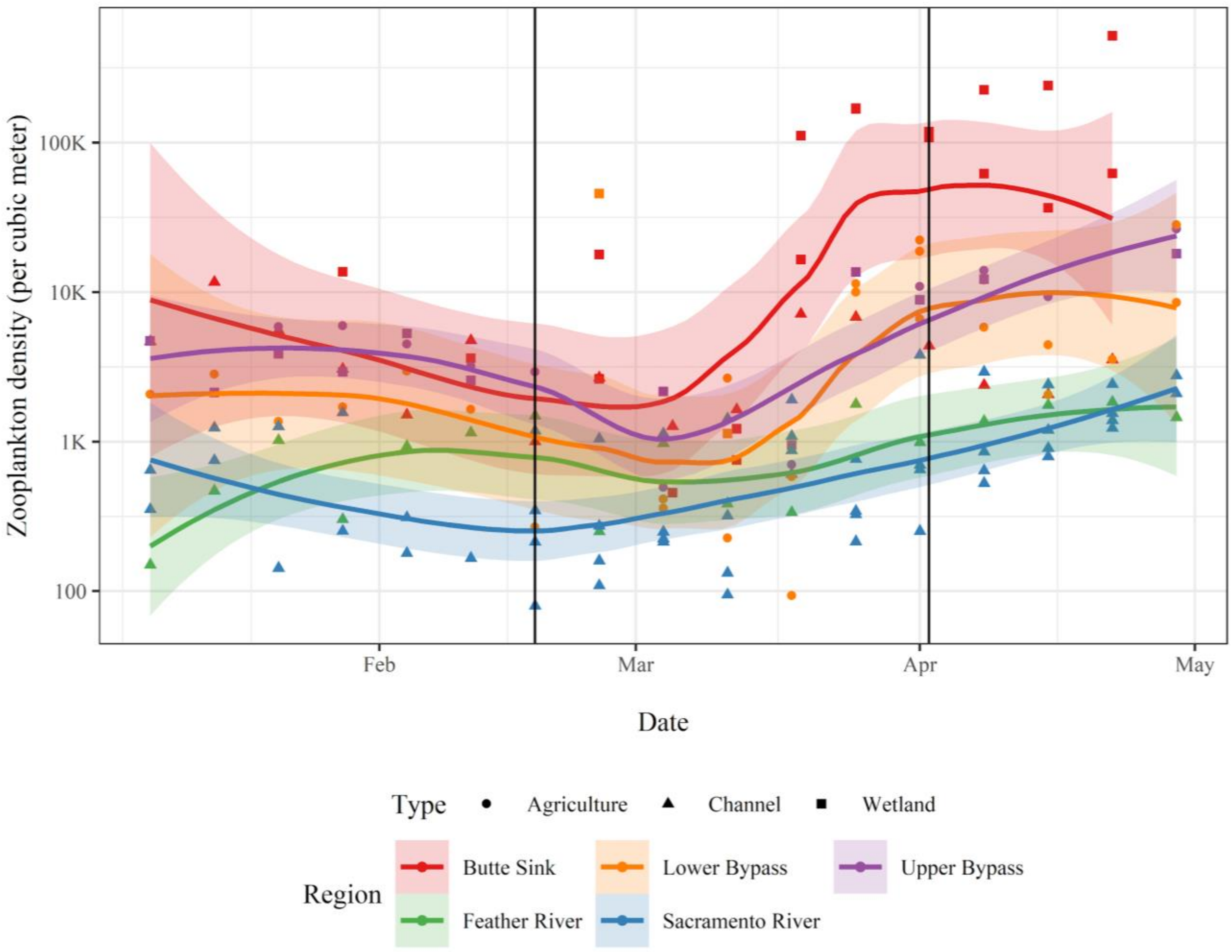

Figure 8. Total zooplankton density (per m³), from ambient zooplankton sampling, summed for all taxa displayed on a log scale with trend lines for the different regions. The symbols represent zooplankton density for the different habitat types. The black vertical lines show the cage experiment time period.

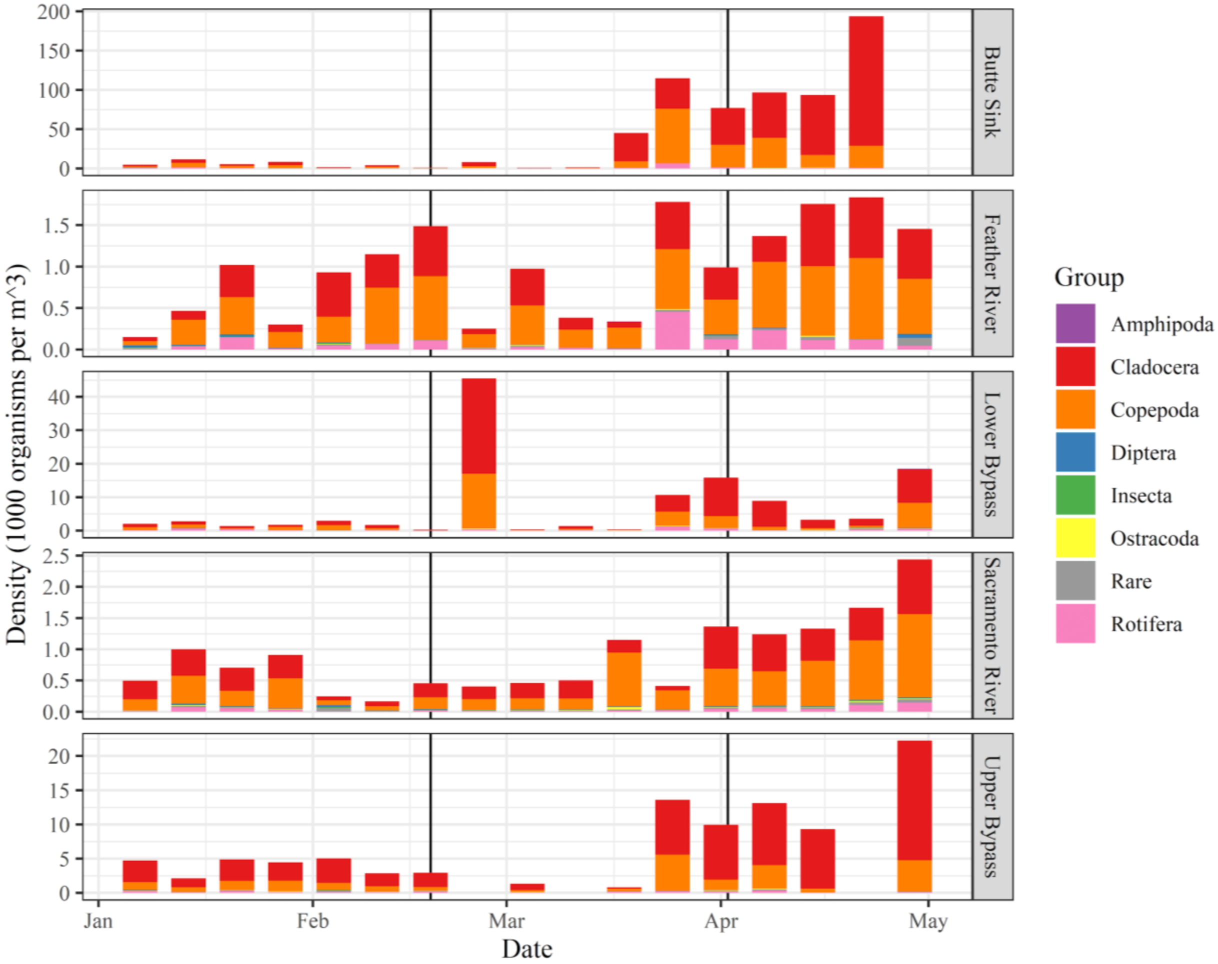

Figure 9. Mean weekly lower trophic species density by region and functional taxonomic group. The black vertical lines show the cage experiment time period.

Caged and wild salmon diet

Caged salmon diet in the Butte Sink was dominated by cladoceran and copepod zooplankton for the entire cage experiment period (Figures 10 and 11). In the Feather and Sacramento Rivers, diet was composed primarily of diptera and insecta species, except at the end of the experiment at SRC4 site and at the beginning at SRC2 with higher density of cladoceran and copepod zooplankton (Figures 10 and 11). SRC2 was likely influenced by upstream inputs from zooplankton rich off-channel pumping into the Sacramento River. SRC4 being downstream of the Sutter Bypass likely received off-channel inputs from the draining bypass toward the end of the experiment. Sutter Bypass gut contents were comprised of a mix of diptera larvae, cladoceran and copepod zooplankton, and amphipods. (Figures 10 and 11).

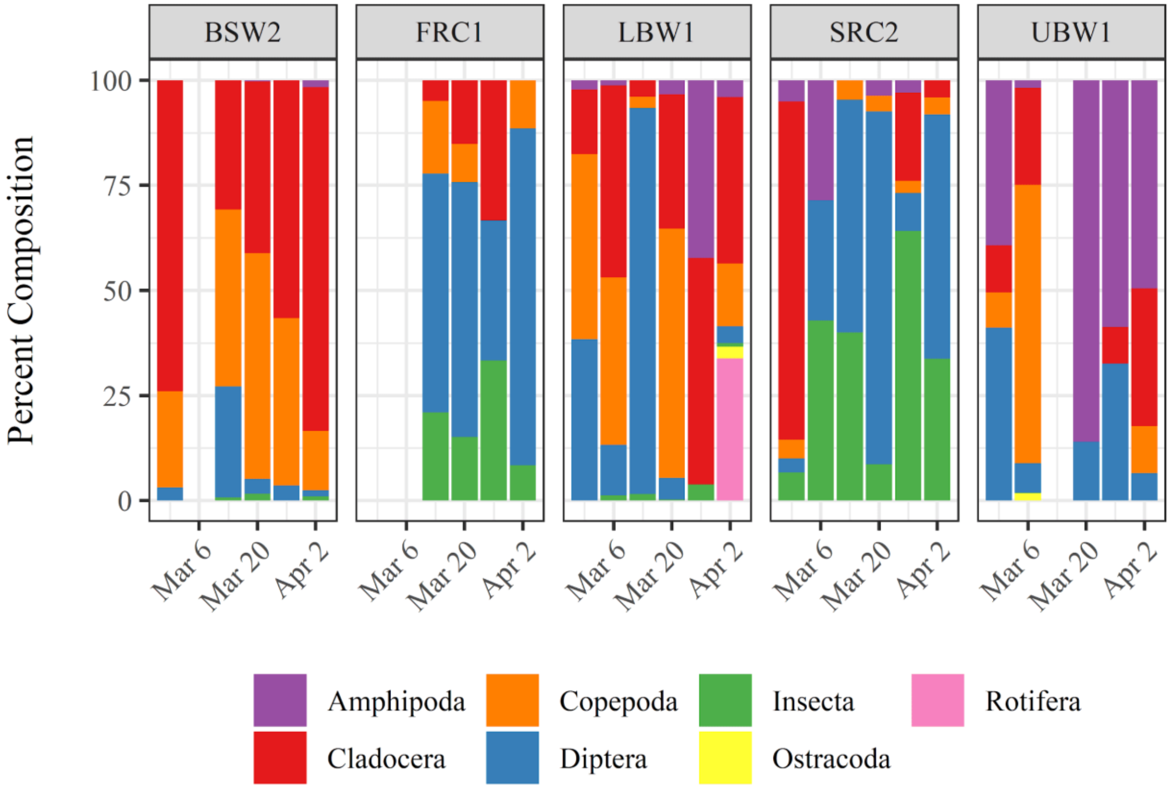

Figure 10. Percent composition of caged salmon gut stomach contents taken at week 2, 4 and 6, in one selected site per region (i.e. BSW2 in Butte Sink, FRC1 in Feather River, LBW1 in Lower Sutter Bypass, SRC2 in Sacramento River, and UBW1 in Upper Sutter Bypass).

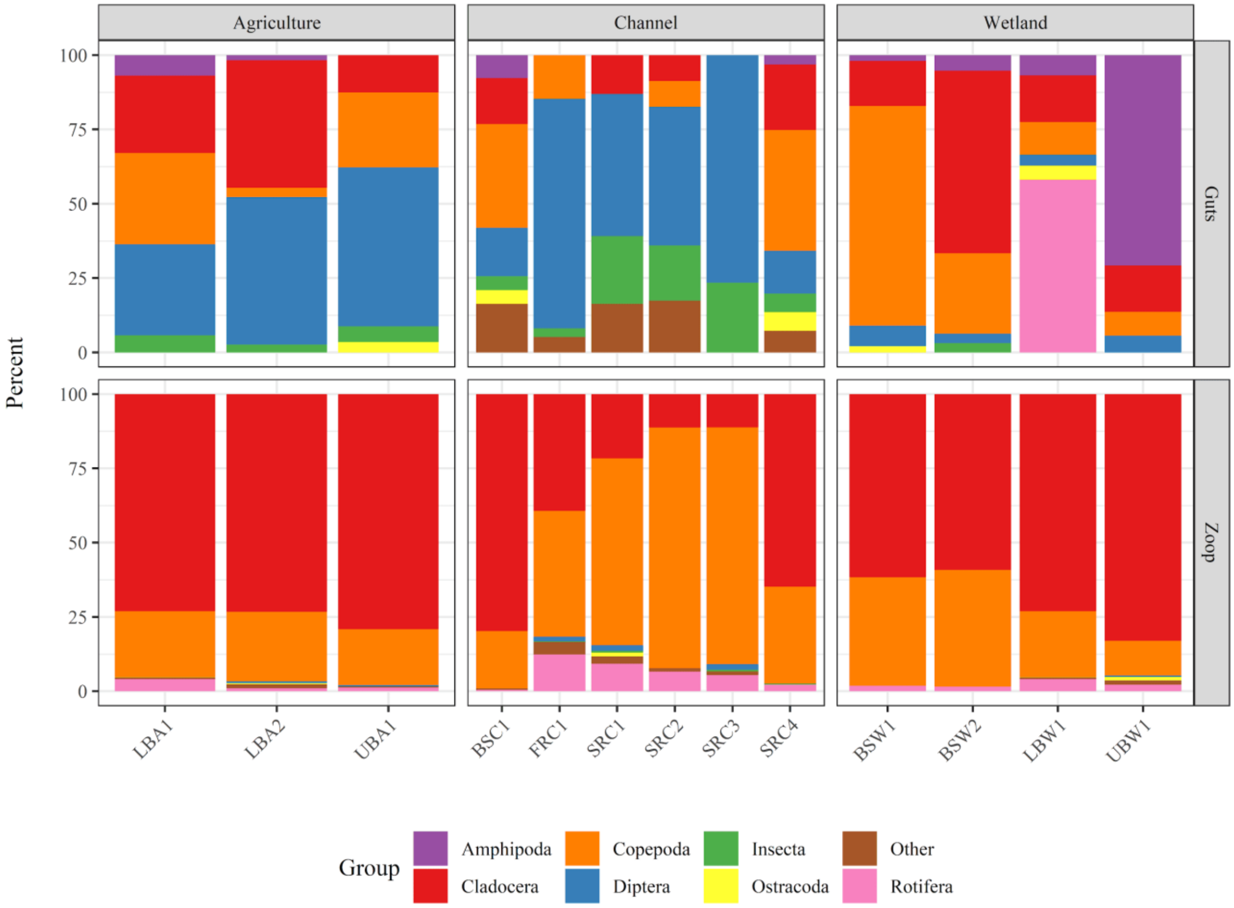

Figure 11. Percent composition of caged salmon gut stomach contents (top panel) and lower trophic sample (lower panel) taken the day prior to cage removal.

Differences observed between species found in gut content and in zooplankton samples suggest that caged fish were actively selecting their prey (Figure 11). Weekly sampling midday is also not likely to fully capture patterns of dipteran and aquatic insect hatches which tend to occur during the crepuscular hours. Salmon in cages, however, feed continuously and are good integrators of the various food sources. Gut contents of wild juvenile Chinook Salmon captured during seining events closely reflected the prey composition of the caged fish (Figure 12). In the Butte Creek, Butte Sink and Sutter Bypass regions the zooplankton composition was similar to the caged fish gut content composition, with a majority of cladoceran as well as some copepod and diptera species. Gut contents of wild fish sampled at Colusa and Tisdale weirs were composed of insecta and diptera species, similar to those observed for Sacramento River caged fish.

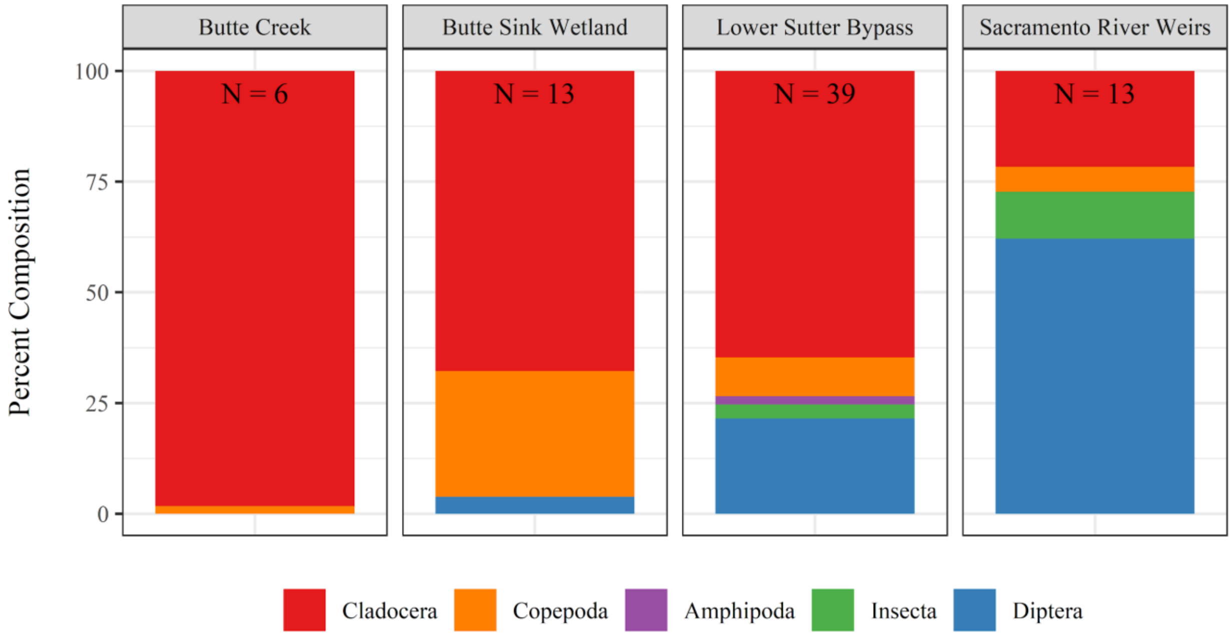

Figure 12. Mean percent composition of wild fall-run sized salmon stomach contents (N = 71) grouped by sampled region. The “Butte Sink Wetland” region includes Mallard Ranch and Sanborn Slough sampling sites, the “Sacramento River Weirs” region is comprised of Tisdale and Colusa weirs sampling sites, and the “Lower Sutter Bypass” region corresponds to Lundberg Farms sampling site (see Figure 18).

Caged salmon growth

Initial fork length (mm) and weight (g) at the time of stocking for the growth cage salmon was 47.7 +/- 3.2mm SD and 1.20 +/- 0.28g SD. At the end of the six-week experiment, size ranged from 53.8 +/- 3.2mm SD and 1.7 +/- 0.40g SD at SRM3 (Sacramento River site) to 70.7 +/- 4.2mm SD and 4.28 +/- 0.74g SD at BSW2 (Butte Sink site). The average daily growth rates ranged from 0.15 mm/day and 0.01 g/day at SRM3 to 0.55 mm/day and 0.07 g/day at BSW2. Percent change in fork length and weight ranged from 12.5% and 28.9% respectively at SRM3 to 47.2% and 255.8% respectively at BSW2.

Growth rates were, in general, higher in the off-channel sites (i.e. wetland and agriculture), compared to the channel sites (Figure 13). Interestingly, due to the sustained tisdale overtopping during the experiment, the lowest Sutter Bypass agricultural site (LBA2) experienced similar water conditions to the Sacramento River at Tisdale site (SRC2), and showed very similar growth rates. Additionally, the growth rate in Butte Creek channel (BSC1) was higher than the other channel locations (i.e. from the

Sacramento and Feather rivers), and also higher than at LBA2 site. This could be due to the occasional transfer of productivity from Butte Sink and upstream agricultural wetland effluent to the channel following high flow events.

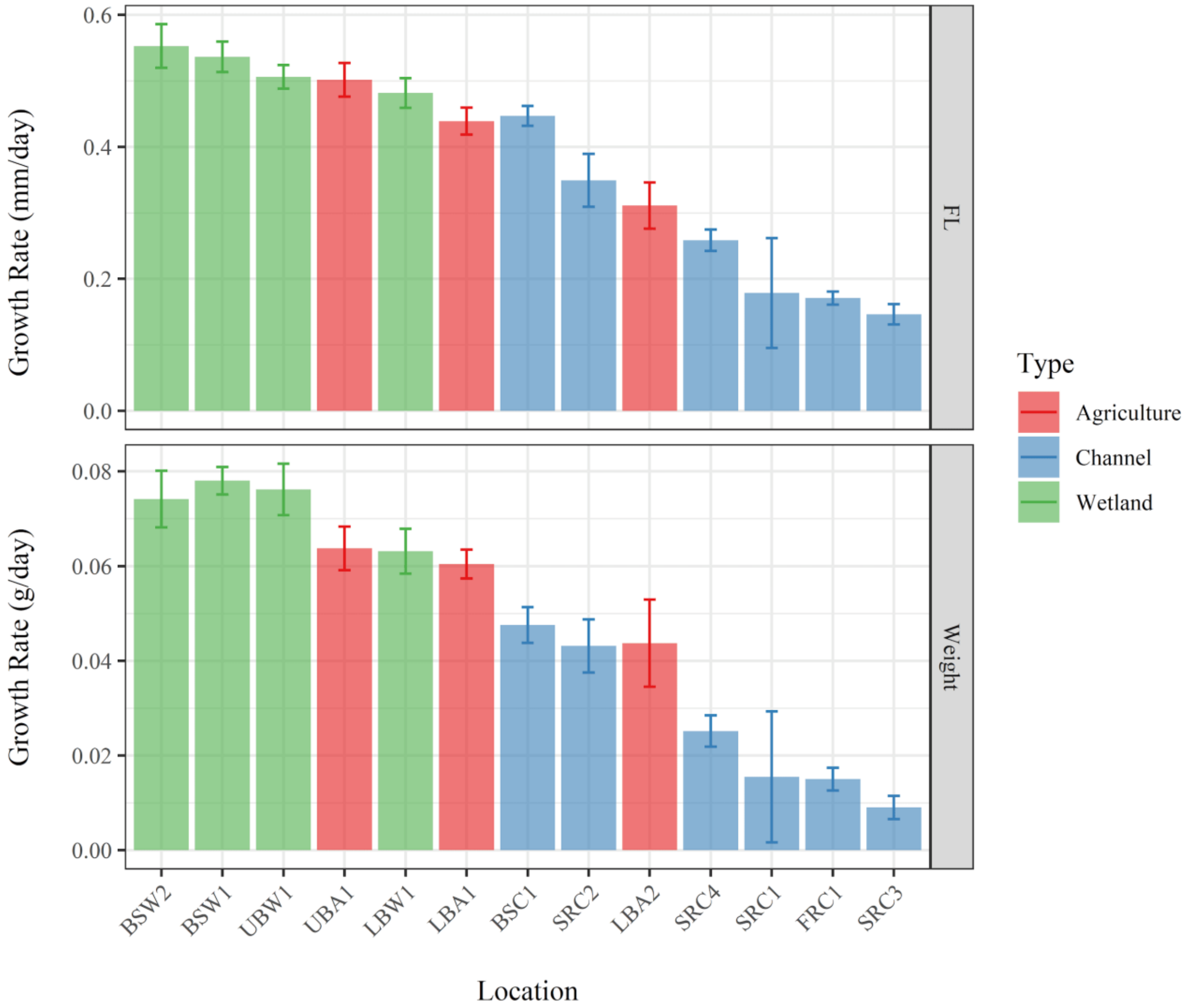

Figure 13. Average daily growth rates in mm/day and g /day at each site location. Error bars denote standard error.

The results from the anova and modelling exercises showed a statistically significant effect of both region and habitat type on the mean daily growth rates (Table 3.A, Figure 14), and a more important effect of the habitat type factor (lower AIC value for the region model; Table 3.B).

Table 3. A. Anova test results showing the significance level of region and habitat type factors on the mean daily growth rate.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Region	4	1.2023	0.30058	44.51	<2e-16 ***
Residuals	78	0.5268	0.00675		
Signif.codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1					

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Habitat type	2	0.9657	0.4829	50.61	6.25e-15 ***
Residuals	80	0.7633	0.0095		
Signif.codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1					

B. Comparison of growth rate mixed effect models, with region or habitat type random variables. Npar= number of model parameters; AICc = Akaike’s information criterion corrected for small sample size; logLik = log likelihood. Lower AICc scores indicate greater relative model parsimony.

Model	AICc	logLik
1 + 1|habitat type	-130.8154	68.40768
1 + 1|region	-151.1596	78.57982

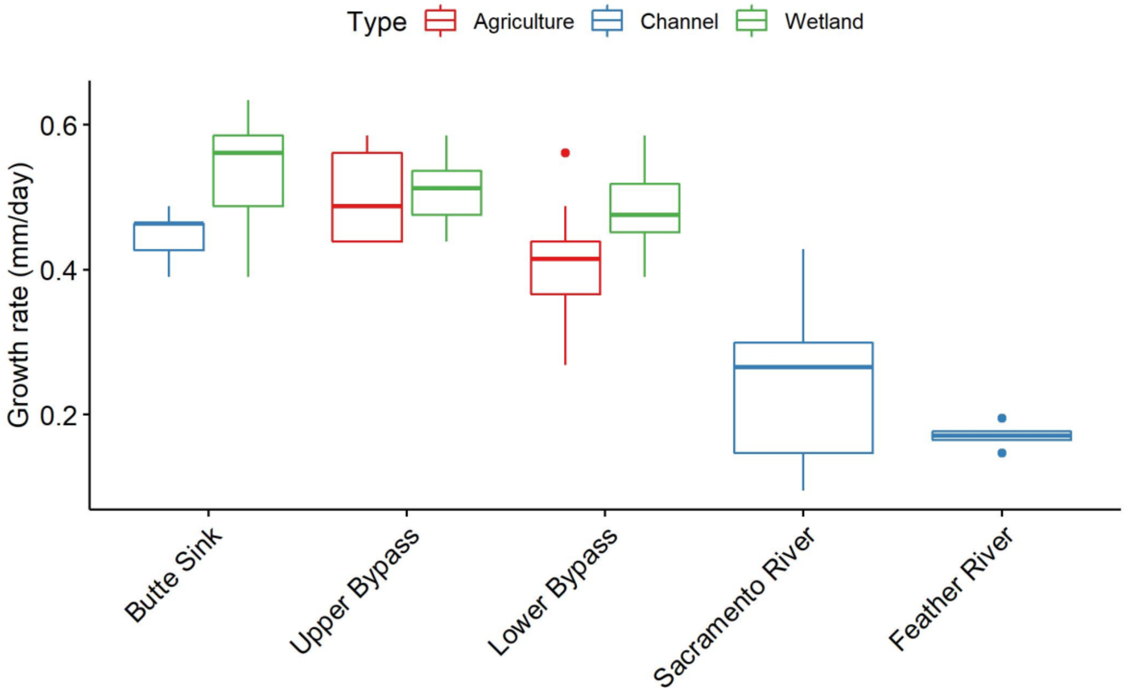

Figure 14. Mean daily fish growth rates (mm/day) boxplot grouped by region and habitat type.

Habitat type influenced growth rate as the Tukey test results showed 1) a significantly lower growth rate in channel in comparison to off-channel agriculture and wetland sites, and 2) a significantly higher growth rate in off-channel wetland in comparison to off-channel agriculture and channel sites (Figure 15.A). As region also had an influence on growth rate, the Tukey test results highlighted 1) a significantly higher growth rate in the Butte Sink than in Feather River, Lower Bypass and Sacramento River regions, 2) a significantly higher growth rate in the Lower and Upper Bypass regions than in the Sacramento and Feather Rivers, and 3) no significantly different growth rates between the Sacramento and Feather Rivers, the Lower and Upper Bypass, and the Upper Bypass and Butte Sink regions (Figure 15.B).

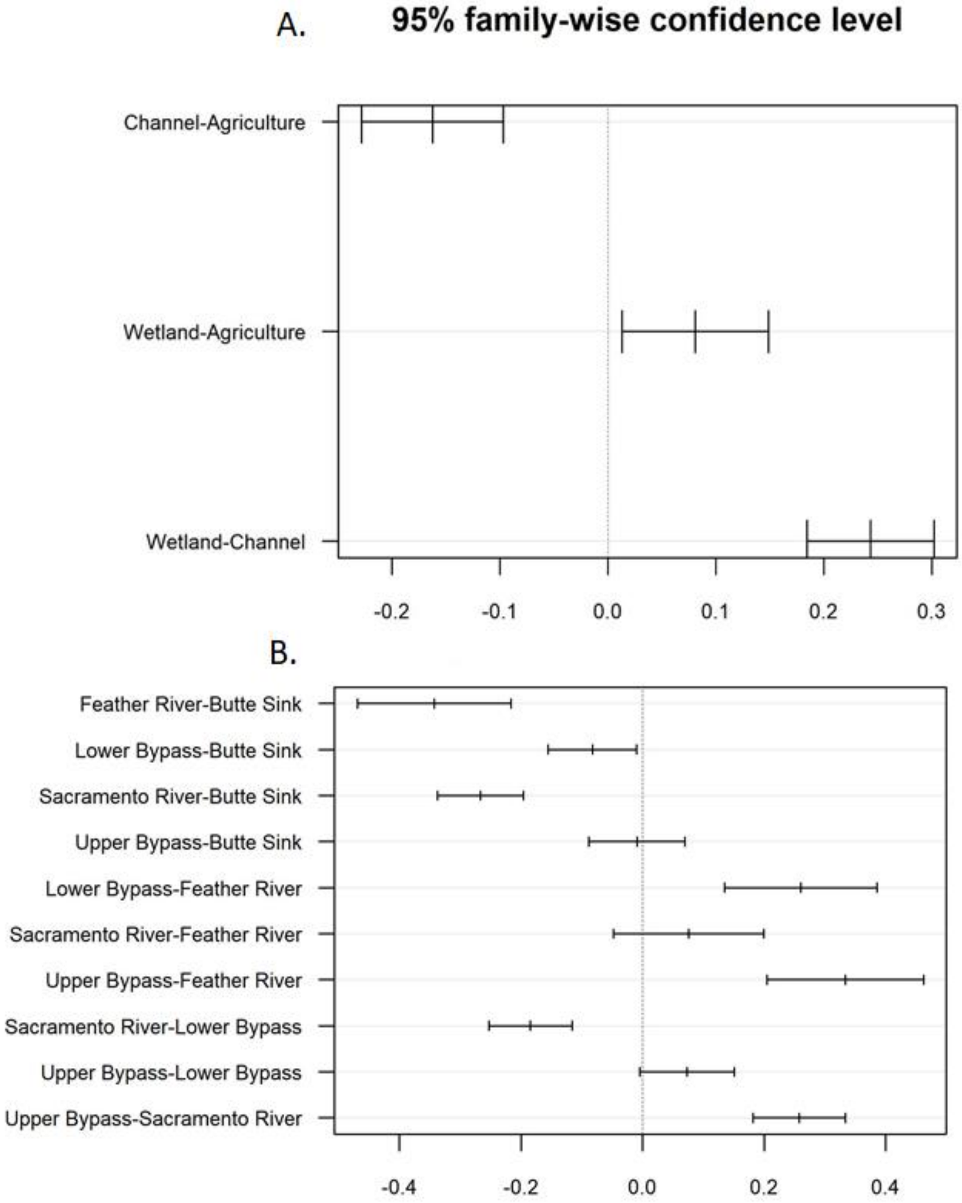

Figure 15. Pairwise comparison of mean daily growth rates (mm/day). A. for each habitat type. B. for each region. If a segment crosses the 0 vertical line, it means that the difference between growth rates is not statistically significant.

Based on the anova results, we used the habitat type factor as a random effect in the mixed effect models developed to further study the influence of biological and environmental factors on caged fish daily growth rates. Out of all the factors tested, zooplankton density was the variable that best described fish growth (Table 4; ΔAIC of the second model larger than 4). Higher density of zooplankton was correlated with faster growth (Figure 16).

Table 4. Comparison of FL growth rate mixed effect models, with habitat type used as a random variable. Npar= number of model parameters; AICc = Akaike's information criterion corrected for small sample size; ΔAICc = difference in AICc score between the given model and the most parsimonious model. Models are ordered from lowest to highest AICc. Lower AICc scores indicate greater relative model parsimony.

Model	**Npar**	**AICc**	**ΔAICc**	**Weight**
log Zoop + 1|type	4	-39.76	0	0.77
1 + 1|type	3	-35.42	4.34	0.09
pH + 1|type	4	-34.16	5.59	0.05
Temp + 1|type	4	-34.04	5.72	0.04
Turb + 1|type	4	-32.16	7.60	0.02
CHL + 1|type	4	-31.98	7.78	0.02
BGA + 1|type	4	-31.48	8.28	0.01
SPC + 1|type	4	-31.43	8.33	0.01

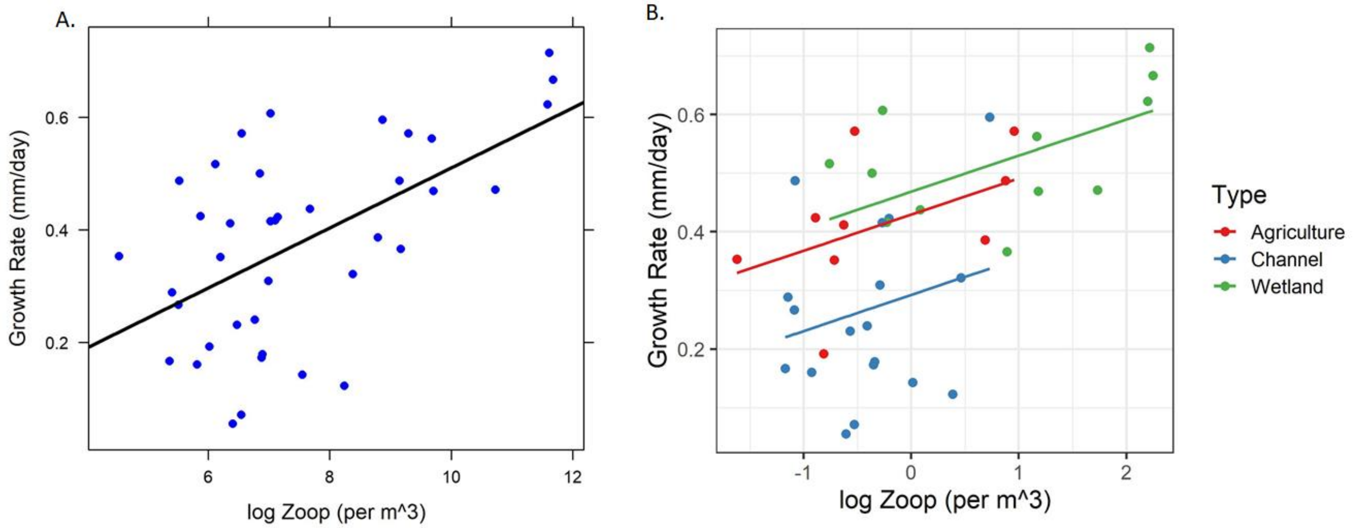

Figure 16. Relationships between caged fish mean daily growth rate (mm/day) and log zooplankton density (per m³). A. for all locations combined, and B. by habitat type. The dots represent the raw data, the black line shows a simple linear regression, and the colored lines show habitat specific daily growth rate predictions from the best mixed effects model.

Wild fish capture

Various native and non-native species were collected during the wild fish seining and fyke netting efforts in the Butte Sink and Sutter Bypass (Figure 17) The majority of fish collected were native species. Among native species collected, were Chinook Salmon, Sacramento blackfish, Sacramento sucker, prickly sculpin, Sacramento pikeminow, and steelhead.

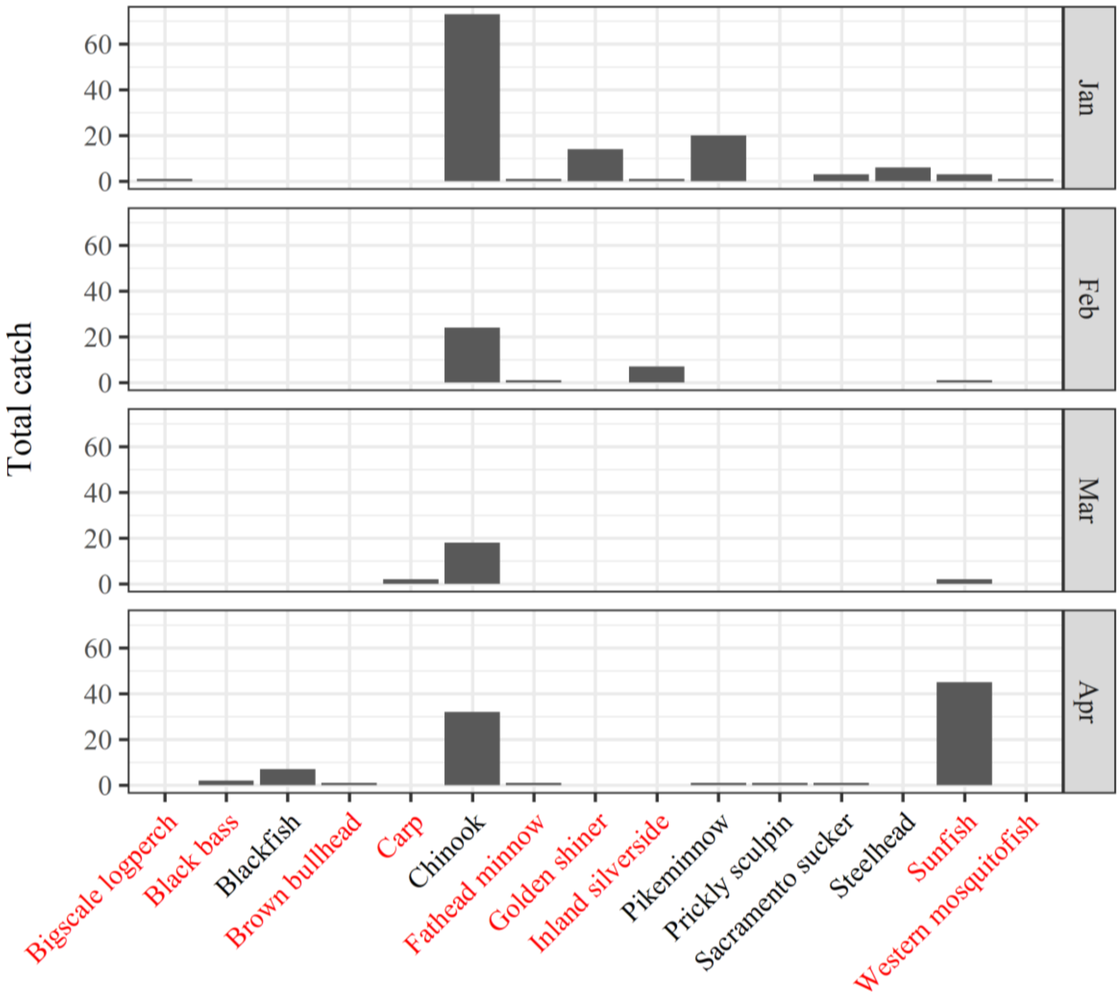

Figure 17. Fish species caught during the wild trapping events performed from January to April in the Butte Sink and Sutter Bypass. Black-colored names correspond to native species while red-colored names correspond to non-native species.

Chinook Salmon ranging from 35 to 132mm in length (Table 5) were caught from January to April. Based on the Length-At-Date criteria, the four races of Chinook Salmon found in the CCV were caught both in the Butte Sink and the Sutter Bypass (Figure 18). Late fall- and winter-run juveniles were mostly caught below Colusa and Tisdale Weir, suggesting that they accessed the Butte Sink and Sutter Bypass during weir overtopping events. They were mostly caught in January, while fall- and spring-run were observed from January to April at a variety of sizes corresponding to size at date criteria where size increased through the sampling effort (Figure 19).

Table 5. Number (N) of wild caught run specific salmon, with their minimum, mean, and maximum fork length (FL).

Run	**Min FL**	**Max FL**	**Mean FL**	**N**
Fall	35	80	47.9	78
Late Fall	124	132	128.0	2
Spring	50	98	73.7	46
Winter	67	102	84.9	24

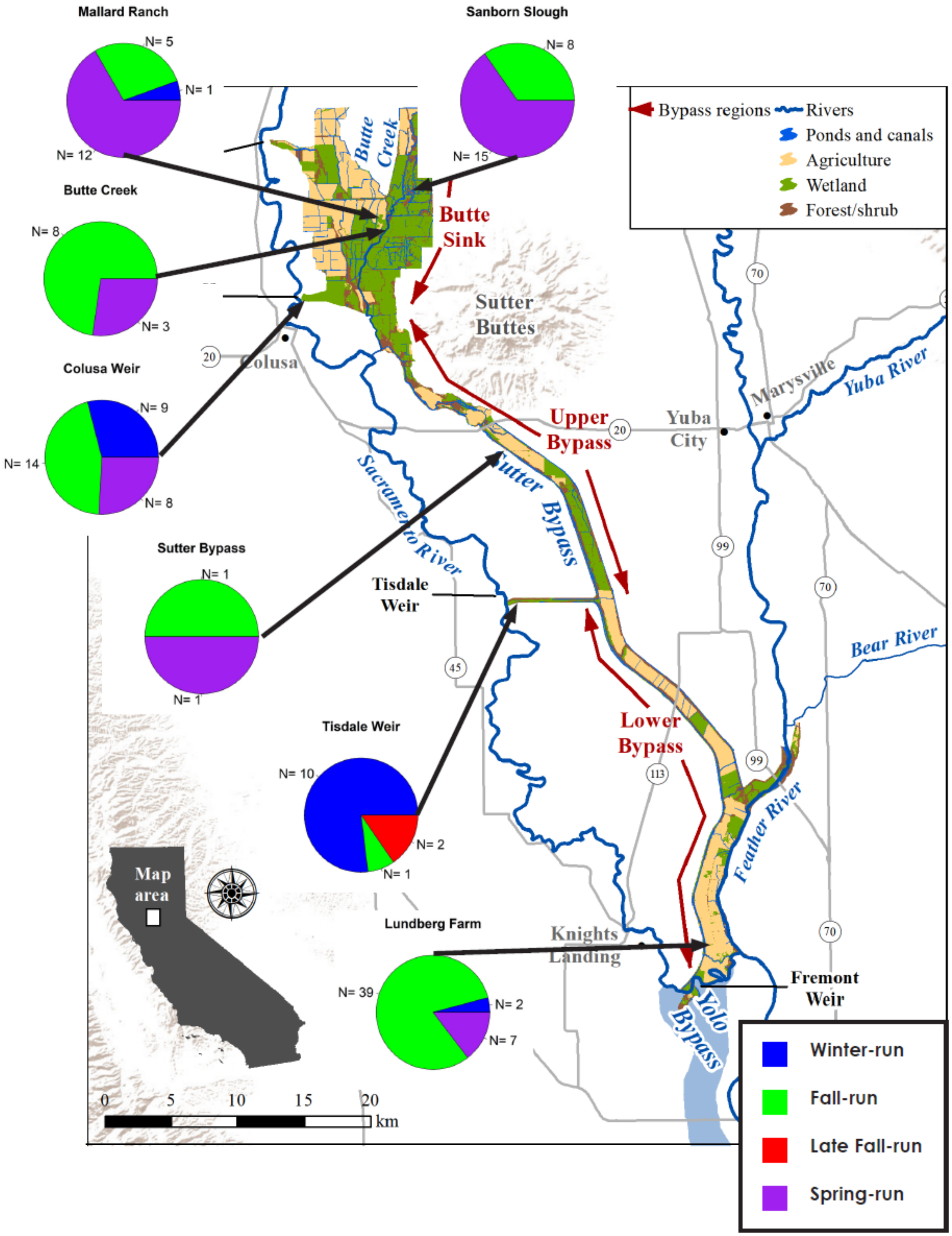

Figure 18. Study area map with pie charts showing the proportion of winter-, fall-, late fall-, and spring-run Chinook Salmon sampled at different locations along the Butte Sink and Sutter Bypass. Run assignment is based on Length-At-Date criteria.

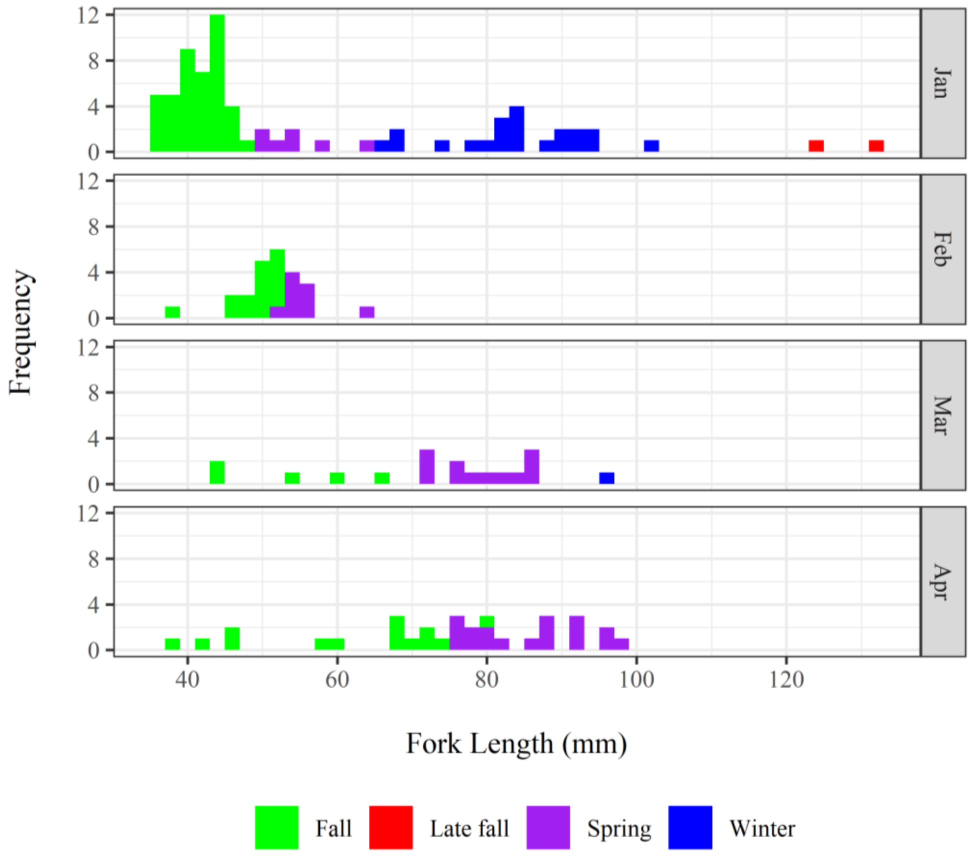

Figure 19. Chinook Salmon size histogram categorized by month from January to April, and by run type. Run assignment is based on Length-At-Date criteria.

DISCUSSION

The above normal water year in 2019 created productive hydrological conditions in the Butte Sink and Sutter Bypass. River water spilling from the Sacramento River, Feather River, and Butte Creek allowed extensive floodplain access for all four runs of CCV Chinook Salmon fry migrating from upstream habitats and the upper Butte Creek watershed. This is to our knowledge the first time endangered winter-run Chinook Salmon were reported in the Sutter Bypass. This supports results from Phillis et al. (2018) highlighting the importance of Sacramento Valley ephemeral and permanent floodplains for winter-run juvenile rearing.

Food web development in the off-channel Butte Sink and Sutter Bypass habitats was significantly higher than the adjacent channel habitats. Numbers of zooplankton were often 10 to 100 times more abundant in the off channel habitats compared to the river channels (Figure 8). The off-channel habitats consisted of both flooded wetlands, primarily duck clubs and the Sutter National Wildlife Refuge, as well as flooded agricultural fields (rice, corn, and other row crops). These habitats generally had higher residence times as highlighted by higher SPC, salinity, and chlorophyll-a values (Figure 6). The exception to this was when there were high flow events when all of the weirs in the Sutter Bypass were being overtopped and the Sutter Bypass water quality looked similar to that of the Sacramento River. During high flow events, the vast majority of the water moving down the Sacramento River is routed through the flood bypass system, as such reducing water residence time on the off-channel locations. As these high flow events receded, velocities slowed on the bypasses and residence times increased resulting in high zooplankton abundances following those events. These same processes have been observed in the downstream Yolo Bypass (Sommer et al. 2001) and relatively natural Cosumnes River floodplain (Ahearn et al. 2006, Grosholz and Gallo 2006, and Jeffres et al. 2008). The high abundances of zooplankton that constitute the lower trophic levels following flooding events create the opportunity for high growth rates for the variety of fishes that utilize the floodplains.

Fish that were placed on the off-channel habitats had significantly higher growth rates compared to those placed in riverine channel habitats (Figure 13). This was likely a consequence of access to abundant food resources as well as warmer temperatures compared to the river channel sites. When food resources are abundant and temperatures are higher, yet within biological thresholds, growth rates can be quite high (Lusardi et al. 2019). This is similar to other studies in floodplains in the Central Valley where similar water conditions and food resources have been observed resulting in relatively high growth rates for juvenile Chinook Salmon (Sommer et al. 2001, Jeffres et al. 2008, Katz et al. 2017). We built a mixed-effects model looking at physical and ecological variables in relation to fish growth in all of our regions and habitat types. Zooplankton abundance was the most important factor in determining fish growth regardless of habitat type or region. There was a linear relation with zooplankton density and fish growth and as such, the Butte Sink and Sutter Bypass, which had the highest zooplankton density, had the highest fish growth. River site where zooplankton abundance was low saw relatively slow growth rates. The type of habitat where fish were located also seemed to have a stronger influence on growth rate compared to the region. Additional years of data under different flow conditions will help to better assess the influence of habitat type versus region on fish growth.

In addition to variation in water quality regionally and between habitat types, we observed lateral banding from west to east within the Bypass, which might also influence fish growth within a given habitat type. Water sources from Butte Creek, Colusa Weir, Tisdale Weir during moderate flow conditions did not laterally mix and would remain “banded” through the Sutter Bypass (Figure 20). This could influence the water quality and food within a habitat over space and time. Because our fish were caged in a single location and not able to move freely through the habitat the results must be taken in this context. This was most evident at the LBA2 location on the west side of the lower Sutter Bypass. This location, during moderate flows, had water quality conditions similar to that of the Tisdale Weir because as water entered the Sutter Bypass from Tisdale Weir it remained along the west side of the Bypass flowing downstream. In contrast, at this same habitat on the east side of the bypass, the water conditions were different. This same band of water just upstream at LBA1, on the east side of the bypass had different water quality parameters and higher abundances of zooplankton. Wild fish that could move freely through the habitat could potentially optimize the benefits of the lateral variability zooplankton abundances.

Figure 20. Satellite imagery showing lateral banding from April 13, 2019 in the lower Sutter Bypass. Image was downloaded from Planet.com.

All four runs of juvenile naturally migrating Chinook Salmon were collected in either Butte Sink or Sutter Bypass during the 2019 sampling effort. The late-fall run fish that were captured were all adipose clipped suggesting that they were hatchery fish released from Coleman National Fish Hatchery and utilizing the Sutter Bypass during their out-migration to the ocean. The fact that all four runs of juvenile salmon were collected from January through April highlights the potential habitat utilization for Central Valley Chinook Salmon. This also highlights the complexities of how fish can move through the watershed and how and when various habitats are available. 2019 was a wet year with extensive flooding. “Normal” water years do not have nearly the availability of habitats to all four runs of Chinook Salmon. It is likely that both spring-run and fall-run Butte Creek juveniles have access to at least flooded wetland in the Butte Sink due to current wetland management practices that keep the wetlands flooded until April to mitigate noxious weed growth. These habitats may function until April in a cool, wet year as we saw in 2019, but in warm dry conditions it is possible that these habitats may not be as beneficial as we observed during this study. Being able to collect data across a variety of years and water year types will help to tell a better story of how the Butte Sink and Sutter Bypass function across a variety of hydrological conditions. These data will provide information to resource managers to think more holistically about how managed off-channel habitats can benefit juvenile salmon across all water year types.

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