Fall Low Salinity Habitat (FLaSH)-Fish Health Study: Otolith Growth and Life History

Prepared by:

James A. Hobbs

Department of Wildlife, Fish and Conservation Biology

University of California-Davis

Prepared for:

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Ecosystem Restoration Program

980 9th Street

Sacramento, Ca 95814

C/O Gena Lasko Project Manager

PROJECT DESCRIPTION

In the Fall of 2011, a large scale multidiscipline study was launched by the Interagency Ecological Program (IEP) to investigate the effects of freshwater outflow on low-salinity zone habitat conditions and measure the response of Delta Smelt (*Hypomesus transpacificus*) to higher than normal fall outflow (**Brown et al. 2014**). High outflow years provide positive benefits to many estuarine species, including species of management importance such as the Delta Smelt (**Sommer et al. 2007; Feyrer et al 2007; Nobriga et al 2008; IEP-MAST 2015**). However; the ecological mechanisms associated with the effects of overall improved habitat conditions and Delta Smelt response are not well understood. The 2009 Biological Opinion for operation of the CVP and SWP in the South Delta required increased fall freshwater outflow to improve rearing conditions for Delta Smelt, conditions which serendipitously existed in the fall of 2011 (**USFWS 2009**).

The purpose of this study was to examine the potential effects of stressors (e.g. contaminants, pathogens/diseases, and poor feeding success) and habitat attributes (Salinity, Temperature, Turbidity etc.) on fish condition and health status in the fall of 2011 (Wet Year) and compare health responses to 2012-2014 (Below Normal to Critically Dry Years). Delta Smelt were collected during the Fall Midwater Trawl (FMWT) and the Spring Kodiak Trawl (SKT) from 2011 to 2014, frozen in liquid nitrogen and necropsied by the UC Davis Aquatic Health Program in the Department of Veterinary Medicine (URL). In this report we used several metrics of otolith growth as proxies for fish growth and condition to explore relationships between fall habitat conditions and the growth response for Delta Smelt.

The approach of this study was to examine otolith based metrics of growth for Delta Smelt in relation to the dynamic (salinity, temperature, turbidity etc.) and static habitat attributes (CDFW sampling stations, and regions of the upper estuary) measured at the sampling site to assess the effects of habitat attributes on fish health and survival from late summer through the winter spawning season. Fish were collected from three regions in the upper San Francisco Bay Delta Estuary (SFE), namely the Cache Slough complex (Cache Slough and Sacramento Deepwater Ship Channel, C/S), the Sacramento/San Joaquin river confluence and Suisun Bay.

In addition, otolith growth metrics were explored to better understand the effect of fish health on reproductive output (fecundity) for female Delta Smelt collected during the Spring Kodiak

Trawl Survey. In this report we focus on otolith based metrics (growth and life history phenotype and salinity history via otolith microchemistry) to assess the effect of habitat attributes on short-term recent growth rates and fall growth rates of Delta Smelt.

INTRODUCTION

Fish are robust indicators of the ecological conditions in aquatic habitats. As such, fish growth is an important endpoint for assessing the effect of environmental stressors on ecological processes and functions. Growth in fish is indeterminate; where fish will continue to grow in perpetuity given suitable habitat and feeding conditions, thus growth can be a reliable indicator of habitat quality. To this end, fish otoliths ("ear-bones") have been commonly used to determine fish age (daily, annual) and age specific growth. Otoliths are comprised of calcium carbonate and proteins, sequentially layered daily onto a primordial core formed prior to birth. The layering of calcium and protein, when examined under light microscopy can be used to quantify daily age, and the width of daily increments can be used as a proxy for daily growth, as the secretion of calcium and protein is tied to the fish's metabolism. However, validation of direct proportional otolith growth and fish growth is required to make full use of this technique. In previous studies, we have validated proportion otolith growth and fish growth for laboratory cultured Delta Smelt (Hobbs et al. 2007). Thus, the growth history of Delta Smelt can be reconstructed from the increment widths recorded since birth.

The chemical composition of the otolith can reveal provenance. Elements with similar chemical properties to calcium are deposited within the otolith (e.g. Sr, Mg, Ba) in relative proportion to the concentrations in the environment. Otoliths are biologically inert, such that, once formed the chemical composition of the otolith is "locked" in place. This is particularly valuable for determining the movement patterns of mobile fishes that undergo movements across the landscape in association with reproduction. In our previous research we have used strontium isotope ratios to reconstruct the salinity history of smelt utilizing the Low-Salinity Zone, as the strontium isotope ratios of freshwater mix conservatively and predictively with saltwater, such that narrow salinity zones can be identified with strontium isotope ratios in otoliths (Hobbs et al. 2010). Thus, otoliths can be used to determine daily growth rates and the salinity habitat where this growth occurred, making otoliths a valuable tool for assessing the effects of environmental variability on habitat quality and fish production.

Conceptual Model

The IEP-MAST life-cycle model of Delta Smelt was applied to develop predictions for Fall Low-Salinity effects on habitat attributes and the response of Delta Smelt. Using published research, knowledge gained from the recent Delta Smelt synthesis effort (IEP-MAST 2015), and expert opinion we made directional predictions for how each variable would respond to high outflow conditions in the fall of 2011 relative to 2012-2014. Predictions were made for Summer (July – August), and Fall (September – December) and Winter (January – March). These seasonal groupings correspond to general periods when Delta Smelt juveniles, subadults and maturing adult are present in the Low-Salinity Zone. These groupings, correspond to the Summer Townet Survey (TNS) Fall Midwater Trawl (FMWT) and Spring Kodiak Trawl (SKT (**Honey et al. 2004)**. The full list of variables, and predictions for each season, are given in Table 1.

Elevated fall freshwater outflow was predicted to effect the distribution of the Delta Smelt and move the population downstream, closer to the ocean and away from water projects in the South Delta. Higher than normal fall outflow was predicted to move X2 into Suisun Bay and increase the area of the Low-Salinity, reduce water clarity and water temperatures. High fall flows were also predicted to improve feeding conditions for Delta Smelt and reduce toxicity. These effects on habitat attributes in the Low-Salinity Zone would predict that Delta Smelt abundance and survival from summer to fall would improve growth and support a more diverse population, with higher fecundity.

The IEP-MAST drought synthesis project work team has evaluated the current monitoring data and other special studies data to evaluate the impact of the recent drought on habitat attributes in the Low-Salinity Zone and the response of Delta Smelt utilizing the MAST conceptual model for Delta Smelt (**IEP-MAST 2015**).

While this effort was designed to address the impact so drought, many of the same results could be examined for the Fall Low Salinity Habitat Study. We examined anomaly values from standardized long-term trends (2004-2014) comparing 2011 to 2012-2014 and have summarized the finding in Table 1. Attributed with a solid black arrow depict the direction of the trend, greyed arrows represent attributes not assessed. Water year 2011 was the second wettest period since the beginning of the century. Freshwater outflows were extremely high and the resulting location of X2, a geographic marker of Low-Salinity Zone was located in further downstream in Suisun Bay in summer and fall, and the total area of Low-Salinity habitat was greater. Air temperature, Mississippi Silverside abundance (larval predators of Delta Smelt) and Ammonia concentrations (Sac Regional WWTP) were lower while water clarity (Secchi depth) Largemouth Bass abundance and food abundances were greater. Delta Smelt were more abundant in 2011, and had a broader spatial distribution resulting in faster growth rates (based on an index of growth), greater life history diversity and higher reproductive output.

In this report we address research questions pertaining to the effect of fall habitat conditions in 2011 on Delta Smelt growth rates in comparison to drier years of 2012-2015. Specifically we quantified "Fall Growth" using the marginal increment widths of otoliths of Delta Smelt collected during the Fall Midwater Trawl and the habitat attributes at the regional level and reconstructed salinity history from otolith strontium isotope ratios to assess habitat attribute effects on Delta Smelt growth. For fish collected during the Spring Kodiak Trawl, we quantified the increment widths of daily increments formed during the Fall. However, fish collected in the winter were beginning the formation of the annual winter band, and thus daily increment periodicity is no longer reliable for back-calculating daily increments to a calendar date. Therefore, we calculated the mean age at calendar dates for the fall months (Sept 1, Oct 1 and Nov 1) of the Delta Smelt yearclass from the fish collected during the Fall Midwater Trawl. Mean ages at calendar dates were then used to back-calculate a fall otolith increment growth (Sept, Oct, and Nov) for Delta Smelt collected in the Spring Kodiak Trawl. Growth rates were assessed among years and salinity history for the corresponding otolith growth using the otolith strontium isotope ratios. Lastly, we examine the relationship between growth rates, life history phenotypes and fecundity of Delta Smelt from 2011-2014.

METHODS

In the current report, delta smelt received from the FMWT and SKT fish survey were removed from liquid nitrogen by staff at the Aquatic Health Program at UC Davis. Fork lengths

(FL) and body weights (BW) were measured while frozen to determine condition factor (CF). Samples were allowed to thaw briefly to allow the skin to appear natural, then pictures were taken, with a ruler and ID tag, for future image analysis. Otoliths were removed for age, growth, and isotopic microchemistry determinations. The gonads and liver were carefully separated from the GI tract. The GI tract was preserved in 95% ethanol at room temperature and sent to Randy Baxter (Co-PI) at DFW for gut content analysis. Liver and gonads were weighed to determine hepatosomatic (HSI) and gonadosomatic (GSI) indices, respectively. When livers and/or gonad weights were greater than 0.005 g the samples were split into two portions. Un-split liver and gonads were placed in 10% buffered formalin. If the liver or gonad were split then the first portion was placed in 10% buffered formalin at room temperature for histopathology. Gonads of females were histologically scored for development and a subset of the ripest females (late stage 4) was selected to quantify fecundity.

Otoliths

Sagittal otoliths were dissected from the head during necropsy and stored dry in tissue culture trays. Before mounting, the otoliths were "cleared" by soaking in 95% ethanol for 24 hours. Otoliths were mounted onto glass slides with Crystal Bond® thermoplastic resin in the sagittal plane, ground to the core on both sides with wet-dry sandpaper and polished with a polishing cloth and 0.3-micron polishing alumina. Otoliths were digitized with a 12 Megapixel digital camera (AM Scope: www.amscope.com) at a magnification of 20X with an Olympus CH30 compound microscope. Otolith increments were enumerated and the distance from the core to each daily ring was measured using Image-J NIH software . Three age readers separately quantified otolith increments; the mean, median, average percent error and the coefficient of variation of each individual fish were assessed. If the age reading by the three readers for an individual fish was greater than 10% average percent error, the sample was selected for processing of the second otolith for age analysis. When age agreement among multiple readers could not be resolved, ageing was conducted by the principle investigator. If age agreement could not be reduced to less than 10% APE the sample was removed from the study.

Otolith accretion for the fall months Sept-Dec were back-calculated from the otolith by counting back from the edge of the otolith on daily increments and extracting the length of otolith accreted for each month. Accretion rates were calculated by dividing by the number of increments in each month.

Microchemistry

Otoliths were mounted on petrographic slides (20 per slide) for otolith microchemistry. Otolith strontium isotope ratios were quantified using methods previously developed (Hobbs et al 2007; 2010). Briefly, the strontium isotope profile from the core to the edge along a similar path used for aging was scanned using a laser beam of 55-microns moving at a speed of 10-microns per second. Laser profiles began at 100-micron in the core to ensure the analysis encompass the entire natal chemistry. The otolith strontium isotope ^{87}Sr:^{86}Sr profile was aligned with the daily increments to determine the age and size at life history transition stages. The strontium isotope ratios were resolved using methods developed for delta smelt (Hobbs et al. 2005). The data were resolved to the micron distance from the core using the scan speed and verified by post laser ablation digital imaging to make sure the laser line-scan length matched the data resolved length.

Habitat Attributes and Environmental Drivers

Delta Smelt habitat attributes were identified using several approaches. Salinity zones were identified (<1psu, 1-6psu and >6pus) using the surface salinity at each station where Delta Smelt were collected during the Fall Midwater Trawl Survey. In addition stations within the Cache Slough and Sacramento Deepwater Ship Channel were further identified amongst the <1psu stations. The salinity zone habitat the fish utilized during the fall was determined using the strontium isotope ratios of the last 200µm of otolith before capture. Our previous work has established a relationship between strontium isotope ratios and salinity (**Hobbs et al 2010**).

RESULTS

Marginal Otolith Accretion and Salinity Habitats

We measured otolith accretion rates (daily increment widths (µm)) and strontium isotope ratios profiles for 325 Delta Smelt collected during the Fall Midwater Trawl from 2011-2014 (Table 2).

A majority of the samples came from 2011 (N = 233) while few fish were collected in 2012 (N = 42), 2013(N = 17) and 2014 (N = 33) (Table 2). Accretion rates did appear to be faster in 2011 for the September, October and November surveys (Figure 1). However, there was a significant ontogenetic effect with trends across months with marginal otolith accretion slowing from September through December and with fish size as approximated by otolith length (Figure 2).

To account for the ontogenetic effect we modelled the marginal accretion of otolith using a generalized linear model with a Gaussian distribution and log link function to account for the otolith size effect and compare models with year as a factor and three metrics for salinity regions including the CDFW region grouping, the Fall-Low Salinity habitat zones (Cache Slough-Sacramento Deepwater Ship Channel, <1psu, 1-6psu and >6psu) at capture, and the fall salinity history from otolith strontium isotope ratios. Modeling was conducted is a stepwise removal procedure and in all models otoliths size and year were retained, and comparisons were made amongst the three models for fall habitat using AIC's. Each model provided a robust fit to data, no heterogeneity in variance was observed and data were residual plots showed no inherent spatial or temporal correlation. The model including the fall salinity habitat derived from the otolith strontium isotope ratios provided the lowest AIC of 2793.4, while the model with CDFW regions provided the second lowest AIC of 2812.5 and the Fall Low-Salinity Habitat salinity region the highest AIC of 2817.3 (Table 3). Marginal otolith accretion appeared to be lower for individuals having spent the fall in salinity habitats greater than 2.5psu (Figure 3).

Fall growth rates estimates from otolith increments of Delta Smelt collected from the Fall Midwater Trawl

Otolith accretion rates in September 2011 were approximately 1.5 times faster than September accretion rates for the 2012-2014 years (ANOVA, MS=30.6, df=3, $p<0.0001$, while October accretion rates were approximately 20% faster in 2011 (ANOVA, MS= 4.518, df=3. $p<0.0001$ (Figure 4). There were no differences in accretion rates in November, and in December accretion rates for 2011 were only faster than 2012, while 2013 and 2014 accretion rates were faster than 2011 (ANOVA, MS= 2.159, $p<0.0001$. Ontogenetic effects were not accounted for in these models.

Mean September otolith accretion rates differed among the regions of the estuary. In 2011 accretion was slower for fish collected in Suisun Bay and the Sacramento Deepwater Ship

Channel (SDWSC), while in 2012 accretion was fastest in Suisun Bay and Montezuma Slough (Figure 5) Overall, fish collected in Montezuma Slough appeared to have the highest otolith accretion rates while the SDWSC had the lowest for the month of September. However, these are general patterns in means and no statistical tests were used since sample sizes were too low in most cases (Figure 5).

Fall growth rates estimates from otolith increments of Delta Smelt collected from the Spring Kodiak Trawl

We back-calculated the otolith accretion that occurred during the fall for 664 fish collected during the Spring Kodiak Trawl (2012 = 195, 2013 = 198, 2014 = 156 and 2015 = 115). Since fish collected during this survey are undergoing the formation of an annual age band, daily otolith increment resolution was not possible and thus precise increment formation at calendar date was not possible. We used the mean age-at-calendar date for the Delta Smelt collected during the Fall Midwater Trawl Survey for each yearclass to select the age increments formed during the fall for SKT fish. Since marginal otolith accretion was significant for September and October, we used only these months to estimate fall growth for SKT fish. Strontium isotope ratios deposited in the otolith during the fall was determined using the mean otolith length-at-age for the Fall period. Salinity zones were then estimated using the described ranges of strontium isotope ratios for defines salinity zones.

Greater than 90% of all Delta Smelt collected in the SKT survey from 2012-2015 reared in habitats with salinity less 2.5psu (Table 4). The proportion of fish rearing in freshwater during the fall and subsequently having spent the entire life in freshwater varied among the study years, with 2013 having the greatest proportion, while the critically dry 2015 contributed the fewest freshwater resident fish. The 2012 survey, which was the 2011 yearclass that experienced the higher than normal fall outflow condition had a larger proportion of fish rearing in salinity habitats from 1.6 to 2.5 psu (Table 4).

To account for the ontogenetic effect we modelled fall otolith accretion using a generalized linear model with a Gaussian distribution and log link function to account for the otolith size effect and test for a significant slope effect for year (survey years of SKT) and for salinity zones as a categorical variable. Examination of diagnostic plots suggested no violation of the homogeneity of variance, independence and normality assumption. The ontogenetic effect (otolith length at Sept. 1), larger-older fish having slower growth than younger-small fish was highly significant $p<0.0001$, thus accounting for the ontogeny when comparing between years was important (Figure 6). Inter-annual growth trends were similar to both back-calculated Fall growth using FMWT fish and for marginal otolith increment accretion of FMWT fish. The 2011 yearclass (SKT 2012 survey) had higher accretion rates than 2012-2014 yearclasses, with a highly significant negative slope through time (Figure 6). Fish rearing in the 0.5-1.0, 1.1-1.5 and 2.1-2.5 had faster otolith accretion rates relative to fish rearing in freshwater (Table 5).

Growth, Life History Phenotype and Fecundity

To determine the effect of fall otolith growth and life history phenotype on fecundity, we examined the fecundity of 97 late stage 4 female Delta Smelt collected during the Spring Kodiak Trawl Survey from 2012-2014 (2012 N = 36, 2013 N = 21 and 2014 N= 40) and fall otolith accretion rate as a proxy for growth and the life history phenotype (freshwater resident or migratory type). Linear regression of fecundity with fork-length, fall growth and life history phenotype as a factor was analyzed using the lm function in R. The model provided a good fit to the fecundity data, with an adjusted R^2 of 0.61, and was highly statistically significant (Table 6). Examination of diagnostic plots suggested no violation of the homogeneity of variance, independence and normality assumption. Fish fork-length and fall growth had a significant positive effect on fecundity and freshwater resident fish had slightly higher fecundity than migratory fish (Figure 7).

DISCUSSION

Delta Smelt responded to the high freshwater outflow conditions in the Fall of 2011 with faster growth rates and higher fecundity. However, we were not able directly assess the cumulative effect of different environmental drivers on growth and fecundity, as with field data, high freshwater flows can have many interactive effects on habitat attributes simultaneously and thus associating effects to any one driver is not possible. Growth rates can be influenced by a variety of habitat attributes including temperature, salinity and prey availability. In general, temperatures were cooler and salinity was lower in the fall of 2011 relative to 2012-2014. We did not directly assess prey availability in this report, however diet data was collected for Delta Smelt collected during the 2012 and 2013 Spring Kodiak Trawl Surveys (2012 = 2011 yearclass and 2013 = 2012 yearclass). Although we did not make direct comparison of otolith growth and stomach fullness, mean stomach fullness did appear to be greater in winter 2012 compared to 2013, thus food availability was likely higher during the wet year of 2011-2012 (*S.Slater unpublished data*). The increased outflow conditions in the fall of 2011 appeared to provide better overall habitat conditions for Delta Smelt rearing in freshwater and the Low-Salinity Zone, which resulted in greater abundance in the fall and winter, a wider spatial distribution, increased feeding conditions and faster growing fish.

Marginal increment accretion showed similar inter-annual trends to fall growth accretion and was driven by other habitat attributes including the salinity history of individuals derived from the otolith strontium isotope ratios. Fish having reared in habitats with salinity greater than 2.5 psu exhibited reduced growth rates. Exposure to higher salinity can incur a greater energetic cost from increased osmoregulation than lower salinity habitats and reduce growth rates. However, Kammerer et al. (2015) showed that growth was not affected by elevated salinities as high as 10 psu in short term lab rearing studies. Diet data for fish rearing in different salinity zones in the fall and winter months exhibited similar stomach fullness indices, but diet composition did vary, and thus prey quality across the salinity zones may be an additional important driver of Delta Smelt growth (*S.Slater unpublished data*). Nutritional indices did not appear to be significantly different among low and high salinity habitats in this study, but there was some tendency for RNA/DNA ratios and TAG concentrations to be slightly higher in freshwater (S. *Teh et al unpublished dat*a). Contaminant exposure may be an additional stressor reducing growth rates in higher salinity habitats, however there is limited information on contaminant exposures collected at appropriate spatial and temporal scales to correspond with otolith growth rates. Hammock et al. (2015) found evidence of nutritional stress in Delta Smelt collected in Suisun Bay, but histological evidence of contaminant effects was greater in the Cache-Liberty region of the North Delta, thus it is less likely reduced growth in high salinity habitats was driven by contaminant stress.

Adaptive management of the Low-Salinity Zone habitat for Delta Smelt, as prescribed by the biological opinion issued for continued operation of the state and federal pumping facilities, call for increased freshwater flows in the fall to increase growth and subsequent fecundity of Delta Smelt. While, it appeared that Delta Smelt growth and fecundity was elevated during a naturally high freshwater outflow in the fall of 2011, such a response may not be directly inferred if freshwater flows were artificially increased during a dry year. Environmental conditions throughout the year influence the growth and production of eggs in Delta Smelt, thus if fish are experiencing poor habitat conditions during a dry spring and summer, it is uncertain whether increased flows in fall are going to produce similar results as measured in 2011. Moreover, warm and dry springs have been associated with poor recruitment to the juvenile stage, thus few fish may benefit from an artificially induced fall flow, and given the financial and political cost of such an action, the result may not be quantifiable if new few are around to benefit. We recommend such an action be utilized when high spring flows support recruitment of juveniles, but summer and fall conditions are anticipated to be poor without a management action.

Using the Delta Smelt life cycle model produced by the IEP-MAST predicted growth and fecundity would be higher in the fall and winter of 2011. Using otolith increment accretion rates of marginal otolith increments deposited during the Fall Midwater Trawl Survey and back-calculated fall increment accretion for fish collected during the Spring Kodiak Trawl, we showed that growth was elevated in the fall of 2011 compared to 2012-2014. Moreover, increased fall growth was associated with increased fecundity. Based on these data we recommend careful management of freshwater outflows not only during the critical fall months, but through-out the year to support growth and reproduction of Delta Smelt. The 2011-2012 years provide the best example of why we suggest environmental conditions need to be maintained year round. The conditions in 2011 resulted in high production of offspring in the spring of 2012, with the 20-mm survey index reaching abundance levels similar years prior the pelagic organism decline. However, by mid-June abundance declined rapidly, as we entered the first year of a significant drought period, thus any benefits the Delta Smelt may gain from increased fall flows could be easily wiped out by poor conditions the following spring. Management of Delta Smelt requires a life-cycle approach, linking the habitat attributes and environmental drivers form life-stage to life-stage much like the model put forth by the IEP-MAST synthesis report.

Table 1. Fall habitat and Delta Smelt response predictions in response to elevated outflow.

Fall Low-Salinity Habitat 2011-(2012-14)	
Conceptual Model Tier & Variable	**September - December**
Landscape Attributes	
Proximity to Ocean	↑
Proximity to Water Projects	↓
Environmental Drivers	
Flows	↑
Water Diversions	↑
Air Temperature	↓
Water Clarity	↑
Invasive Clam Grazing	↔
MSS Abundance	↓
LMB Abundance	↑
Contaminant Loading	↓
WWTP Ammonium	↓
Food Production	↑
Habitat Attributes	
Water Temperature	↓
Position of LSZ	↓
Area of LSZ	↑
Harmful Algal Blooms	↔
Toxicity	↓
Food Availability	↑
Predation Risk	↓
Entrainment Risk-Projects	↓ or ↑
Entrainment Risk- Small Diversions	↓ or ↑
Delta Smelt Responses	
Abundance	↑
Distribution	↑
Life History Diversity	↑
Growth	↑
Fecundity	↑

Table 2. Fall Midwater Trawl Survey samples sizes for growth and life history

	September	October	November	December
2011	37	45	26	125
2012	1	21	11	9
2013	4	2	3	8
2014	3	3	0	27

Table 3. GLM model results for marginal otolith accretion.

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	142.0	32.6	4.357	0.00002	***
Otolith.Length	-0.0015	0.0001	-12.658	<0.00001	***
Year	-0.0679	0.0162	-4.191	0.00004	***
FallSalinity[T.1]	0.0038	0.0543	0.070	0.94460	
FallSalinity[T.2]	0.0662	0.0523	1.264	0.20700	
FallSalinity[T.3]	-0.0218	0.0576	-0.379	0.70530	
FallSalinity[T.4]	-0.0154	0.0586	-0.263	0.79270	
FallSalinity[T.5]	-0.2466	0.1221	-2.020	0.04420	*
FallSalinity[T.6]	-0.2269	0.0967	-2.347	0.01950	*
FallSalinity[T.7]	-0.2703	0.1228	-2.201	0.02840	*

(Dispersion parameter for gaussian family taken to be 313.2745)

Null deviance: 168855 on 323 degrees of freedom
Residual deviance: 98368 on 314 degrees of freedom
AIC: 2793.4

Table 4. The proportion of total catch rearing in different salinity habitats during the fall based on otolith strontium isotope ratios.

	Fresh	0.5-1.0	1.1-1.5	1.6-2.0	2.1-2.5	2.6-3.0	3.1-4.0	4.1-5.0	5.1-6.0	Total
2012	22%	9%	22%	17%	22%	5%	3%	0%	0%	194
2013	48%	20%	16%	6%	6%	1%	2%	1%	1%	197
2014	24%	21%	25%	10%	11%	4%	3%	2%	0%	155
2015	12%	24%	33%	15%	13%	3%	1%	0%	0%	112

Table 5. GLM model results for Fall otolith accretion for Delta Smelt collected during the Spring Kodiak Trawl Survey 2012-2015 (2011-2014 Yearclasses).

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	308.2	18.320	16.822	<0.00001	***
Otolith.Length	-0.0012	0.000	-12.772	<0.00001	***
Year	-0.1525	0.009	-16.727	<0.00001	***
FallSalinity[T.1]	0.0939	0.026	3.683	0.00025	***
FallSalinity[T.2]	0.0813	0.023	3.489	0.000519	***
FallSalinity[T.3]	0.0120	0.029	0.416	0.677566	
FallSalinity[T.4]	0.0664	0.026	2.507	0.012405	*
FallSalinity[T.5]	0.0462	0.046	1.001	0.317317	
FallSalinity[T.6]	0.0551	0.056	0.986	0.324396	
FallSalinity[T.7]	-0.0722	0.135	-0.535	0.592541	
FallSalinity[T.8]	0.0575	0.252	0.228	0.819619	

(Dispersion parameter for gaussian family taken to be 0.2237039)

Null deviance: 295.43 on 657 degrees of freedom
Residual deviance: 144.74 on 647 degrees of freedom
AIC: 894.92

Table 6. Linear regression model results for fecundity with fish fork-length, Fall otolith accretion rate and the life history phenotype (0 = freshwater resident, 1 = migratory)

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-3212.36	384.014	-8.365	< 0.0001	***
fork_length	64.451	5.794	11.124	< 0.0001	***
Fall.g.d	176.582	46.91	3.764	0.000294	***
migration[T.1]	-174.893	75.492	-2.317	0.02274	*

Residual standard error: 290.9 on 92 degrees of freedom
(5 observations deleted due to missingness)
Multiple R-squared: 0.6234, Adjusted R-squared: 0.6111
F-statistic: 50.75 on 3 and 92 DF, p-value: < 2.2e-16

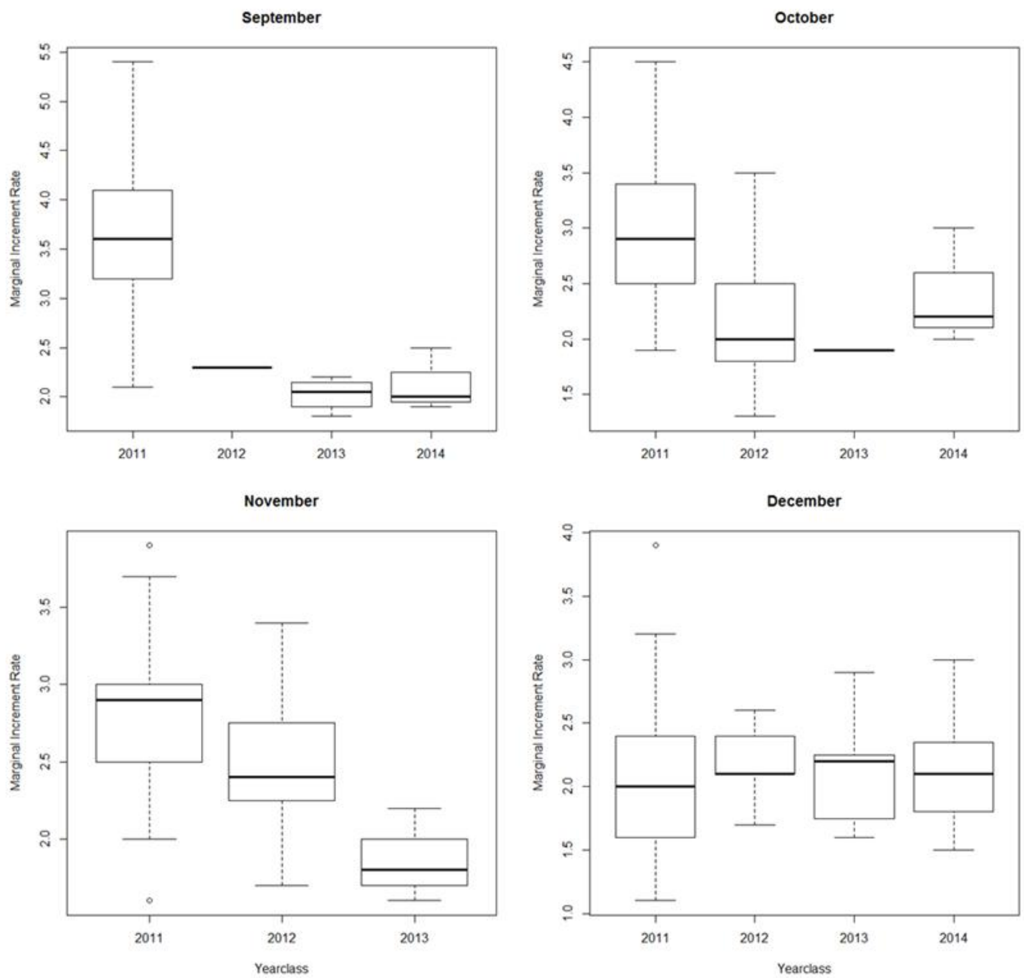


Figure 1. Otolith marginal increment accretion rate (μm/day) for Delta Smelt collected in the Fall Midwater Trawl from September to December in 2011-2014.

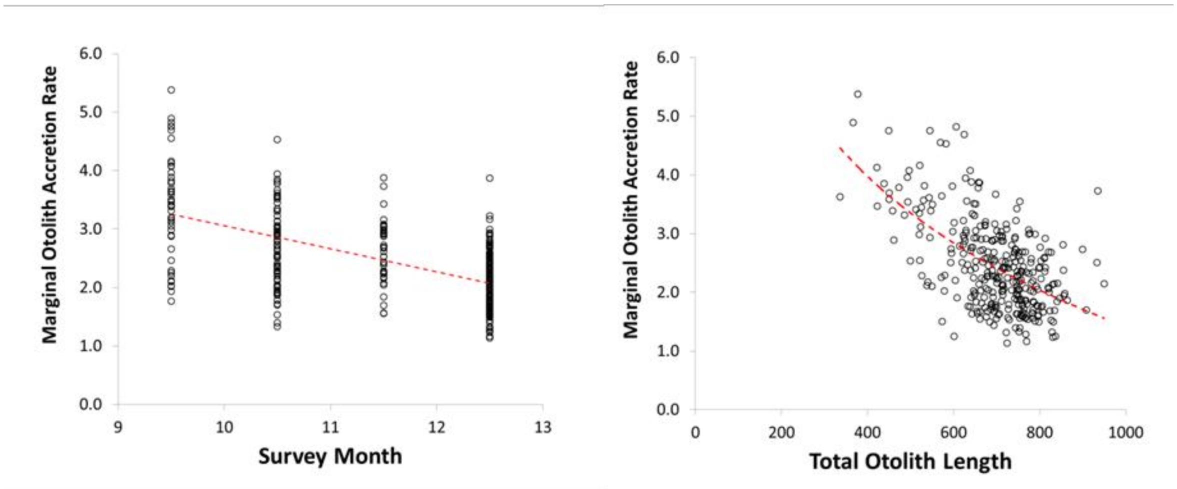
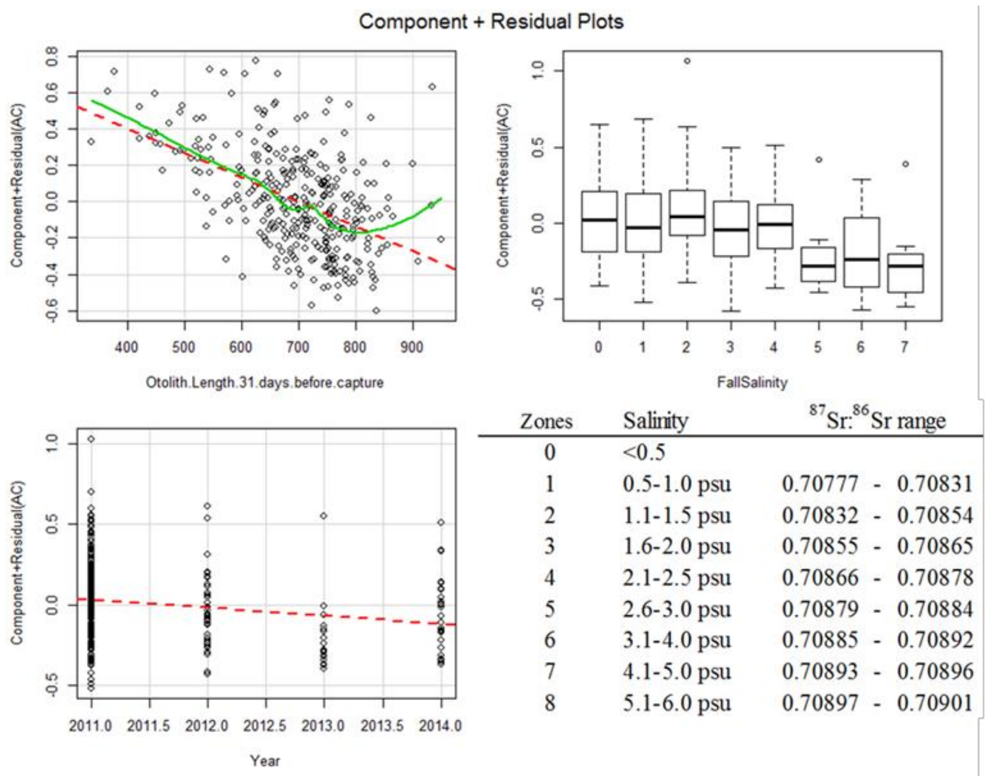


Figure 2. Marginal otolith increment accretion rate (μm/day) for Delta Smelt collected in the Fall Midwater Trawl Survey by Survey Month (left) reflecting the decreasing growth over time (and age) and by the total otolith length (right) depicting the ontogenetic influence of fish size.



Zones	Salinity	$^{87}Sr{:}^{86}Sr$ range
0	<0.5	
1	0.5-1.0 psu	0.70777 - 0.70831
2	1.1-1.5 psu	0.70832 - 0.70854
3	1.6-2.0 psu	0.70855 - 0.70865
4	2.1-2.5 psu	0.70866 - 0.70878
5	2.6-3.0 psu	0.70879 - 0.70884
6	3.1-4.0 psu	0.70885 - 0.70892
7	4.1-5.0 psu	0.70893 - 0.70896
8	5.1-6.0 psu	0.70897 - 0.70901

Figure 3. GLM results for marginal otolith accretion accounting for the otolith size ontogenetic effect, and fall salinity habitat derived from otolith strontium isotope ratios and the year effect.

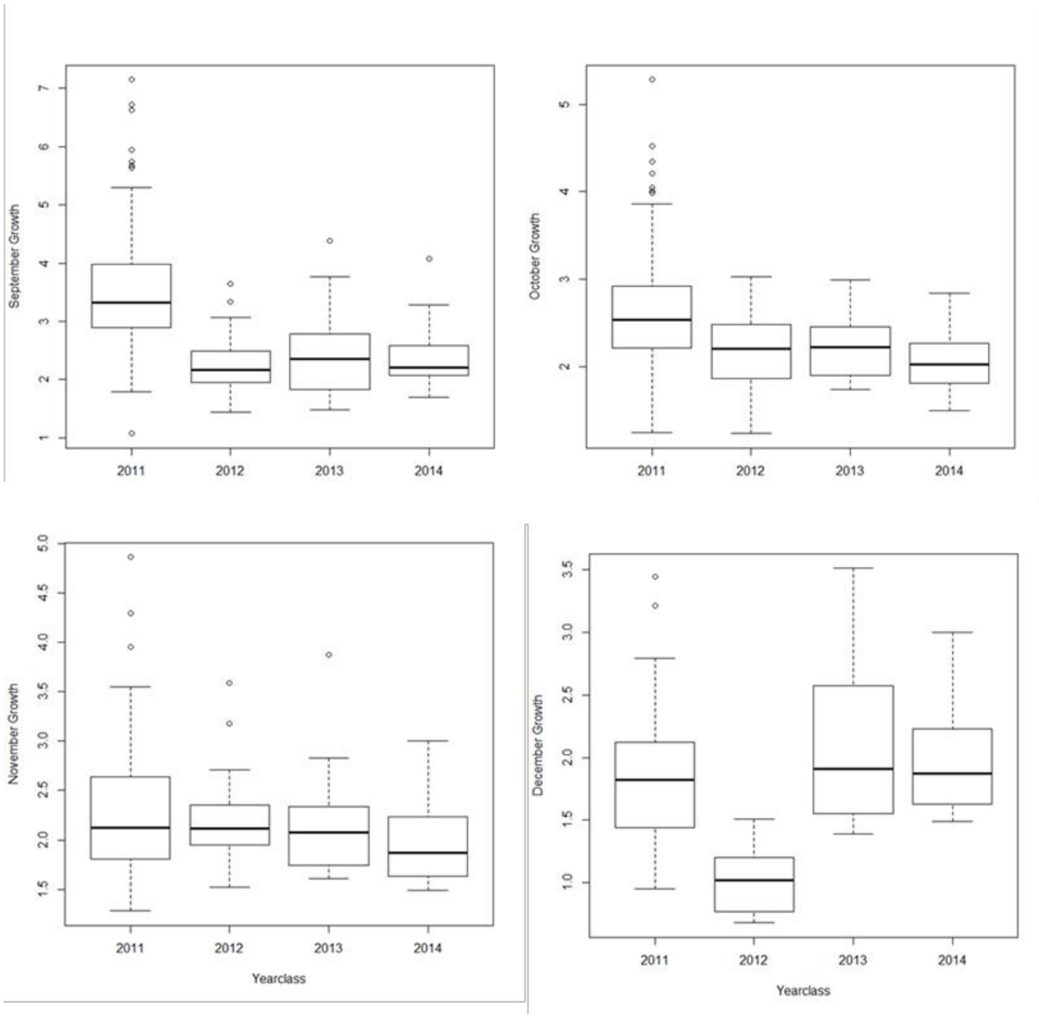
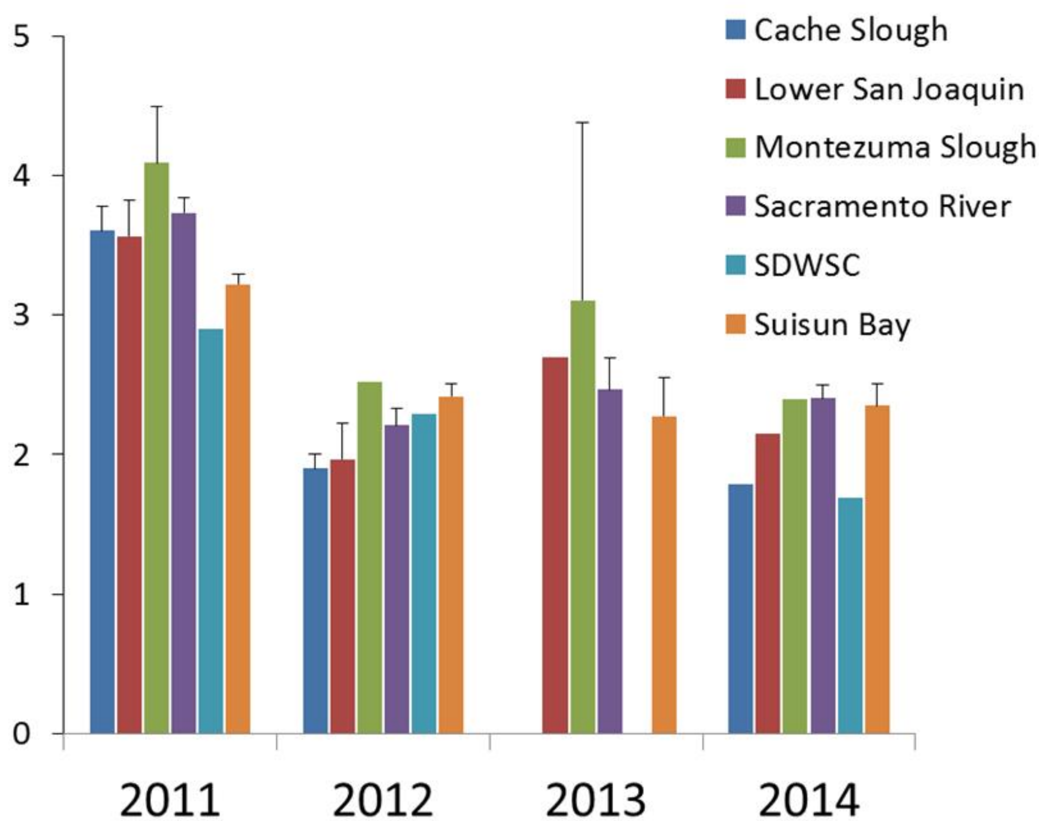
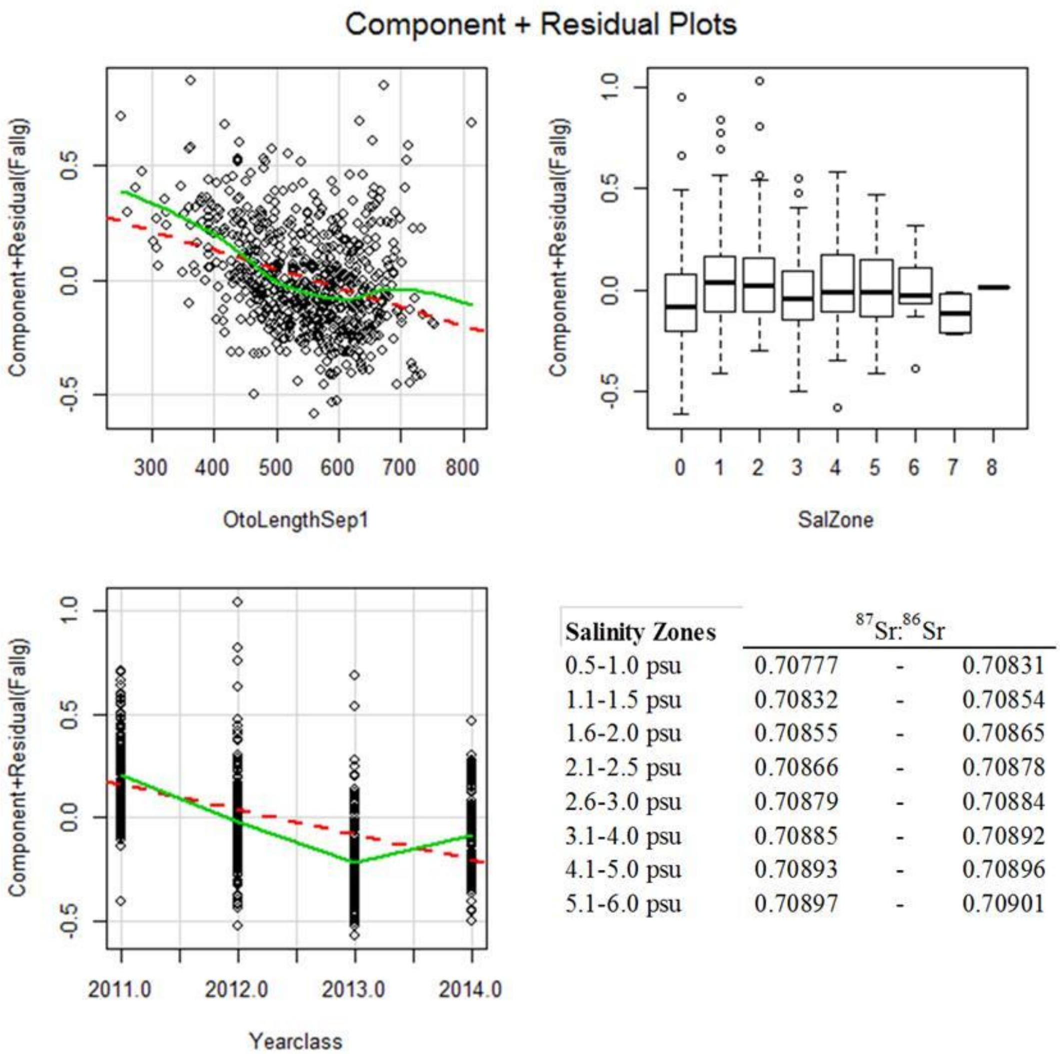


Figure 4. Boxplots of otolith accretion rate (μm/day) accreted during the months of Sept-Dec. Data are from fish collected during the Fall Midwater Trawl 2011-2014.



Year	Cache Slough	Lower SJR	Montezuma	Lower SR	SDWSC	Suisun Bay
2011	17	12	11	89	3	100
2012	3	3	1	21	1	13
2013		1	2	6		8
2014	1	1	1	27	1	2

Figure 5. Bar plot of mean otolith accretion rate (µm/day) for the month of September. Data are from the Fall Midwater Trawl 2011-2014. Error bars depict ± 1SE. Bars without error bars had only single individuals capture and analyzed for growth. Table under figure is the sample size for each bar. No statistical test were attempted with this data.



Salinity Zones	$^{87}Sr{:}^{86}Sr$		
0.5-1.0 psu	0.70777	-	0.70831
1.1-1.5 psu	0.70832	-	0.70854
1.6-2.0 psu	0.70855	-	0.70865
2.1-2.5 psu	0.70866	-	0.70878
2.6-3.0 psu	0.70879	-	0.70884
3.1-4.0 psu	0.70885	-	0.70892
4.1-5.0 psu	0.70893	-	0.70896
5.1-6.0 psu	0.70897	-	0.70901

Figure 6. GLM results for Fall otolith accretion accounting for the otolith size ontogenetic effect, and fall salinity habitat derived from otolith strontium isotope ratios and the year effect.

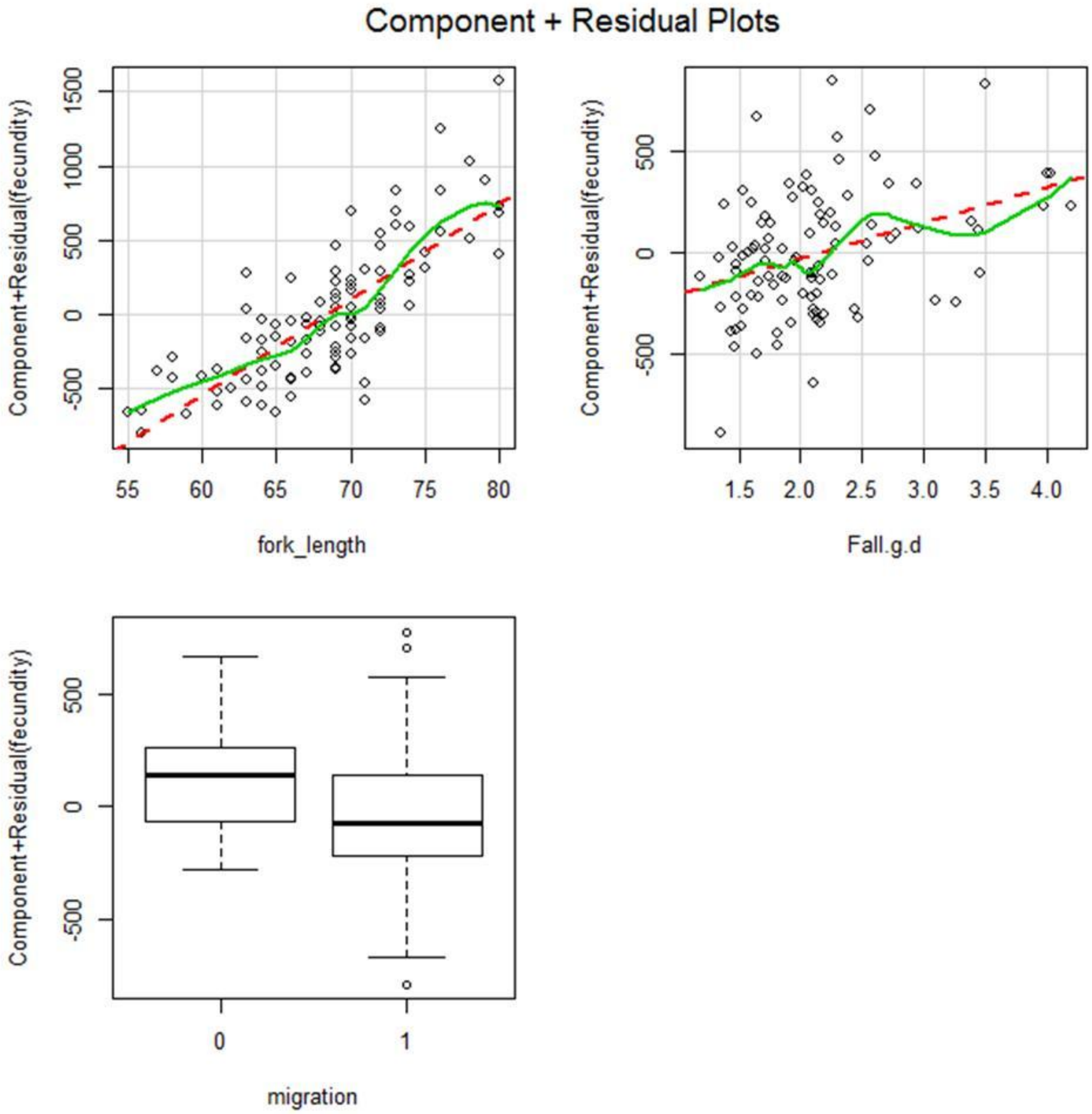


Figure 7. Linear regression model results for Fecundity with fork-length (mm), fall otolith accretion (Fall.g.d) and life history phenotype (0 = freshwater resident, 1 = migratory) as predictor variables.

REFERENCES

Baxter, R., and coauthors. 2010. Interagency Ecological Program 2010 Pelagic Organism Decline Work Plan and Synthesis of Results. Interagency Ecological Program.

Bennett, W. A. 2005. Critical assessment of the Delta Smelt population in the San Francisco Estuary, California. San Francisco Estuary and Watershed Science 3(2).

Bennett, W., and J. R. Burau. 2015. Riders on the Storm: Selective Tidal Movements Facilitate the Spawning Migration of Threatened Delta Smelt in the San Francisco Estuary. Estuaries and Coasts 3:826–835.

Brown, L.R., Baxter, R., Castillo, G., Conrad, L., Culberson, S., Erickson, G., Feyrer, F., Fong, S., Gehrts, K., and Grimaldo, L., Herbold, B, Kirsch, J, Mueller-Solger, A, Slater, S, Sommer T, Souza, K, and E.V. Nieuwenhauyse 2014. Synthesis of Studies in the Fall Low Salinity Zone of the San Francisco Estuary, September-December 2011. US Geological Survey Scientific Investigations Report **5041**: 136.

Brown, L. R., W. A. Bennett, R. W. Wagner, T. Morgan-King, N. Knowles, F. Feyrer, D. H. Schoellhamer, M. T. Stacey, and M. Dettinger. 2013. Implications for Future Survival of Delta Smelt from Four Climate Change Scenarios for the Sacramento–San Joaquin Delta, California. Estuaries and Coasts 36:754–774.

California Fish and Game Commission. 2009. Office of Administrative Law's Notice ID #Z2009-0106-06. Office of Administrative Law's File ID #2009-1119-01S. Section 670.5, Title 14, CCR, Uplist Delta Smelt from threatened to endangered species status. December 21, 2009. [cited 2011 Jun 09]. Available from: *http://www.fgc.ca.gov/ regulations/2009/#670_5ds*

Chapman, B.B., Brönmark, C., Nilsson, J.Å., and Hansson, L.A. 2011. The ecology and evolution of partial migration. Oikos **120**(12): 1764-1775.

Conrad,L and co-authors. 2014. Assessment of 2013-2014 Drought Effects on the Sacramento-San Joaquin Delta Aquatic Ecosystem. Report to the Interagency Ecological Program: Management Analysis and Synthesis Team and the California Department of Fish and Wildlife Drought Operations Team. December 2014.

Dege, M., and L. R. Brown. 2003. Effect of outflow on spring and summertime distribution and abundance of larval and juvenile fishes in the upper San Francisco Estuary. Pages 49–66 American Fisheries Society Symposium.

Dettinger, M. D., F. M. Ralph, T. Das, P. J. Neiman, and D. R. Cayan. 2011. Atmospheric rivers, floods, and the water resources of California. Water 3:445-478.

Dettinger, M., and D. R. Cayan. 2014. Drought and the California Delta - A matter of extremes. San Francisco Estuary and Watershed Science 12(2).

Drought Operations Plan 2014. Central Valley Project and State Water Project Drought Operations Plan and Operational Forecast. April 2, 2014-November 15, 2014

Duffy, Elisabeth J., and David A. Beauchamp. "Rapid growth in the early marine period improves the marine survival of Chinook salmon (Oncorhynchus tshawytscha) in Puget Sound, Washington." Canadian Journal of Fisheries and Aquatic Sciences 68.2 (2011): 232-240.

Federal Register. 1993. Endangered and threatened wildlife and plants; determination of threatenedstatus for the delta smelt. Friday, March 5, 1993. Rules and regulations. Fed Regist [cited 2008 Jul 03];58(42):12854–12864. Available from: *http://ecos.fws.gov/docs/federal_register/fr2235.pdf*

Federal Register. 2010. Endangered and threatened wildlife and plants; 12-month finding on a petition to reclassify the Delta Smelt from threatened to endangerd throughout its rang. Fed Regist [cited 2010 Apr 07];75(66):17667–17680. Available from: http://www.gpo.gov/fdsys/pkg/FR-2010-09-22/pdf/2010-23571.pdf

Feyrer, F., Nobriga, M.L., and Sommer, T.R. 2007. Multidecadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Canadian journal of fisheries and aquatic sciences **64**(4): 723-734.

Gillanders, B.M., Izzo, C., Doubleday, Z.A., and Ye, Q. 2015. Partial migration: growth varies between resident and migratory fish. Biology letters **11**(3): 20140850.

Gleason, T.R., and Bengtson, D.A. 1996. Size-selective mortality of inland silversides: Evidence from otolith microstructure. Transactions of the American Fisheries Society **125**(6): 860-873.

Hobbs, J.A., Yin, Q.-z., Burton, J., and Bennett, W.A. 2005. Retrospective determination of natal habitats for an estuarine fish with otolith strontium isotope ratios. Marine and Freshwater Research **56**(5): 655-660

Hobbs JA, Burton JE, Bennett WA (2007). Modification of the biological intercept model to account for ontogenetic effects in laboratory-reared delta smelt (*Hypomesus transpacificus*).Fishery Bulletin 105:28-37.

Hobbs, J.A., Lewis, L.S., Ikemiyagi, N., Sommer, T., and Baxter, R.D. 2010. The use of otolith strontium isotopes (87Sr/86Sr) to identify nursery habitat for a threatened estuarine fish. Environmental Biology of Fishes **89**(3-4): 557-569.

Honey, K., and coauthors. 2004. IEP long-term fish monitoring program element review. I. E. P. o. t. S.-S. J. D. o. t. S.-S. J. Estuary, editor.

Houde, E., and Hoyt, R. 1987. Fish early life dynamics and recruitment variability. Am. Fish. Soc. Symp. **2**.

IEP Management, Analysis, and Synthesis Team. 2015. An updated conceptual model for delta smelt: our evolving understanding of an estuarine fish h. Page 205. Technical Report 90, January, 2015. Interagency Ecological Program for the San Francisco Bay/Delta Estuary. http://www.water.ca.gov/iep/docs/Delta_Smelt_MAST_Synthesis_Report_January%202015.pdf

Jonsson, B., Duffy, E.J., and Beauchamp, D.A. 2011. Rapid growth in the early marine period improves the marine survival of Chinook salmon (Oncorhynchus tshawytscha) in Puget Sound, Washington. Canadian Journal of Fisheries and Aquatic Sciences **68**(2): 232-240.

Komoroske, L. M., R. E. Connon, K. M. Jeffries, and N. A. Fangue. 2015. Linking transcriptional responses to organismal tolerance reveals mechanisms of thermal sensitivity in a mesothermal endangered fish. Molecular ecology.

Komoroske, L. M., R. E. Connon, J. Lindberg, B. S. Cheng, G. Castillo, M. Hasenbein, and N. A. Fangue. 2014. Ontogeny influences sensitivity to climate change stressors in an endangered fish. Conservation Physiology 2:cou008.

Kuivila, K.M., and G.E. Moon. 2004. Potential exposure of larval and juvenile delta smelt to dissolved pesticides in the Sacramento-San Joaquin Delta, California. In American Fisheries Society Symposium, 229-242: American Fisheries Society.

Lindberg, J. C., G. Tigan, L. Ellison, T. Rettinghouse, M. M. Nagel, and K. M. Fisch. 2013. Aquaculture Methods for a Genetically Managed Population of Endangered Delta Smelt. North American Journal of Aquaculture 75:186–196.

Mac Nally, Ralph, et al. "Analysis of pelagic species decline in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR)."Ecological Applications 20.5 (2010): 1417-1430.

Mahardja, B.,N. Ikemiyagi, and B. Schrier. 2015. Evidence for increased utilization of the Yolo Bypass by Delta Smelt. Interagency Ecological Program Newsletter. V28, N1.13-18.

Maunder, Mark N., and Richard B. Deriso. "A state–space multistage life cycle model to evaluate population impacts in the presence of density dependence: illustrated with application to delta smelt (Hyposmesus transpacificus)."Canadian Journal of Fisheries and Aquatic Sciences 68.7 (2011): 1285-1306.

Merz, J.E., Hamilton, S., Bergman, P.S., and Cavallo, B. 2011. Spatial perspective for delta smelt: a summary of contemporary survey data. California Fish and Game **97**(4): 164-189.

Miller, Jessica A., et al. "Disentangling bottom-up and top-down effects on survival during early ocean residence in a population of Chinook salmon (Oncorhynchus tshawytscha)." Canadian Journal of Fisheries and Aquatic Sciences 70.4 (2013): 617-629.

Miller, William J., et al. "An investigation of factors affecting the decline of delta smelt (Hypomesus transpacificus) in the Sacramento-San Joaquin Estuary."Reviews in Fisheries Science 20.1 (2012): 1-19.

Morrongiello, J.R., and Thresher, R.E. 2015. A statistical framework to explore ontogenetic growth variation among individuals and populations: a marine fish example. Ecological Monographs **85**(1): 93-115.

Murphy, D.D., and Hamilton, S.A. 2013. Eastward Migration or Marshward Dispersal: Exercising Survey Data to Elicit an Understanding of Seasonal Movement of Delta Smelt. San Francisco Estuary and Watershed Science **11**(3).

Nobriga, M. L., T. R. Sommer, F. Feyrer, and K. Fleming. 2008. Long-term trends in summertime habitat suitability for delta smelt (Hypomesus transpacificus). San Francisco Estuary and Watershed Science 6.

Rose, Kenneth A. "Why are quantitative relationships between environmental quality and fish populations so elusive?." Ecological Applications 10.2 (2000): 367-385.

Rose, Kenneth A., et al. "Individual-based modeling of Delta Smelt population dynamics in the upper San Francisco Estuary: I. Model description and baseline results." Transactions of the American Fisheries Society 142.5 (2013): 1238-1259.

Rose, Kenneth A., et al. "Individual-based modeling of Delta Smelt population dynamics in the upper San Francisco Estuary: II. Alternative baselines and good versus bad years." Transactions of the American Fisheries Society 142.5 (2013): 1260-1272.

Secor, D.H. 1999. Specifying divergent migrations in the concept of stock: the contingent hypothesis. Fisheries Research **43**(1): 13-34.

Slater, S. B., and R. D. Baxter. 2014. Diet, prey selection and body condition of age-0 Delta Smelt, *Hypomesus transpacificus*, in the upper San Francisco Estuary. San Francisco Estuary and Watershed Science 12(3):23.

Sogard, S.M. 1997. Size-selective mortality in the juvenile stage of teleost fishes: a review. Bulletin of Marine Science **60**(3): 1129-1157Swanson, C., and J. J. Cech. 2000. Comparative environmental tolerances of threatened delta smelt (Hypomesus transpacificus) and introduced wakasagi (H. nipponensis) in an altered California estuary. Oecologia 123:384–390.

Sommer, T., and Mejia, F. 2013. A Place to Call Home: A Synthesis of Delta Smelt Habitat in the Upper San Francisco Estuary. San Francisco Estuary and Watershed Science **11**(2).

Sommer, T., Mejia, F.H., Nobriga, M.L., Feyrer, F., and Grimaldo, L. 2011. The spawning migration of delta smelt in the upper San Francisco Estuary. San Francisco Estuary and Watershed Science **9**(2).

Sommer, T., Armor, C., Baxter, R., Breuer, R., Brown, L., Chotkowski, M., Culberson, S., Feyrer, F., Gingras, M., and Herbold, B. 2007. The collapse of pelagic fishes in the upper San Francisco estuary: El colapso de los peces pelagicos en la cabecera del estuario San Francisco. Fisheries **32**(6): 270-277.

Swanson, C., and J. J. Cech. 2000. Comparative environmental tolerances of threatened delta smelt (Hypomesus transpacificus) and introduced wakasagi (H. nipponensis) in an altered California estuary. Oecologia 123:384–390.

Swain, D. L., and coauthors, editors. 2014. The extraordinary California drought of 2013/2014: Character, context, and the role of climate change, volume Bulletin of the American Meteorological Society.

Thomson, James R., et al. "Bayesian change point analysis of abundance trends for pelagic fishes in the upper San Francisco Estuary." Ecological Applications 20.5 (2010): 1431-1448.

U.S. Bureau of Reclamation, 2012, Adaptive management of fall outflow for delta smelt protection and water supply reliability: U.S. Bureau of Reclamation, Sacramento, Calif., *http://deltacouncil.ca.gov/sites/default/files/documents/files/Revised_fall_X2_Adaptive_MgmtPlan_EVN_06_29_2012_final.pdf*.

U.S. Fish and Wildlife Service, 2010a, 2008, CVP/SWP coordinated operations delta smelt fall habitat action adaptive management program implementation plan: Sacramento, Calif., U.S. Fish and Wildlife Service, 54 p. *http://deltacouncil.ca.gov/sites/default/files/documents/files/DRAFT_FHA_AMP_Plan_v2.pdf*.

U.S. Fish and Wildlife Service, 2008, Formal Endangered Species Act consultation on the proposed coordinated operations of the Central Valley Project and State Water Project: Sacramento, Calif., U.S. Fish and Wildlife Service, 410 p., *http://www.fws.gov/sfbaydelta/documents/swp-cvp_ops_bo_12-15_final_ocr.pdf*.

Werner, I., L.A. Deanovic, V. Connor, V. de Vlaming, H.C. Bailey, and D.E. Hinton. 2000. Insecticide-caused toxicity to *Ceriodaphnia dubia* (CLADOCERA) in the Sacramento–San Joaquin River delta, California, USA. *Environmental Toxicology and Chemistry* 19: 215-227.

Weston, D.P., A.M. Asbell, S.A. Lesmeister, S.J. Teh, and M.J. Lydy. 2014. Urban and agricultural pesticide inputs to a critical habitat for the threatened delta smelt (*Hypomesus transpacificus*). *Environmental Toxicology and Chemistry* 33: 920-929.

Zuur, A., Ieno, E.N., Walker, N., Saveliev, A.A., and Smith, G.M. 2009. Mixed effects models and extensions in ecology with R. Springer Science & Business Media.