

1 **FINAL REPORT**

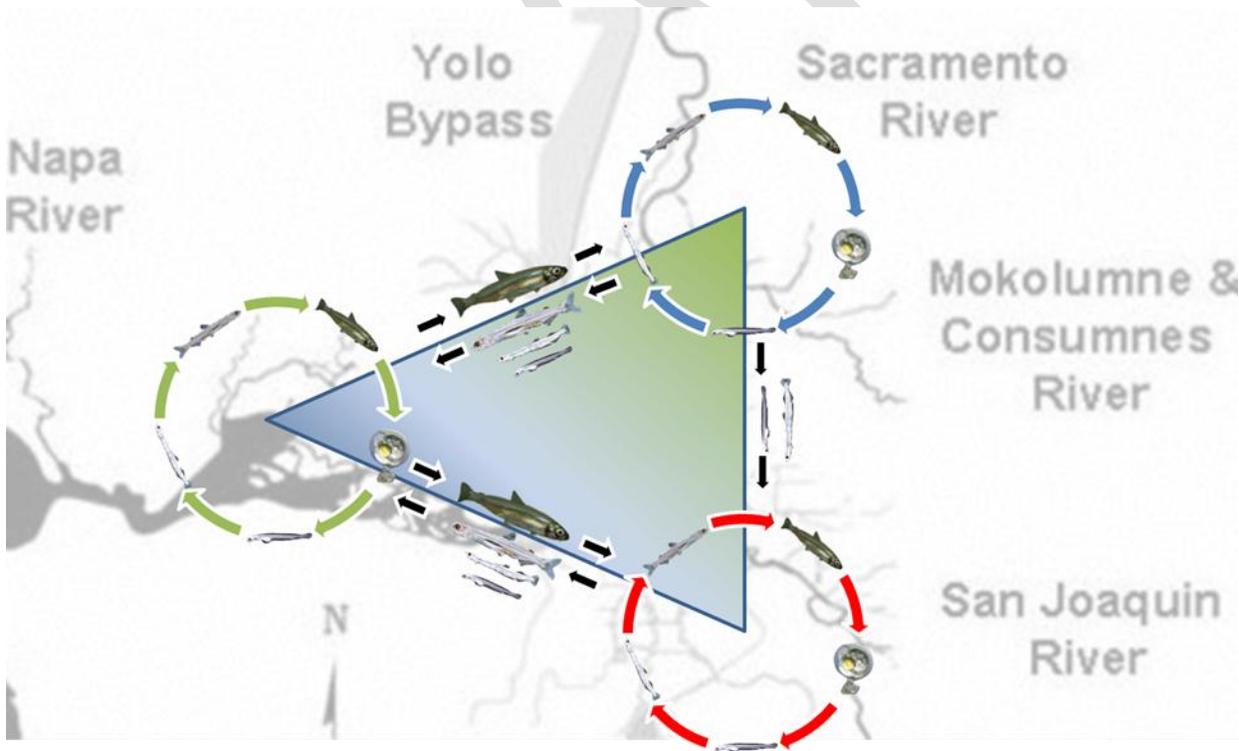
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3 **A Synthesis of Delta Smelt Growth and Life-History Studies**

4
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12
13 Conceptual model of the Migratory Triangle for Delta Smelt

15 **EXECUTIVE SUMMARY**

16 This report represents a synthesis of research investigating the inter-annual variability of
17 growth and life history of the endangered Delta Smelt (*Hypomesus transpacificus*) and the
18 potential environmental drivers associated with long-term trends. Analyses and results presented
19 in this report were focused on two Interagency Ecological Program sponsored studies; the Fall
20 Low-salinity Habitat Study (FLaSH) and the Drought Synthesis Study. Both studies are
21 interested in the effects of the freshwater outflow on habitat in the upper San Francisco Estuary
22 and the response of Delta Smelt to environmental variability. Using otolith micro-structure and
23 micro-chemistry we present a suite of methods to assess the growth and life history response of
24 Delta Smelt environmental variability from 1999-2014. This research was supported by several
25 contracts from both state and federal agencies to the lead author and collaborating authors within
26 the IEP, and is listed within the title page for each section.

27 *Drought Studies*

28 The 2014 Drought Operations Plan (DOP), developed jointly by state and federal agencies in
29 response to Governor Jerry Brown's declaration of a drought emergency in January 2014 called
30 for a data synthesis effort aimed at understanding the impact of the drought on the Sacramento-
31 San Joaquin Delta ecosystem, with particular attention to Chinook Salmon (*Oncorhynchus*
32 *tshawytscha*), Delta Smelt (*Hypomesus transpacificus*), and Longfin Smelt (*Spirinchus*
33 *thaleichthys*) (**DOP 2014**). Given the severity of conditions in the current drought in the context
34 of long-term climate data (unprecedented moisture deficit, record high temperatures), this
35 synthesis effort to understand the drought impacts on the Delta Smelt is a necessary step for
36 informed management of its critical natural resources. Sections I and II of this report examine
37 growth and life history variability during the recent drought period 2012-2014 in comparison to
38 the 2007-2009 drought and to non-drought years since 2003 to address the effects of drought on
39 predicted responses of Delta Smelt. This report focuses on Delta Smelt growth rates during the
40 summer months for fish collected during the Summer Townet Survey; fall months for fish
41 collected during the Fall Midwater Trawl Survey; and winter months for fish collected during the
42 Spring Kodiak Trawl Survey. Analyses were conducted in collaboration with the IEP-MAST
43 Drought Synthesis Project Management Team led by Dr. Louise Conrad of the California
44 Department of Water Resources.

45 Apparent growth and absolute growth rates derived from otolith micro-structure analyses
46 were reduced by approximately 10% from the long-term mean during the recent drought (2012-
47 2014) with 2014 exhibited the slowest growth rates in the time series (1999-2014). However,
48 growth rates during the 2007-2009 drought were more variable, with slow growth rates in 2007
49 and 2008, while growth rates were high in 2009. When drought years were combined and
50 analyzed categorically, growth rates were significantly reduced during droughts. We created a
51 composite variable of environmental drivers (temperature, X2, conductivity, food and water
52 clarity) at seasonal scales and examined inter-annual variability in summer growth rates in
53 response to the composite environmental drivers and found significant aggregate effects of
54 environmental drivers on growth. High conductivity, secchi depth and summer water
55 temperatures were associated with poor growth, while food was the only driver associated with
56 high growth rates.

57 *FLaSH Studies*

58 In the Fall of 2011, a large scale multidiscipline study was launched by the U.S. Bureau of
59 Reclamation (BOR) in cooperation with the Interagency Ecological Program (IEP) to investigate
60 the effects of freshwater outflow on low-salinity zone habitat conditions and the response of
61 Delta Smelt (*Hypomesus transpacificus*) to higher than normal fall outflow in 2011 (**Brown et**
62 **al. 2014**). High outflow years provide positive benefits to many estuarine species, including
63 species of management importance such as the Delta Smelt (**Sommer et al. 2007; Feyrer et al**
64 **2007; Nobriga et al 2008; IEP-MAST 2015**). However; the ecological mechanisms associated
65 with the effects of overall improved habitat conditions and Delta Smelt response are not well
66 understood. This study was motivated by the Biological Opinion (BiOP) on operations of the
67 Central Valley Project (CVP) and State Water Projects (SWP) issued by the U.S. Fish and
68 Wildlife Service (USFWS) in 2008 regarding the potential for continued operations to jeopardize
69 the endangered Delta Smelt (**U.S. Fish and Wildlife Service 2008**). The BiOP issued a series of
70 Reasonable and Prudent Alternatives (RPA) for continued operation. Adaptive management of
71 fall freshwater outflow to improve rearing conditions for Delta Smelt was identified based
72 primarily on relationships between fall habitat conditions and the presence of Delta Smelt
73 (**Feyrer et al 2007; U.S. Fish and Wildlife Service 2010**).

74 Analysis and results presented in sections III-V of this report addresses hypotheses outlined
75 by the Adaptive Management Plan for Fall Low-Salinity Habitats (FLaSH) focusing on summer
76 and fall habitat conditions effects on Delta Smelt growth and Life History (**U.S. Bureau of**
77 **Reclamation 2012**). Section III focuses on habitat conditions during the summer, examining
78 Delta Smelt collected during the Summer Towntnet Survey and was funded by IEP and BOR
79 contract number R13AP20021. In section IV we focus on adult Delta Smelt collected during the
80 Spring Kodiak Trawl during the FlaSH study years (2005-2006 & 2010-2011). The final section
81 focuses on Delta Smelt collected during the Fall Midwater Trawl from 2011-2014 and the Spring
82 Kodiak Trawl from 2012-2015.

83 In section (III) we examined patterns in growth rates, somatic condition and life history
84 parameters (natal origins and hatch-date) at regional scales and across bi-weekly surveys during
85 the summer of 2012 and 2013. In addition we calculated an abundance index for each region and
86 survey to examine mortality and emigration rates. In both years abundance was highest in the
87 North Delta including the Cache-Liberty Slough regions and the Deepwater Ship Channel during
88 the first two surveys, but declined shortly there-after. Survival from survey 1 to survey 2 in both
89 years appeared to be dependent on growth rates, with fish growing slower than 0.35-mm per day
90 not represented in later surveys in the North Delta. In addition, condition factors for fish
91 remaining in the North Delta declined suggesting fish rearing in this region were in poor health.
92 Some fish rearing in the North Delta during the first survey had migrated to the Low-Salinity
93 Zone in between survey 1 and survey 2, and these fish had growth rates greater than 0.35-mm
94 per day supporting the observation that poor growth fish are not surviving through June. These
95 results are particularly important when examining recruitment of the 2012 yearclass, which were
96 the offspring of the large 2011 yearclass. The 20-mm survey in 2012 was relatively high,
97 suggesting a large number of larvae were produced from the 2011 spawning stock, however, the
98 Summer Towntnet Survey index was low suggesting recruitment failure occurred during the
99 summer. This study further pinpoints this recruitment failure to have occurred between June 15th
100 and June 25th, primarily in the North Delta, when water temperatures increased rapidly to above
101 22°C. Hammock et al 2015, examined the health and condition status of this fish using
102 biomarkers and discovered high incidence of contaminant related stress in the North Delta, thus
103 recruitment failure in 2012 was likely an interaction of food limitation, peaking water
104 temperatures and contaminants.

105 In section (IV) we examined growth rates and life history patterns from adult Delta Smelt
106 collect by the Spring Kodiak Trawl Survey, for the paired dry-wet study years of 2005-2006 and
107 2010-2011. Life history patterns were determined via otolith strontium isotope ratios ($^{87}\text{Sr}:$ ^{86}Sr)
108 profiled with laser ablation from the core to the edge of the otolith and growth was quantified as
109 30-day otolith increment widths along the same otolith trajectory. To account for both intrinsic
110 and extrinsic effects of otolith growth, we used a mixed effects regression modelling approach,
111 accounting for the auto-correlative nature of otolith growth, seasonal variability and individual
112 specific effects. Life history diversity and growth rates were predicted, a priori, to be higher
113 during the wet years of 2006 and 2011. Three distinct life history phenotypes were identified in
114 this study. The dominant type was migratory, moving from freshwater natal sites to the low-
115 salinity zone, while individuals that resided in freshwater through-out their life were apparent
116 and contributed a larger percentage to the population in 2010 and 2011 when water temperatures
117 in freshwater were lower. A third type was identified as fish born in the low-salinity zone and
118 found to rear there for the majority of their lives. This contingent of the population contributed
119 significantly to the population in 2006. Growth rates did vary between year classes, with the
120 2010 and 2011 year class exhibiting higher growth and the 2011 year class exhibiting faster
121 growth during the fall months. Seasonal and age specific random effects were apparent,
122 suggesting strong ontogenetic effects occur and the interaction of ontogenetic lifestage and
123 seasonal variability is an important dynamic to account for when examining otolith growth.
124 Overall the mixed effects model with fixed intrinsic and extrinsic effects and random effects was
125 able to account for 85% of the variance in otolith growth. There did not appear to be a difference
126 in growth for the life history types, suggesting freshwater and low-salinity habitats provide
127 similar rearing conditions when water temperatures are cool in freshwater during the summer.
128 However, the lack of freshwater resident fish in 2006, a wet year, when water temperatures in
129 freshwater were high, suggests survival may be impacted during warm summers regardless of
130 freshwater flows.

131 In section (V) we explored relationships between fall growth rates and habitat attributes for
132 Delta Smelt collected during the FMWT (2011-2014) using marginal increment analysis and
133 compared 2011 to 2012-2014 using back-calculated fall growth from otolith increment widths
134 accreted during the fall for fish collected in the FMWT and the SKT Surveys. Marginal
135 increment analysis showed that growth rates were reduced for fish rearing in the fall in habitats

136 with salinities greater than 2.5psu, as determined from the otolith strontium isotope ratio method.
 137 Fall growth rates were greater in 2011 compared to 2012-2014 and 2014 had the lowest overall
 138 growth recorded to date. Fall conditions in 2011 provided better rearing habitat for Delta Smelt,
 139 with higher than normal freshwater outflow and relatively cool water temperatures. The years
 140 from 2012-2014 were below normal to critically dry and much warmer than 2011. Mean
 141 fecundity was higher in 2011 as well and was significantly increased for fish with higher fall
 142 growth rates. Fecundity also appeared to vary among life history phenotypes, with freshwater
 143 resident fish exhibiting higher fecundity than migratory fish when accounting for allometric
 144 effects of fish size, and fall growth rates.

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171 **ABBREVIATIONS**

172	BOR	Bureau of Reclamation
173	CDFW	California Department of Water Resources
174	CVP	Central Valley Project
175	Delta	Sacramento-San Joaquin River Delta
176	FLaSH	Fall Low-Salinity Habitat Study
177	IEP	Interagency Ecological Program
178	LSZ	Low-Salinity Zone
179	MAST	Management, Analysis, and Synthesis Team
180	POD	Pelagic Organism Decline
181	SFE	San Francisco Estuary
182	SKT	Spring Kodiak Trawl
183	SWP	State Water Project
184	TNS	Summer Towntnet Survey
185	JD	Julian Day of Year- number of days from Jan 1

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191 **I. The effect of Drought on the Low-Salinity Zone and the**
192 **Response of Delta Smelt**

193

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212 BACKGROUND

213 Water year 2014 was the third consecutive year of dry conditions and signaled the next
214 significant period of dry conditions in California. The 2013-2015 drought falls in line with a
215 somewhat regular pattern of dry conditions occurring approximately every 15 years in California
216 (**Dettinger and Cayan 2014**). However, the 12-month period from February 2013 through
217 January of 2014 had the lowest amount of precipitation than any 12-month period in over 100
218 years (**Swain et al. 2014**), rendering the current drought even worse than previous extreme
219 droughts in California, such as the 1976–1977 and 1987–1992. In response to the unprecedented
220 dry conditions, Governor Jerry Brown issued an official drought proclamation on January 17,
221 2014 enacting state agencies to prepare for drought conditions.

222 California’s Central Valley Mediterranean climate has traditionally been characterized by
223 dramatic seasonal and inter-annual variation, with each year’s freshwater flow classification (as
224 Wet, Above Normal, Below Normal, Dry, or Critical, [http://cdec.water.ca.gov/cgi-](http://cdec.water.ca.gov/cgi-progs/iudir/WSIHIST)
225 [progs/iudir/WSIHIST](http://cdec.water.ca.gov/cgi-progs/iudir/WSIHIST)) largely dependent on the arrival of just a few storms, mainly during the
226 months of December and January (**Dettinger et al. 2011**). Therefore, single dry years do not
227 signify a drought; rather, they are expected within the normal range of hydrologic variability.
228 Multi-year dry periods that challenge the storage capacity of the water supply infrastructure,
229 however, are generally thought of as droughts and are likely to affect Delta ecology in addition
230 to disrupting agricultural and urban water use.

231 As a consequence of long-term climate variability, California’s native fish fauna is adapted to
232 variation in freshwater flows to the Delta. However; due to significant anthropogenic
233 modification of the Delta and estuary, native fish response to environmental variability have
234 been diminished. The population abundance of Delta Smelt and Longfin Smelt has been at
235 record lows during this unprecedented drought. Moreover, salvage of Delta Smelt and Longfin
236 Smelt has been low; possibly due to additional management actions to curtail export of the
237 species, but likely also a result of there being so few smelt left in the Delta. Thus, the low
238 abundance of smelt during the drought is likely the effect of extreme environmental variability.

239 ***Drought Predictions-IEP-MAST Drought Synthesis***

240 Conceptual models have been a cornerstone for management of the Delta and San Francisco
241 Estuary, not only to document current understanding of species-environment relationships
242 (**Baxter et al. 2010; Sommer et al. 2007**), but also for the purpose of developing predictions
243 necessary for adaptive management of fall outflow levels (**US Bureau of Reclamation 2012**)
244 and the impact of the recent drought on the low-salinity zone habitat and Delta Smelt (**Conrad et**
245 **al. 2015 draft report**). The Interagency Ecological Program's Management Analysis and
246 Synthesis Team, (IEP-MAST) has recently completed a major synthesis and review of Delta
247 Smelt biology, that included an updated conceptual model for the species and factors influencing
248 its habitat (**IEP-MAST 2015**). This model was chosen for assessing drought effects because it
249 includes many biological, chemical, and physical factors of management relevance, and because
250 it summarizes their relationships in an organized way. The Delta Smelt Conceptual Model
251 adopts a multi-tiered hierarchical approach to reflect our current understanding of how the Delta
252 landscape, as well as abiotic and biotic variables that comprise the environmental drivers and
253 habitat attributes that together influence the Delta Smelt population demographics, reproduction,
254 and distribution.

255 The four-tiered approach incorporates the broad spatial and temporal scales on which drivers
256 of the Delta Smelt population act. Specifically, the first tier of the model, the Landscape
257 Attributes tier, contains fixed aspects of habitat that change depending on where Delta Smelt are
258 located (e.g., bathymetry, or proximity to South Delta CVP and SWP water diversions). The
259 second tier, Ecosystem Drivers, reflects factors that influence Delta Smelt habitat but do not
260 directly affect Delta Smelt population dynamics (e.g., clam grazing influences plankton density,
261 which affects food abundance for Delta Smelt). Habitat Attributes, the third tier, include
262 characteristics of habitat that have direct impacts on Delta Smelt (e.g., water temperature). The
263 fourth tier, Delta Smelt Responses, describes the resulting abundance, distribution, and
264 reproduction of Delta Smelt. Factors relevant to Delta Smelt are described for each of these tiers
265 throughout the adult, larval, juvenile, and sub-adult life stages of Delta Smelt that roughly
266 coincide with the four seasons of the year, with some inter-annual variation and overlap between
267 life stages. The conceptual model is further described in detail in the IEP MAST synthesis report.

268 *Application of the Updated Delta Smelt Conceptual Model for Drought Predictions*

269 As the newly updated Delta Smelt conceptual model (hereafter, conceptual model)
270 encompasses a wide range of attributes of the aquatic ecosystem of the Delta, it is a convenient
271 framework for assessing drought impacts on the interior estuary as a whole, in addition to
272 specific impacts on Delta Smelt. The structure of the conceptual model also calls for evaluation
273 of ecosystem attributes throughout the seasons, allowing for a consideration of drought impacts
274 not only during typically wet seasons when expected precipitation is lacking, but also during
275 summer and early fall when the lack of rainfall during preceding winter and spring months may
276 have important ecological impacts.

277 The IEP-MAST conceptual model was used to develop predictions for drought impacts by
278 first summarizing all the variables from each tier contained in the conceptual model. Using
279 published research, knowledge gained from the recent Delta Smelt synthesis effort (IEP MAST
280 2015), and expert opinion we made directional predictions for how each variable would respond
281 to sustained reduced inflow into the Delta during drought. Predictions were then made for each
282 season of the year with the following monthly groupings: Winter (January – March), Spring
283 (April – June), Summer (July – August), and Fall (September – December). These seasonal
284 groupings correspond to general periods when Delta Smelt adults, larvae, juveniles, and sub-
285 adults are present in the Delta, respectively. These groupings, perhaps most importantly for data
286 synthesis efforts, correspond to four routinely-conducted IEP surveys used to develop abundance
287 indices for Delta Smelt and Longfin Smelt: Spring Kodiak Trawl (SKT), 20mm Survey (20mm),
288 Summer Townet Survey (TNS), and Fall Midwater Trawl (FMWT) (Honey et al. 2004). The full
289 list of variables, and predictions for each season, are given in Table 1. Lastly, only evaluated a
290 partial list of these predictions because data were not available for all variables, and some
291 predictions require development of new metrics, based on more careful consideration than time
292 allowed for this progress report.

293 Preliminary analyses show that the current drought (2012-2014) has brought warmer air and
294 water temperatures, increased water clarity, a more landward location of the low-salinity zone
295 (LSZ), increased presence of the cyanobacteria *Microcystis*, and increased abundance of non-
296 native predators of larval and juvenile or small-bodied fishes (Mississippi Silverside and black
297 basses) (Conrad et al 2015). As predicted, these conditions have meant reduced abundance of
298 Delta and Longfin Smelt. For Delta Smelt, the remaining population was distributed farther

299 upstream during IEP monitoring surveys for the recent drought, where habitat area and quality is
300 generally reduced, even in non-drought conditions. In fact, the relative abundance of Delta Smelt
301 in the toe-drain portion of the Yolo Bypass has increased dramatically since 2011 (Majardga et al
302 2015).

303 *Delta Smelt Response to Drought*

304 To assess the effect of drought on growth of Delta Smelt we examined the mean lengths-at-
305 date using bi-monthly surveys of the Summer Townet Survey, monthly surveys from the Fall
306 Midwater Trawl Survey (sub-adult growth rated during fall) and Spring Kodak Trawl Survey
307 (adult growth rates during the winter). This approach is very common in fish monitoring studies
308 for approximating population mean changes in length as a proxy for growth, however, estimates
309 can be biased for species with variable or protracted spawning periods and when gear selectivity
310 occurs for fish size. Gear selectivity is a current area of study for the IEP, however robust results
311 that would provide a means to adjust data have yet to be produced. Delta Smelt exhibit a
312 relatively long spawning period, often occurring from March-June in most years. Bennett (2005)
313 demonstrated with laboratory studies that Delta Smelt spawning and hatching occurs during a
314 period of time when water temperatures were between 12°C and 20°C, and coined this
315 phenomenon the “Temperature Window” for spawning. To account for the protracted spawning
316 period we used the calendar date for each year when daily mean water temperatures measured at
317 the Rio Vista CDEC water quality station were between 12°C and 20°C to serve as a proxy for
318 when fish were hatched (born). The Julian day of the year equidistant from when mean daily
319 temperature reached 12°C and exceeded 20°C was used as the mean hatch-date for the yearclass.
320 Apparent growth rate was then estimated for each survey by simply dividing the mean length-at-
321 survey by the estimated age, where age was estimated by subtracting the mean hatch-date from
322 the capture date.

323 *Summer Townet Survey*

324 Length frequency data from the Summer Townet Survey were expanded so that the dataset
325 had a length for each fish collected from 2003-2014. This dataset does not include the “plus-
326 counts”; fish counted but not measured during the survey. We assume there was no size bias in
327 the plus counting of Delta Smelt. The length data were not normally distributed (Shapiro-Wilks

328 $W = 0.983$, $p\text{-value} = 2.51e-16$). To compare lengths among the study years 2003-2014 a
329 generalized linear model (GLM) was fit with a gaussian log link function with fork-length a
330 function of survey and year. Survey had a strong effect on length ($F = 183.8$, $df = 5$ $p < 0.0001$)
331 and increased from survey 1 to survey 6 as fish grew (Table 2). Length varied among study
332 years ($F = 34.6$, $df = 11$, $p < 0.0001$) and were generally smaller in 2006, 2011 and 2012 when
333 accounting for survey effects (Figure 2).

334 *Fall Midwater Trawl Survey*

335 Fall midwater trawl length data were expanded as with the Summer Towntnet Survey and did
336 not account for plus counts. Length data was again not normally distributed (Shapiro-Wilks, W
337 $= 0.9845$, $p\text{-value} = 1.377e-08$), thus a log link function was used in a GLM. Survey had a
338 strong effect of fork-length ($F = 69.3$, $df = 3$, $p < 0.0001$), as did year ($F = 36.5$, $df = 11$,
339 $p < 0.0001$) (Table 3). Fish lengths increased with survey month and were much smaller in 2003
340 and 2006 (Figure 3).

341 *Spring Kodiak Trawl Survey*

342 Spring Kodiak trawl length data from 2002-2014 were expanded as with the Summer Towntnet
343 Survey and did not account for plus counts. Note that the Spring Kodiak Trawl study year
344 corresponds to the previous calendar year yearclass of fish. Length data was again not normally
345 distributed (Shapiro-Wilks, $W = 0.9523$, $p\text{-value} = 1.4727e-08$), thus a log link function was
346 used in a GLM. Survey had a strong effect of fork-length ($F = 711.1$, $df = 4$, $p < 0.0001$), as did
347 year ($F = 212.6$, $df = 12$, $p < 0.0001$) (Table 4). Fish increased in length through the survey
348 months, and were smaller in 2002, 2004, 2007 and 2012 (Figure 4).

349 *Apparent growth using estimate hatch-dates from the temperature window*

350 Estimated mean hatch-date for the yearclass provided a good approximation for mean hatch-
351 date using traditional otolith age methods (Figure 5). Apparent growth rates during the recent
352 drought 2012-2014 for the summer and fall appeared to be significantly reduced relative to the
353 previous two years, a Wet Year (2011) and Below Normal Year (2010), and similar to the 2007
354 Critically Dry Year and 2008 Dry Years, however 2009 was also a Dry Year but growth rates
355 were elevated for that year (Figure 6). The apparent growth of adult Delta Smelt collected

356 during the Spring Kodiak Trawl did not exhibit a similar pattern to the summer and fall surveys.
357 Overall growth was much slower over the winter months and may be driven by winter conditions
358 rather than carry over from summer and fall conditions.

359 **DISCUSSION**

360 Delta Smelt lengths-at-survey varied among the study years, however patterns were
361 not consistent as hypothesized. Mean fork-lengths tended to be smaller in the wet years
362 (2006, and 2011) during all surveys (not SKT corresponds to 2007 and 2012 for 2006 and
363 2011 years); dry years tended to have the opposite pattern. While gear bias likely has
364 some effect on the length distributions, the timing of hatching may have a strong
365 influence on the fish size-at-survey. Hatchdate distributions back-calculated from otolith
366 age varied over the years of study and was associated with spring temperatures. Thus the
367 length-at-survey analyses would need to account for the variability in hatch-date. This
368 could be done using mean lengths-at-survey and the estimated mean hatch-date for the
369 yearclass, but detailed analyses at the individual level would not be possible and
370 statistical inference would be limited, but would serve as a reasonable proxy for inter-
371 annual variability of apparent growth.

372 Apparent growth rate varied among the study years and was consistent with the
373 predictions from the MAST model. Growth appeared to be reduced during the 2012-
374 2014 drought period for Summer Towntnet Survey and Fall Midwater Trawl but was not
375 different during the Spring Kodiak Trawl. The years 2007 and 2008, of the previous
376 drought period exhibit similar results, although 2009, the third year of that drought had
377 high apparent growth in the Summer and Fall, thus other factors may be influence
378 patterns in apparent growth. If apparent growth patterns can be validated with years of
379 otolith derived empirical growth, this technique for indexing apparent growth may
380 provide a valuable tool for assessing long-term trend in the variability of growth using
381 historic survey data and water temperature data.

382 In conclusion, using length-at-survey data revealed patterns that did not support the
383 predicted effect of drought on fish size, but apparent growth using the estimated mean
384 hatch-date from the water temperature window more likely reflected inter-annual patterns

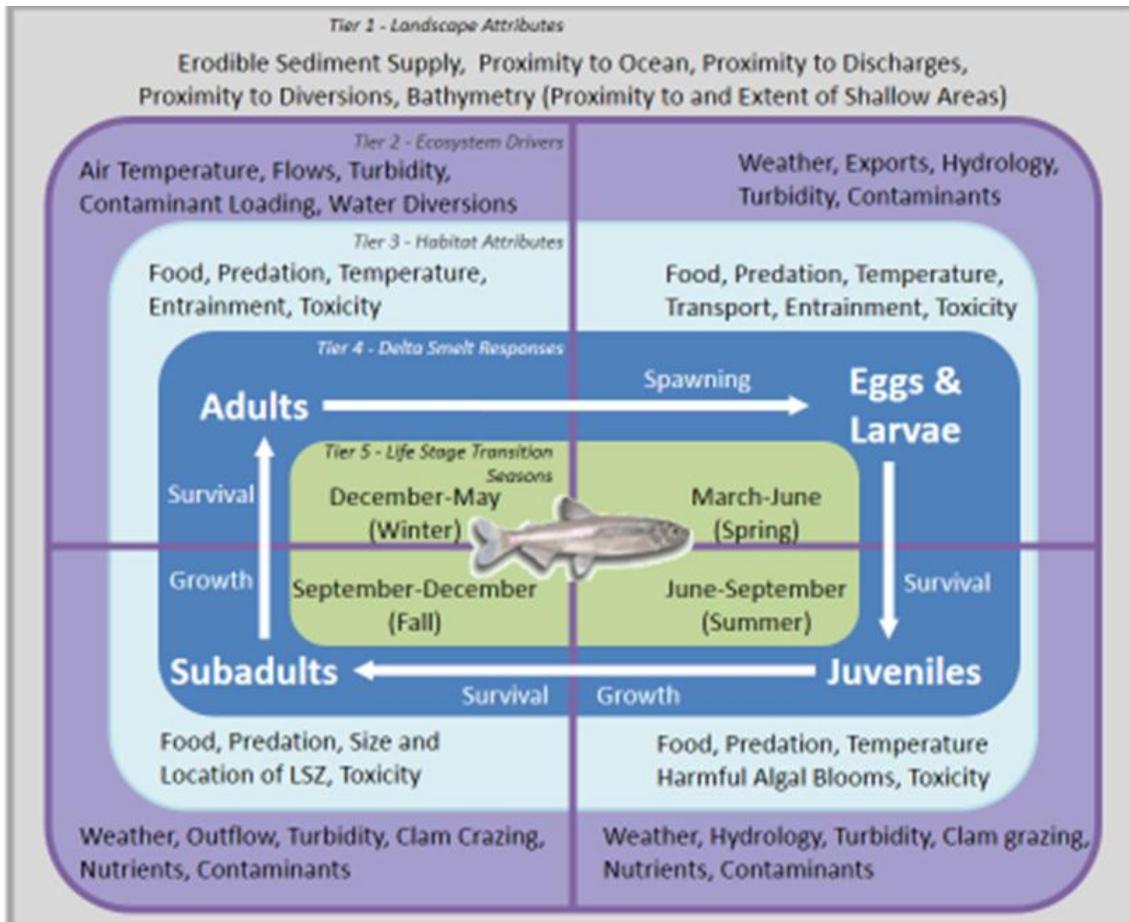
385 in growth rate. As predicted from the MAST conceptual model, apparent growth was
386 reduced during drought periods during the summer and fall months. Fish lengths-at-
387 survey, particularly for the SKT survey are still an important metric of Delta Smelt
388 response to environmental conditions as length is likely a strong driver of individual
389 fecundity and it remains to be seen how growth rates may influence fecundity
390 independent of fish size. Thus in years when fish may hatch early, growth may be less
391 important for reaching a larger length during the spawning season as in years when
392 spawning may be delayed by cool spring temperatures, which often occur during wet
393 years. The inconsistency inter-annual patterns of lengths-at-survey during the SKT
394 survey compared to the FMWT and TNS may suggest that either a persistent length bias
395 occurs between these sampling gears or growth compensation is occurring during the
396 late fall-early winter in years when fish are small during the summer and fall.

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402 Figure 1. The MAST life-cycle conceptual model for Delta Smelt. Fish responses (dark blue
 403 box) to habitat attributes (light blue box), which are influenced by environmental drivers (purple
 404 box) in the four “life-stage/seasons”(green box).

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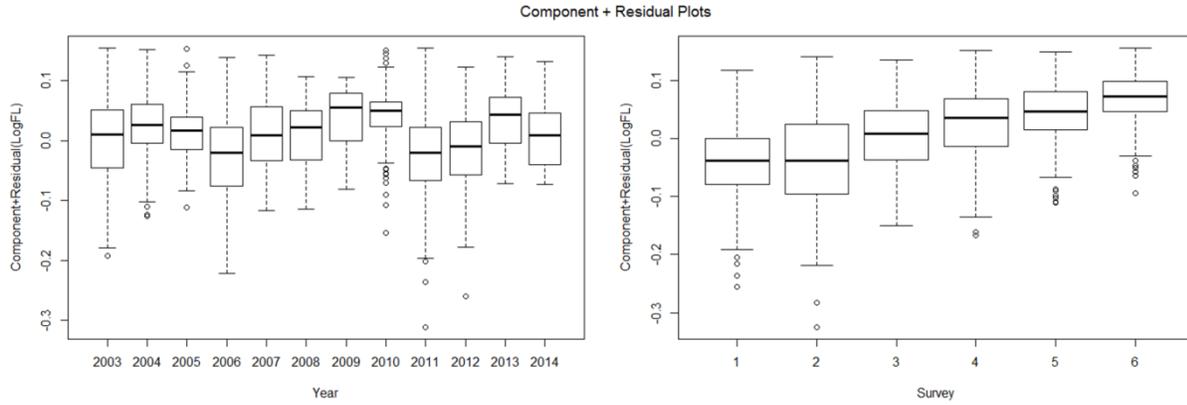
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412 Figure 2. Boxplot of length-frequency expanded fork-lengths from all 6 surveys of the Summer
 413 Towntnet Survey (right) from 2003-2014 (left).

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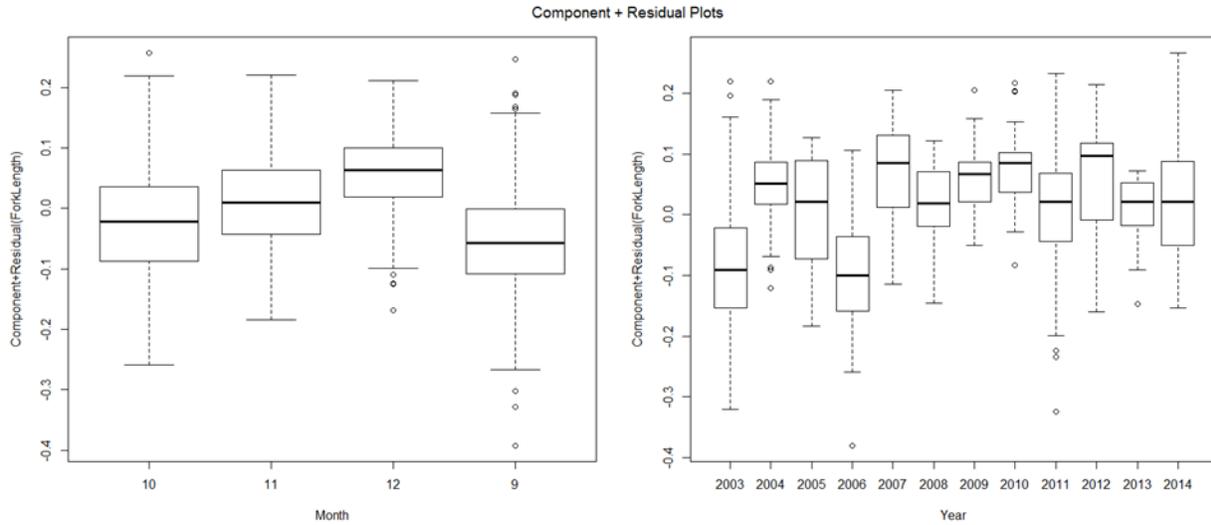
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432 Figure 3. Boxplots of length-frequency expanded fork-lengths from the four monthly surveys
 433 (Sept-Dec) of the Fall Midwater Trawl Survey from 2003-2014.

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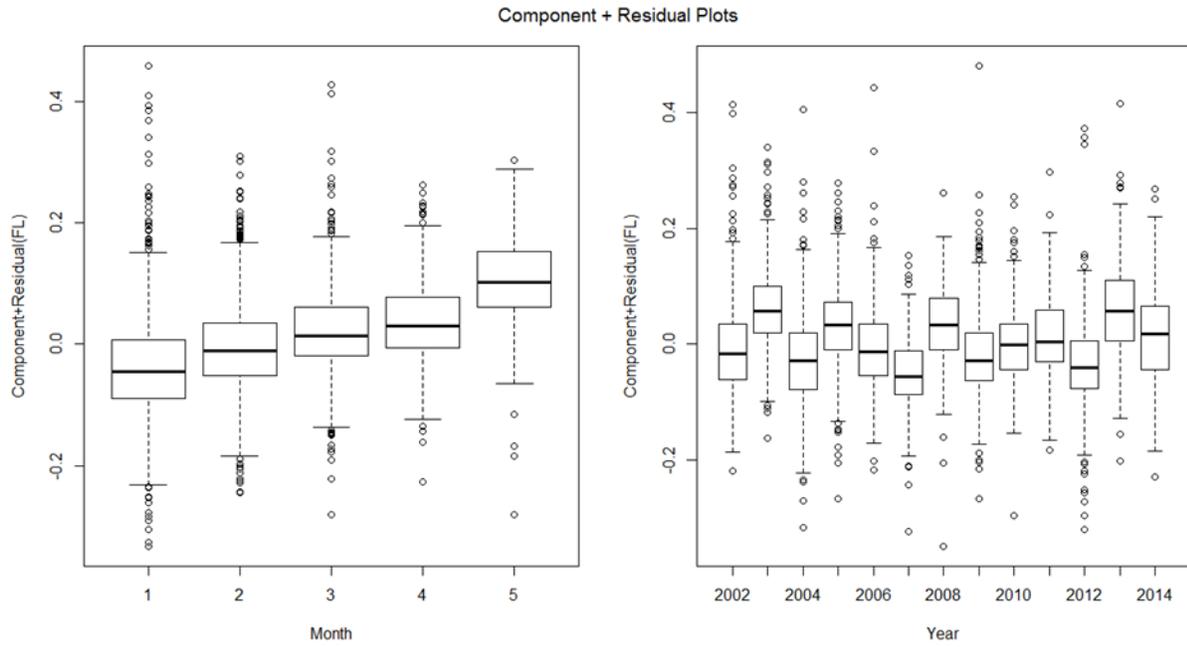
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445 Figure 4. Boxplots of length-frequency expanded fork-lengths from the five monthly surveys
 446 (Jan-May) of the Spring Kodiak Trawl Survey from 2003-2014.

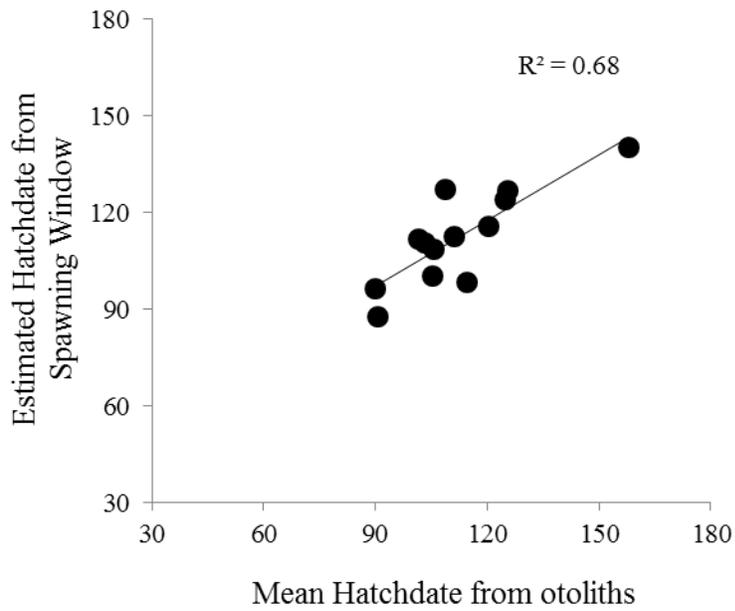
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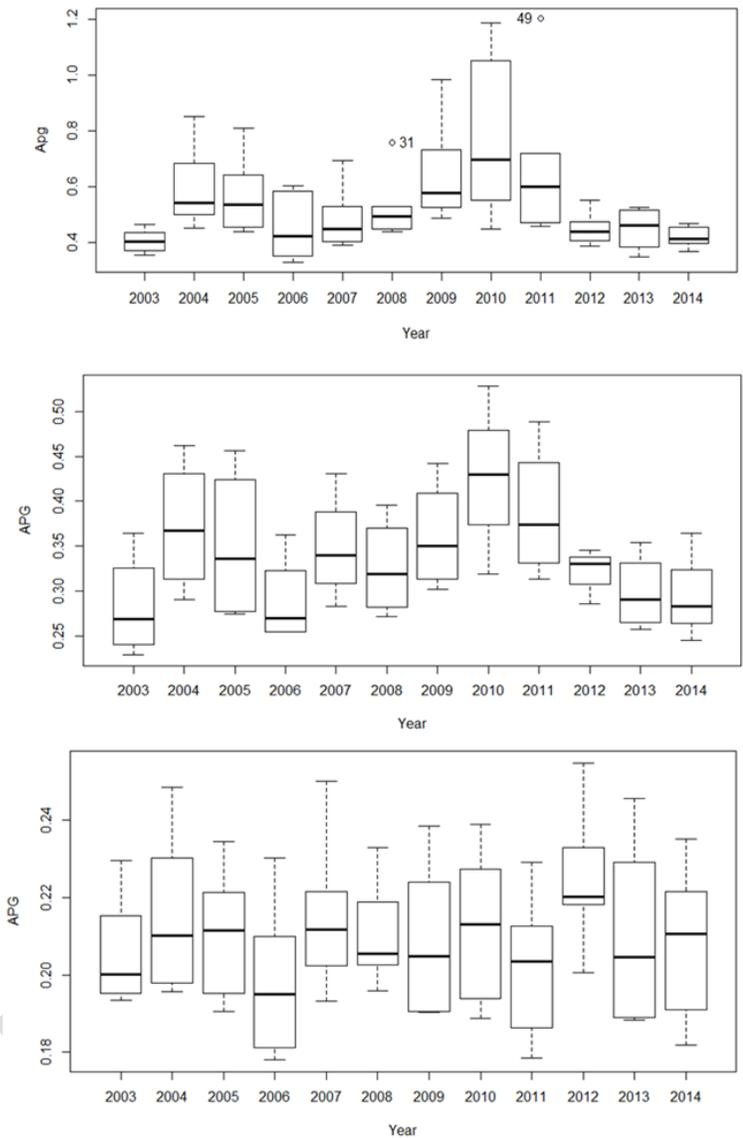
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453 **Figure 5.** Correlation between mean hatch-date derived from otolith back-
 454 calculation and the estimated hatch-date derived from the temperature based
 455 spawning window.



456

457 **Figure 6.** Apparent Growth Rate for the IEP Summer Trawl Survey (Top), Fall Midwater
 458 Trawl (middle) and Spring Kodiak Trawl (bottom), from 2003-2014. Note the SKT survey takes
 459 place the follow calendar year than the other surveys, thus to facilitate comparisons Year
 460 represent the yearclass so 2014 in the bottom panel was the 2015 Spring Kodiak Trawl.

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465 **Table 1.** Directional predictions for drought effects on the Delta LSZ ecosystem, with variables derived from the
 466 Delta Smelt conceptual model, compared to the previous decade. ↑ = predicted increase, ↓ = predicted decrease, ↔
 467 = no change predicted, ↓ or ↑ = prediction for increase or decrease can both be made, and black box = no prediction
 468 made. For clam biomass, *Pot.* = *Potamocorbula amurensis* and *Corb.* = *Corbicula fluminea*. Only predictions in
 469 black font were evaluated in the IEP-MAST Drought Synthesis Report (Conrad et al. 2015). Prediction for Longfin
 470 Smelt were assumed to be the same as for Delta Smelt.

Conceptual Model Tier & Variable	January - March	April - June	July - August	September - December
Landscape Attributes				
Proximity to Ocean	↓	↓	↓	↓
Proximity to Water Projects	↑	↑	↑	↑
Proximity to Small Water Diversion Sites	↑	↑	↑	↑
Proximity to Contaminant Discharge Sites	↑	↑	↑	↑
Proximity to and Extent of Shallow Areas	↓	↓	↓	↓
Erodible Sediment Supply	↓	↓	↓	↓
Environmental Drivers				
Flows	↓	↓	↓	↓
Water Diversions	↓	↓	↓	↓
Air Temperature	↔	↔	↔	↔
Water Clarity	↑	↑	↑	↑
Invasive Clam Biomass	↑ <i>Pot.</i> , ↓ <i>Corb.</i>			
MSS Abundance		↔		
LMB Abundance	↔		↓	↓
Contaminant Loading	↓	↓	↓	↓
WWTP Ammonium	↔	↔	↔	↔
Food Production	↓ or ↑	↓ or ↑	↓ or ↑	↓ or ↑
Food Retention	↑	↑	↑	↑
STB Abundance	↓		↓	↓
Habitat Attributes				
Water Temperature	↔	↔	↔	↔
Position of LSZ			↑	↑
Harmful Algal Blooms		↑	↑	↑
Size of LSZ			↓	↓
Toxicity	↑	↑	↑	↑
Food Availability	↓	↓	↓	↓
Predation Risk	↑	↑	↑	↑
Entrainment Risk-Projects	↓ or ↑	↓ or ↑	↑	↑
Entrainment Risk- Small Diversions	↓ or ↑	↓ or ↑	↑	↑
Delta Smelt Responses				
Abundance	↓	↓	↓	↓
Distribution		↑	↑	↑
Life History Diversity	↓	↓	↓	↓
Growth	↓	↓	↓	↓
Fecundity	↓			
Genetic Diversity	↓	↓	↓	↓

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473 Table 2. Genelized linear model results for Summer Townt Survey

	Estimate	Std.Error	t-value	Pr(> t)	
(Intercept)	0.401955	0.0042	95.709	< 2e-16	***
Year[T.2004]	0.021526	0.0055	3.914	9.34E-05	***
Year[T.2005]	0.012529	0.006209	2.018	0.043709	*
Year[T.2006]	-0.035577	0.007126	-4.992	6.40E-07	***
Year[T.2007]	0.014292	0.008674	1.648	0.099535	.
Year[T.2008]	0.011637	0.00722	1.612	0.107165	
Year[T.2009]	0.035378	0.008757	4.04	5.51E-05	***
Year[T.2010]	0.038736	0.005241	7.391	2.00E-13	***
Year[T.2011]	-0.025906	0.003932	-6.588	5.47E-11	***
Year[T.2012]	-0.017245	0.005124	-3.365	0.000777	***
Year[T.2013]	0.033245	0.00557	5.969	2.75E-09	***
Year[T.2014]	0.0065	0.007577	0.858	0.391067	
Survey[T.2]	0.005289	0.003967	1.333	0.182581	
Survey[T.3]	0.047499	0.003811	12.465	< 2e-16	***
Survey[T.4]	0.070086	0.003923	17.865	< 2e-16	***
Survey[T.5]	0.085982	0.004612	18.642	< 2e-16	***
Survey[T.6]	0.111581	0.004629	24.106	< 2e-16	***

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491 Table 3. Generalized linear model results for Fall Midwater Trawl Survey

	Estimate	Std. Error	t value	Pr(> t)	
(Intercept)	3.957073	0.006544	604.72	< 2e-16	***
Month[T.11]	0.031075	0.009187	3.382	0.000748	***
Month[T.12]	0.080799	0.007364	10.972	< 2e-16	***
Month[T.9]	-0.03309	0.008624	-3.836	0.000133	***
Year[T.2004]	0.136478	0.009294	14.685	< 2e-16	***
Year[T.2005]	0.079407	0.017443	4.552	5.99E-06	***
Year[T.2006]	-0.02464	0.018361	-1.342	0.179913	
Year[T.2007]	0.151353	0.016572	9.133	< 2e-16	***
Year[T.2008]	0.106034	0.018924	5.603	2.75E-08	***
Year[T.2009]	0.145501	0.018653	7.8	1.62E-14	***
Year[T.2010]	0.156885	0.013	12.068	< 2e-16	***
Year[T.2011]	0.095404	0.008477	11.255	< 2e-16	***
Year[T.2012]	0.15011	0.013315	11.274	< 2e-16	***
Year[T.2013]	0.09273	0.020084	4.617	4.43E-06	***
Year[T.2014]	0.10378	0.027135	3.825	0.00014	***

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510 Table 4. Generalized linear model results for Spring Kodiak Trawl Survey

	Estimate	Std. Error	t value	Pr(> t)	
(Intercept)	4.145575	0.002689	1541.651	< 2e-16	***
Month[T.2]	0.034597	0.001911	18.105	< 2e-16	***
Month[T.3]	0.059415	0.002038	29.159	< 2e-16	***
Month[T.4]	0.074326	0.002234	33.265	< 2e-16	***
Month[T.5]	0.145107	0.00289	50.202	< 2e-16	***
Year[T.2003]	0.068685	0.003073	22.354	< 2e-16	***
Year[T.2004]	-0.01691	0.002922	-5.789	7.29E-09	***
Year[T.2005]	0.042176	0.003118	13.528	< 2e-16	***
Year[T.2006]	0.005552	0.003825	1.452	0.1466	
Year[T.2007]	-0.03996	0.003692	-10.824	< 2e-16	***
Year[T.2008]	0.04511	0.004618	9.769	< 2e-16	***
Year[T.2009]	-0.00698	0.003698	-1.887	0.0592	.
Year[T.2010]	0.007658	0.003861	1.983	0.0474	*
Year[T.2011]	0.022552	0.004097	5.504	3.79E-08	***
Year[T.2012]	-0.0255	0.003208	-7.949	2.07E-15	***
Year[T.2013]	0.073881	0.004313	17.129	< 2e-16	***
Year[T.2014]	0.021702	0.004423	4.906	9.42E-07	***

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**Ila. Growth of Estuarine Smelts: Putting the Extreme
Drought into a Long-Term Context**

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The Interagency Ecological Program

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535 INTRODUCTION

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537 Quantifying vital rates across fish life stage transitions is central to understanding and
538 predicting variability in recruitment (**Rose 2000**). The ability to mathematically describe
539 variation in the growth and survival of delta smelt was recently shown to be a powerful tool for
540 testing alternative hypotheses about why and how delta smelt abundance has varied through time
541 (**Rose et al. 2013a,b**). This recently developed capability marks a large scientific step forward
542 from numerous previous studies that relied on correlation-based analyses, which often had
543 inconsistent results (**Bennett 2005; Mac Nally et al. 2010; Thomson et al. 2010; Maunder and**
544 **Deriso 2011; Miller et al. 2012**).

545 Classical fishery science predicts that environmental conditions and particularly predation
546 pressure select for rapid growth of fishes during their early life stages (**Houde 1987; Sogard**
547 **1997; Duffy and Beauchamp 2011**). However, individual studies have found the highest
548 predation pressure can occur on the fastest growing individuals of a cohort (**Gleason and**
549 **Bengsten 1996**) and a recent study of young Chinook salmon found that fast growth only
550 increased survival when ocean productivity was poor (**Miller et al. 2013**). This basic conceptual
551 framework suggests two analogous possibilities may occur for delta smelt. One possibility is
552 that when we compare growth rates of fish collected in 2014 to those of fish collected in
553 previous years, we will find that growth rates are similar because fast growth is persistently
554 selected for. The other possibility is that we will find faster growth in 2014 (and possibly other
555 dry years) relative to years of better overall environmental conditions because rapid growth is
556 strongly selected for when conditions are poor like we expect they will be this summer due to
557 warm weather and low outflow.

558 Our second conceptual model can be stated simply that not all spawning and rearing habitats
559 are created equal. The prevailing hypothesis is that both delta smelt and longfin smelt spawn in
560 freshwater (mainly in the Delta and Suisun Marsh; Moyle 2002). Recent research has shown that
561 delta smelt can spawn as far west as the Napa River (**Hobbs et al. 2005; 2007**). Although larval
562 stages of these fishes can be widely distributed throughout freshwater to mesohaline habitats of
563 the estuary, we have recently found that longfin smelt larvae that rear in the low-salinity zone are

564 more likely to survive (**Hobbs et al. 2010**) and that delta smelt have both freshwater-resident and
565 low-salinity resident contingents that survive to adulthood (Hobbs unpublished data). Given the
566 extreme drought conditions forecast for summer 2014, we expect the low-salinity zone to extend
567 landward into regions generally considered to be poor rearing habitat. Further, we expect this
568 year's drought conditions to limit the seaward distribution of delta smelt rearing habitat by
569 constricting it mainly to the legal Delta and to limit the landward distribution of longfin smelt
570 rearing habitat.

571 Resiliency can be described as the tendency to return to an average state following a
572 perturbation. Variable weather patterns and climate variability can have significant effects on
573 estuarine fish populations. However, estuarine species are particularly adapted to such dynamic
574 environmental variability, with life history strategies optimized to compensate for such
575 variability. The use of otolith micro-structure and micro-chemical analysis will enable us to
576 determine how resilient Delta Smelt life history strategies are to extreme drought. This
577 information will help fishery managers plan habitat restoration that is resilient to future droughts.

578 **BACKGROUND**

579 The delta smelt, is a small euryhaline fish, endemic to the upper San Francisco Estuary. It
580 completes its life cycle in only a year, has a low fecundity and is sensitive to warm temperatures
581 and high salinity. Indeed the life history of this species is a conundrum, given its persistence in a
582 highly altered Mediterranean estuarine habitat. In this study we are investigating the role of
583 phenotypic expression of life history variability in providing the species with the resiliency to
584 survive its changing world. With the use of state of the art otolith microstructure and
585 microchemistry tools, we have discovered the delta smelts strategy for dealing with climate
586 variability. However, data from recent years suggests the resiliency, that life history diversity
587 may afford, is disappearing. While researchers have been frantically investigating the myriad
588 factors contributing to their demise, the ultimate culprit may be climate change. Long-term
589 changes in the timing of the spring transition and warming of the Delta, have had subtle but
590 important effects on the reproductive timing and recruitment of the delta smelt, leading to
591 reduced life history diversity and resiliency. Given future climate predictions, the fate of the
592 delta smelt is bleak.

593

594 Delta smelt is a mesothermal species found commonly at temperatures from 10°C to 22°C.
595 Wild caught delta smelt show a critical thermal maximum of 25.3°C for juvenile fish acclimated
596 to 17°C (**Swanson and Cech 2000**). Hatchery smelt acclimated to 16°C have a critical thermal
597 maximum of about 28°C but thermal tolerance differs among life stages with tolerance
598 decreasing from late-larval to post-spawning fish (**Komoroske et al. 2014, 2015**). Molecular
599 assays suggest that thermal stress can begin at about 20-21°C depending on life history stage,
600 and delta smelt are unable to compensate for thermal stress, meaning short term exposure to
601 stressful conditions can lead to chronic stress (**Komoroske et al. 2015**). These results are
602 consistent with reduced smelt catch at higher temperatures. The majority of delta smelt juveniles
603 (Summer Townet Survey, STN) and pre-adults (Fall Midwater Trawl Survey, FMWT) are caught
604 at water temperatures of <22°C (**Nobriga et al. 2008, Komoroske et al. 2014**). This is consistent
605 with absence of delta smelt from the San Joaquin River and south/central Delta during summer.
606 Presumably, delta smelt in the wild will avoid areas where water temperatures are near their
607 thermal maximum and would be less likely to be captured in surveys.

608

609 Early life history and growth of smelt in the San Francisco Estuary has been well studied.
610 Using otolith microstructure and microchemistry, daily growth can be estimated from otolith
611 increments and the location of growth can be inferred from strontium isotope ratios deposited in
612 the otolith and assayed with laser ablation techniques (**Hobbs et al. 2006,2007 and 2010**). In
613 this study, we explore the response of Delta Smelt to changing environmental conditions and the
614 recent critical drought in the Sacramento-San Joaquin Delta using otolith microstructure and
615 microchemistry to reconstruct life history diversity, natal origins and hatch-date distribution from
616 1999 to 2014.

617

618 *Research Questions:*

- 619 (1) What are the growth rates of Delta Smelt during 2014 and how do they compare to
620 growth rates of fish collected in previous years?
621 a. Is growth rate reduced during droughts?
622
623 (2) Are life history attributes effected by drought
624 a. Does drought effect the natal origin distribution?

- 625 b. Does drought effect the phenology (hatch-date distribution)
626 c. Does drought effect life history diversity?

627

628 **METHODS**

629

630 Delta Smelt were collected by IEP staff during the Summer Townet Survey (June-August)
631 between 2002 and 2011, measured for forklength (mm) onboard, individually cataloged and
632 given a unique identification number and preserved in 95% ethanol. Samples from 1999-2001
633 were individually cataloged and given a unique identification number and measured for fork-
634 length (mm) by UCD staff onboard during the Summer Townet Survey. Beginning in August
635 2011 UC Davis staff followed the IEP surveys in shadow boat and was responsible for
636 cataloging and archiving Delta Smelt in liquid nitrogen. In the lab, Delta Smelt were thawed,
637 weighed, measured for length, and digitally photographed for additional measurements. Sagittal
638 otoliths were dissected from the head using ultra-fine forceps (Dupont® SE140, stainless steel)
639 and stored dry in tissue culture trays. Before mounting, the otoliths were “cleared” by soaking in
640 95% ethanol for 24 hours. Otoliths were mounted onto glass slides with Crystal Bond®
641 thermoplastic resin in the sagittal plane, ground to the core on both sides with wet-dry sandpaper
642 and polished with a polishing cloth and 0.3-micron polishing alumina on a MIT Corp. polishing
643 wheel. Otoliths were digitized with a 12-Megapixel digital camera (AM Scope:
644 www.amscope.com) at a magnification of 20X with an Olympus CH30 compound microscope.
645 Digital images at 20X magnification were merged into a complete image of a transect from the
646 core to the dorsal edge at a 90° angle from the primary axis of the otolith.

647

648 Age and Growth

649

650 Otolith increments were enumerated to estimate age using Image-J NIH software. Aging was
651 conducted by a minimum of two readers, and the mean, median, average percent error between
652 age readers was assessed. If the age reading by the independent readers for an individual fish
653 was greater than 10% average percent error, the sample was selected for processing of the second
654 otolith for age analysis. If age discrepancy among readers was found for the second otolith, that
655 sample was discarded. The absolute growth rate AGR (g) for individual fish was calculated by:

656

$$AGR (g) = \frac{FL_{catch} - FL_{hatch}}{Age_{mean}}$$

657

658 Where length-at-hatch was 5.2mm. Otolith increment counts have been shown to be an accurate
659 measure of age from hatch (Hobbs et al. 2007).

660

661 The hatch-date for each fish was calculated by subtracting the age from the capture date and was
662 reported as the number of days from January 1 to facilitate plotting.

663

664 Growth Rates

665 AGR's were compared between years and water year index with ANOVA. Tukey multiple
666 comparisons were used to compare instantaneous growth rates among years and water year
667 types. Diagnostic plots of residuals were explored to assess model assumptions, including
668 normality (QQ-plot), homogeneity of variance (residuals vs. fitted values), constant variance
669 (scale-location plot) and outliers with cook's distance plot as suggested by Zuur et al 20x.. The
670 use of AGR's in comparing populations requires an assumption of linear growth during the time
671 period of study, thus we examined the age-length relationship with a linear and non-linear model.

672

673 Environmental Drivers

674 Environmental variables identified to be affected by drought conditions and potentially effect
675 Delta Smelt growth and survival during the spring-summer and summer-fall transition periods
676 were explored as predictor variables for annual mean AGR (See Conrad et al 2015 for a list).
677 Annual indices for each variable were transformed to anomaly values by subtracting the annual
678 index from the global mean for each variable and dividing by the global standard deviation.
679 Next univariate correlation analyses were conducted for each environmental driver and AGR.
680 Finally, Principle Components Analysis was used to combine environmental drivers into a
681 composite (Eigenvalue) variable and then used as a predictor variable for AGR in linear
682 regression analysis.

683

684 Temperature

685 Water temperatures (15-min intervals) from continuous water quality monitoring stations
686 were retrieved for Martinez (MRZ), Mallard Slough (MAL) and Rio Vista (RIV) from the

687 California Data Exchange Center (<http://cdec.water.ca.gov/>) on November 24th 2015. Data were
688 recorded in Fahrenheit (°F) and transformed to Celsius (°C) using:

689

$$^{\circ}\text{C} = \frac{^{\circ}\text{F} - 32}{1.8}$$

690

691 Daily means for each station were calculated from 15-minute interval data from January 1, 1999
692 to December 31, 2014. Finally, the daily mean temperature was calculated among the three
693 stations (MRZ, MAL and RIV). The daily mean temperature between July 1 and August 31 was
694 used as an index of summer water temperatures for analysis.

695

696 X2

697 The mean position of X2 was calculated from DAYFLOW from March 1 to July 31 of each year.

698

699 Water Clarity and Conductivity

700 Water clarity was quantified using Secchi disk depths (cm) and conductivity (µs) was
701 measured using a hand-held YSI meter at IEP-Summer Towntnet Survey stations (excluding the
702 South Delta and Napa River station). The mean value from all bi-weekly surveys within a year
703 was used as an annual index.

704

705 Food

706 Zooplankton data from the IEP-Environmental Monitoring Program (EMP) was used to
707 calculate an index of prey abundance using the Clark-Bumpus net and the microzooplankton
708 pump data for *Limnoithona* spp. Data consisted of density (numbers of target taxa per cubic
709 meters of water filtered) from monthly surveys conducted between March and August of each
710 study year. Data for stations in San Pablo Bay were excluded from the dataset. The mean
711 density of common prey taxa was calculated for each year and used as an annual index. Prey
712 taxa included *Eurytemora affinis* (EURYTEM), *Pseudodiaptomus forbesii* (PDIAPFOR),
713 *Acanthocyclops vernalis* (AVERNAL), Other Calanoid adults (OTHCALAD) and Calanoid
714 Copepodids (ALLCALJUV) and *Limnoithona* spp (TotalLimno). The index was calculated by
715 summing annual means of each taxa. An index of food abundance was calculated with and

716 without *Limnoithona* sp. since it dominated to total abundance and is not a dominant taxa found
717 in Delta Smelt diets.

718
719 **RESULTS**

720
721 For this report we processed and examined 138 fish from the 2014 Summer Townet Survey
722 (STS), 161 fish from the 2011 STN and 55 fish from the 2010 STN and 4 fish from the 2009 for
723 age and growth and natal origins. These data were included into the existing dataset of STS
724 sampled which from 1999 to present (note we are missing 2003 and 2008 and the 4 individuals
725 from 2009 were excluded from the analyses due to too few samples). This dataset now includes
726 data for 72 fish from one Critically Dry year (2014), 555 fish from 5 Dry years, 350 fish from 4
727 Below Normal years and 480 fish from 4 Wet years, as determine by the water year index system
728 for a total of 1461 fish for age and growth (Table 1).

729 The relationship between fork-length (mm) and age (days) exhibited a linear relationship
730 from 20 days of age to approximately 120 days, after which the growth in length begins to slow
731 relative to age (Figure 1). Data for 28 fish greater than 130 days and 16 less than 40 days of age
732 were excluded from the statistical analysis to meet the assumption of linearity of growth rates.
733 AGR's (g) varied between years, with growth rates ranging from 0.23 to 0.45 mm/day (25th and
734 75th percentile) ANOVA (MS 0.06, F= 20.46, df = 12 p<0.001) (Table 1). The year-classes,
735 2006, 2007, 2012-2014 had significantly reduced growth rates (Figure 2). The mean AGR in
736 2014, a Critically Dry year was the lowest mean AGR on record with mean of 0.37 mm/day \pm
737 0.4, 1 σ , a reduction in AGR of 9% from the grand mean for 1999-2013, ANOVA MS= 0.06,
738 F=16.2 df= 3 p<0.001. Tukey multiple comparisons were significant for the Critically Dry year
739 among all comparisons (p<0.0001), while the Dry Years were slower than the Below Normal
740 Years (p=0.003) and Wet Years were significantly slower than Dry Years (p=0.010) but not
741 different than Below Normal Years (Figure 3).

742
743 **Anomalies**

744 Anomaly values for X2 were consistent with water year type, positive anomalies (position up
745 estuary) occurred for Dry Years (2001, 2002, 2007 and 2013) and for Below Normal Years
746 (2004, 2010 and 2012) and negative (position down estuary) in one Below Normal Year (2005)
747 which had unseasonal high flows in May, and Wet Years (1999, 2000, 2006 and 2011) (Figure

748 4). Salinity responded similarly with positive anomalies in 2000, 2002, 2004, 2007, 2012, 2013,
749 2014 (Figure 4). Mean summer water temperatures (July-Aug) did not correspond with water
750 year types, with positive anomalies for years 2000, 2001, 2002, 2004, 2005, 2006, 2013 and
751 2014, and negative for 1999, 2002, 2007, 2010, 2011, 2012(Figure 4). Food was more abundant
752 in 1999, 2000, 2005, 2006, 2011 with positive anomalies and less abundant in 2001, 2004, 2007,
753 2010, 2012, 2013, 2014 exhibiting negative anomalies (Figure 4). Water clarity as measure by
754 Secchi disk depth measurements exhibited a trend through time with negative anomalies from
755 1999-2006 and switching to positive anomalies in 2007 (Figure 4). Conductivity ($\rho = -0.50$), X2
756 ($\rho = -0.40$) summer temperature ($\rho = -0.45$) and secchi ($\rho = -0.40$) exhibited negative correlations
757 with AGR and positive correlations with food ($\rho = +0.30$), however, all trends were not
758 statistically significant.

759

760 Principle Component Analysis

761 Environmental drivers were combined by principle component analysis into three components
762 explaining overall 94% of the variance (Table 2). The first principle component explained 56%
763 of the variance and was positively associated with, in order of strength, X2-Conductivity-
764 Summer Temperature and Secchi, while food was the only variable to load negatively on PC
765 1(Table 2). The second principle component an additional 20% of the variance with Secchi
766 loading positively and Summer Temperatures negatively, while the remaining variables were
767 weakly associated with PC 2 (Table 2). Principle component 3 explained an additional 17% of
768 the variance with Food, Secchi, Summer Temperatures and Secchi loading negatively and X2
769 loading positively on PC3 (Table 2). Loading scores for each year were plotted against the three
770 principle axis (Figure 5). Years loading positively on PC were the drier years, with 2014, the
771 Critical Dry Year having the largest score (-2.51), while Wet years loaded negatively (1999,
772 2006 and 2011) (Figure 5). Years loading positively on PC 2 were recent years in the time series
773 when water clarity (Secchi has increased), while years loading negatively on PC were warm
774 summers (2001 and 2006) (Figure 5). Years loading positively on PC 3 cooler and had higher
775 X2 values, while years loading negatively were had either more food (2006) or were warmer
776 (2014) (Figure 5). AGR anomalies were marginally correlated to PC 1 (Kendall's tau =0.41, p-
777 value = 0.057), while PC 2 (tau= -0.12, p-value = 0.59)and PC 3 tau= -.10, p-value = 0.67) were
778 not correlated to AGR (Figure 6).

779

780 **DISCUSSION**

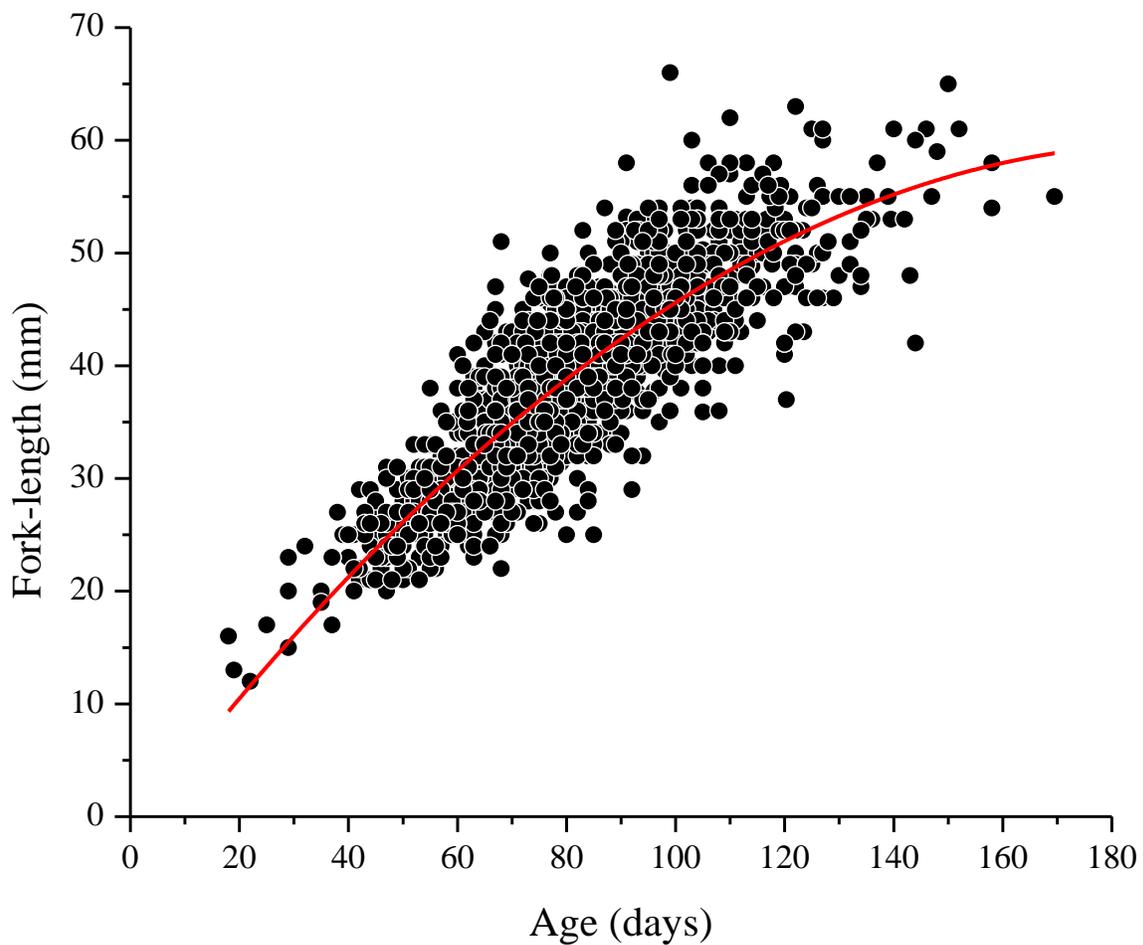
781

782 Delta Smelt growth rates (Absolute and Apparent Growth) were significantly reduced during
783 the recent drought (2013-2014), with growth rates in 2014 down approximately 10% over the
784 study period. This reduction in growth rate can have a significant impact for both survival to the
785 adult stage and fecundity. While a 10% reduction in absolute growth could result in smaller
786 adults (7-10mm) and ~500-1000 eggs per female, the additional mortality to the population
787 would be exponentially greater for a population experiencing growth selective mortality. The
788 reduction in growth rates observed for 2014 were similar to rates modelled by Rose et al (2013a)
789 which resulted in roughly a 5-fold change in the population growth parameter (λ). Indeed, in this
790 modelling exercise, 2001 was estimated to have had the lowest growth rate during the juvenile
791 stages in late summer and fall for the years 1995-2004 (Rose et al 2013b). Our empirical growth
792 rates for the years 2006-2007 and 2012-2014 exhibited lower growth rates than those observed in
793 2001, thus growth rates for a majority of these years were likely poor enough to result in
794 significant reduction in population abundance.

795 Several environmental drivers responded to drought as predicted, with reduced freshwater
796 outflow resulting in the position of X2 moving upstream, and salinity in Suisun Bay increased.
797 Water temperatures for the recent drought were high, and exceptionally high for 2014. The
798 abundance of prey tended to be lower during the drier years (2001, 2007 and 2012-2014).
799 Combining environmental drivers into a composite variable for years provided a reasonable
800 predictor of growth rates for Delta Smelt during the summer supporting the hypothesis that
801 multiple environmental drivers interact to influence habitat and growth condition for Delta
802 Smelt.

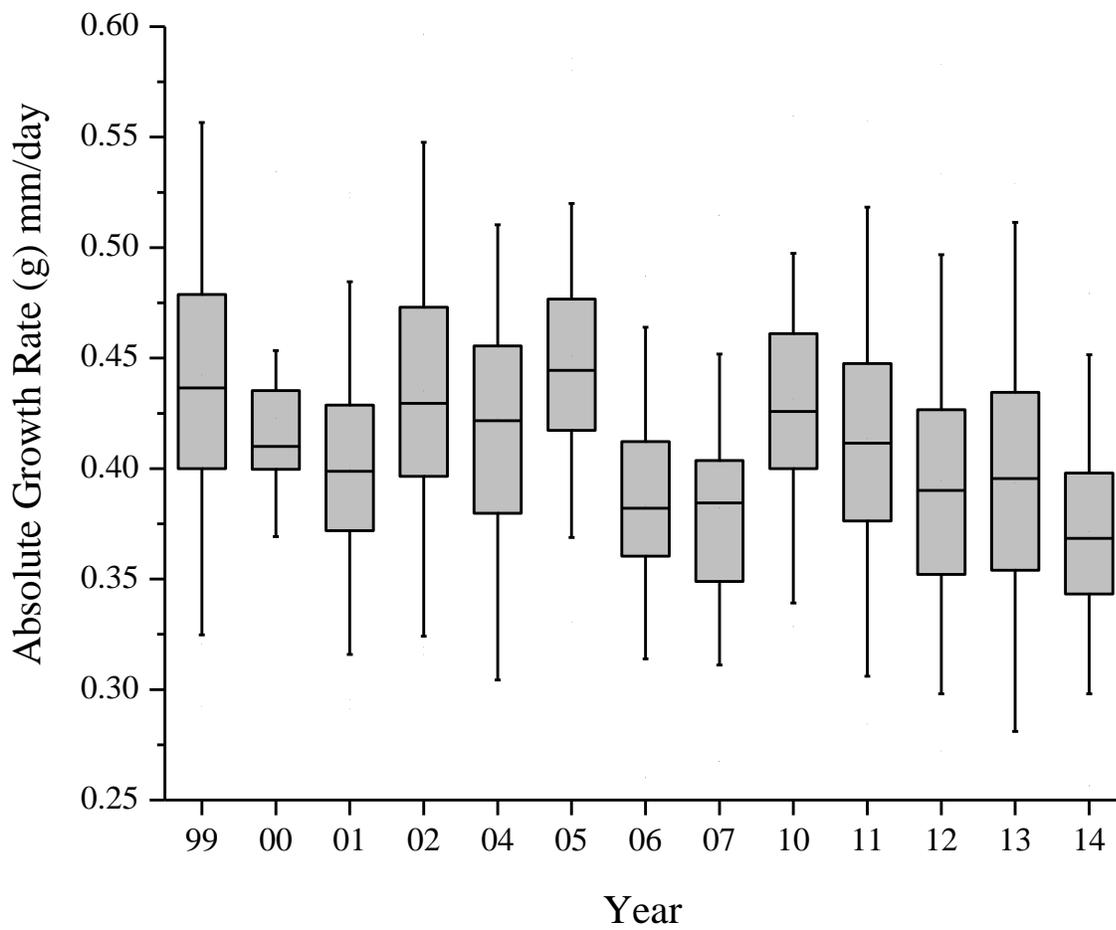
803 Water clarity, (secchi depth) exhibited a linear trend through time and may be an underlying
804 driver of long-term change in the upper estuary. The expansion of submerged aquatic vegetation
805 and the loss of sediment supply behind reservoir dams are likely the causes of increased water
806 clarity. Delta Smelt have been shown to depend on turbid habitats for feeding and avoiding
807 predation. The interaction of increasing water clarity through time and inter-annual variability in
808 the abundance of prey may lead to non-linear growth dynamics through time. Indeed Secchi was
809 an important variable included in the environmental driver component for explain variation in
810 Delta Smelt growth rates.

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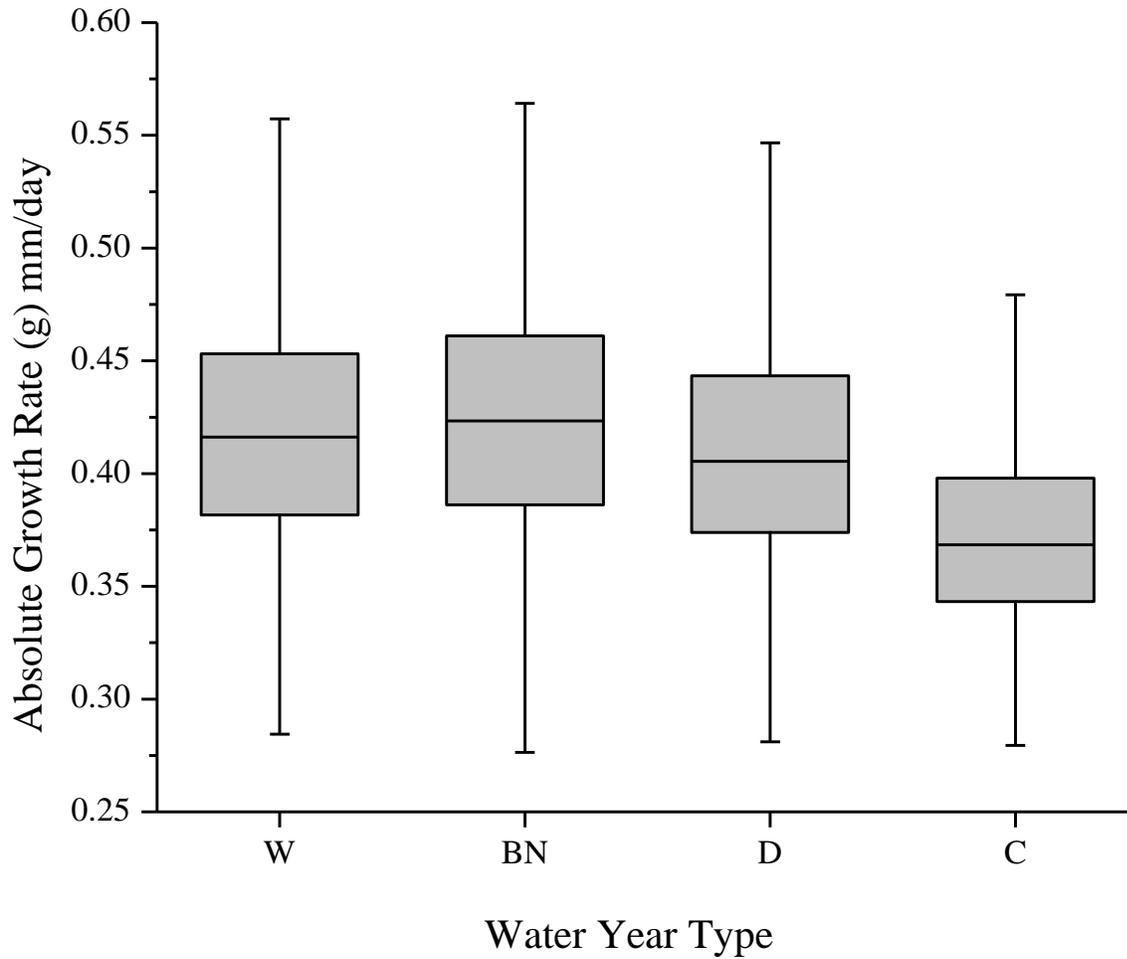


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822 **Figure 1.** Age-Length relationship for Delta Smelt collected during the Summer Townet
823 Survey. Red line is a polynomial function fit to the age-length data showing deviation from a
824 linear relationship at ages greater than 120 days of age.
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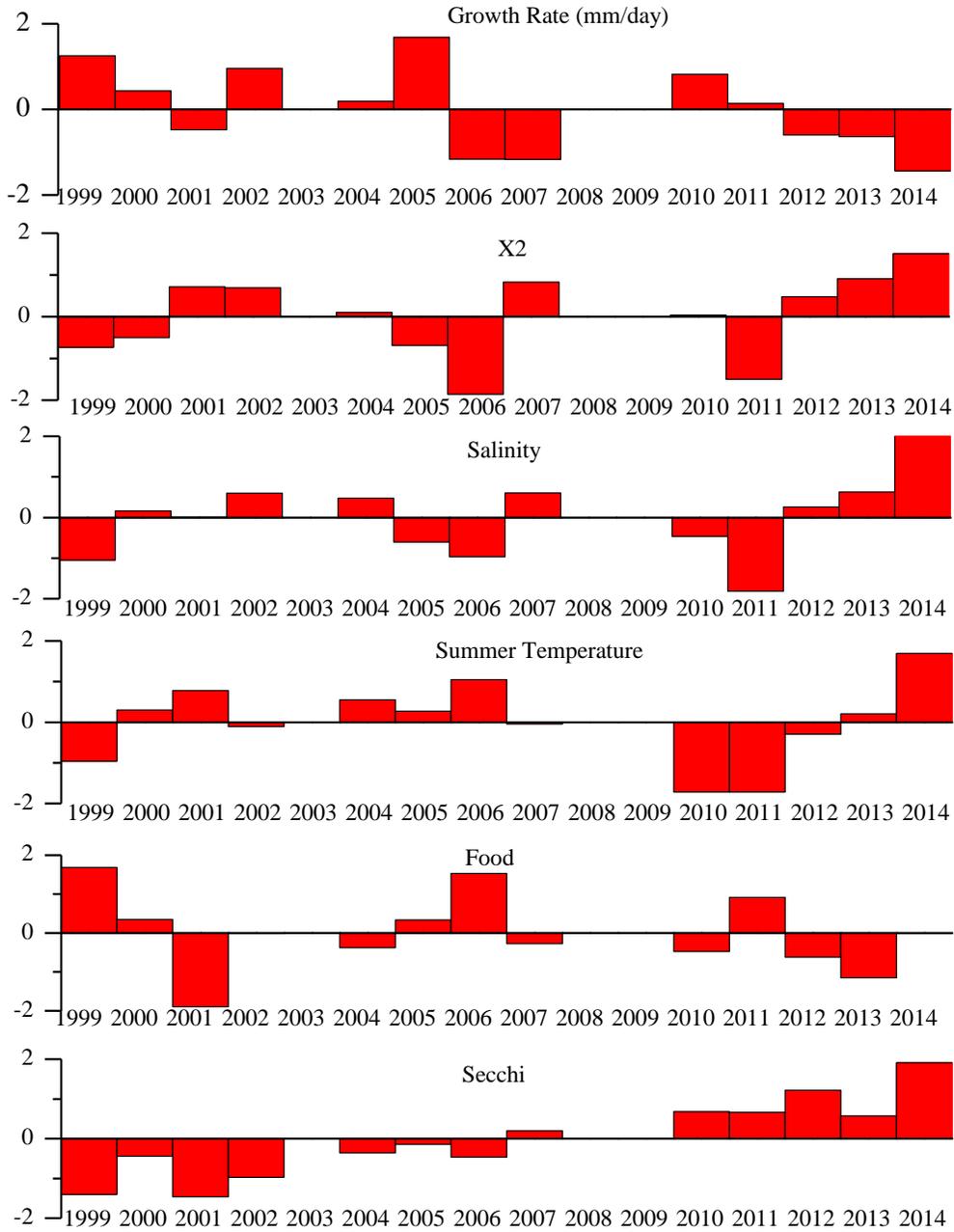


835
836 **Figure 2.** Boxplot of growth rate (g) mm/day for the year-class cohorts 1999-2014 (-2003, 2008
837 and 2009). Box represents the median, 25th and 75th percentile, and whiskers the 5th and 95th
838 percentile.
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 842 **Figure 3.** Boxplot of growth rate (g) mm/day for water year type (W=Wet, BN= Below Normal,
 843 D= Dry and C = Critical). Box represents the median, 25th and 75th percentile, and whiskers the
 844 5th and 95th percentile.

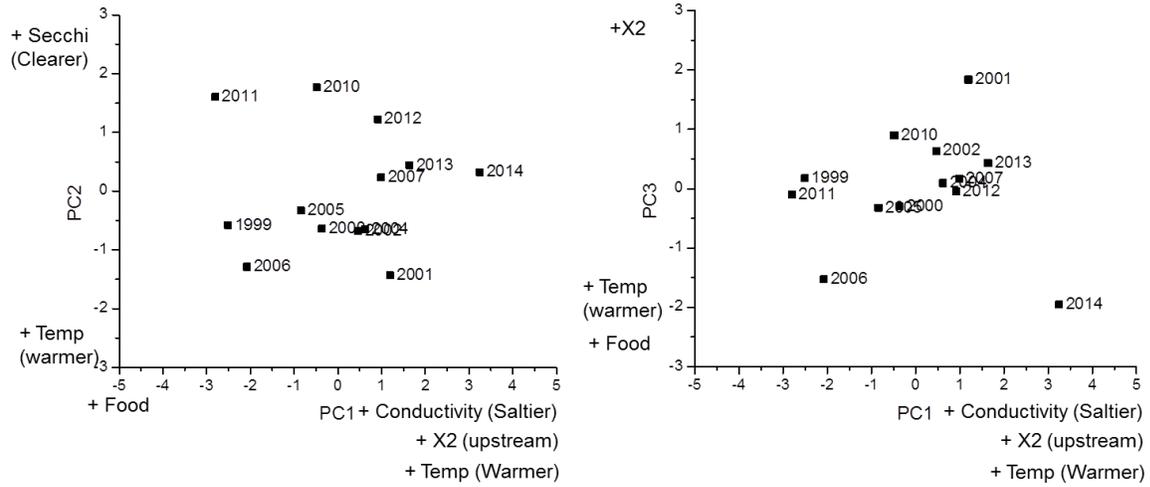
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Figure 4. Anomalies for growth and environmental drivers from 1999-2014

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Figure 5. Plot of principle component analysis scores for years with variable components labelled along the axis.

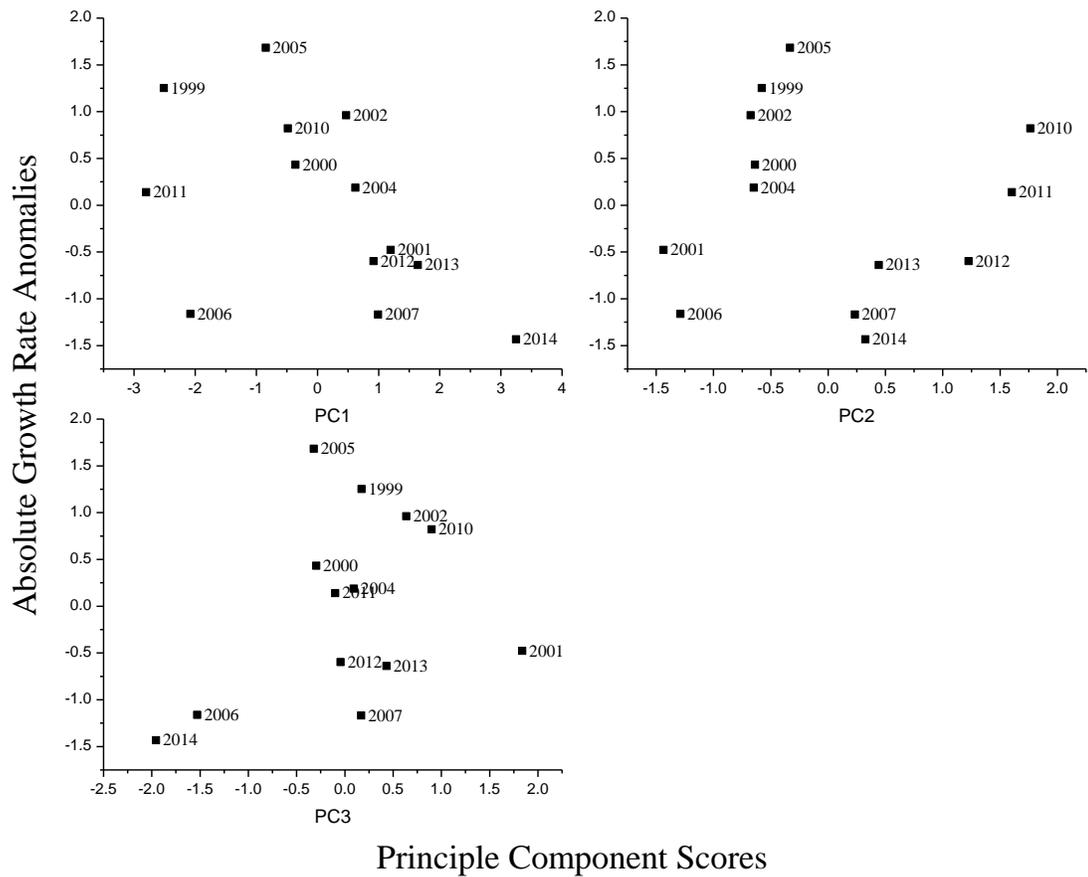


Figure 6. Principle component scores for the three principle axis explain 94% of the variance against the AGR anomaly value.

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882 **Table 1.** Number of otoliths examined by year and Water Year Type.
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Year	mean	1 sd	25 th %	75 th %	n	WYT
1999	0.44 ± 0.06	0.29	0.48	177	W	
2000	0.42 ± 0.04	0.37	0.43	20	W	
2001	0.40 ± 0.04	0.29	0.43	182	D	
2002	0.44 ± 0.06	0.32	0.47	199	D	
2004	0.42 ± 0.06	0.30	0.46	89	BN	
2005	0.45 ± 0.05	0.33	0.48	101	BN	
2006	0.38 ± 0.04	0.26	0.41	61	W	
2007	0.38 ± 0.05	0.27	0.40	48	D	
2010	0.43 ± 0.05	0.33	0.46	55	BN	
2011	0.41 ± 0.06	0.23	0.45	222	W	
2012	0.39 ± 0.06	0.25	0.43	105	BN	
2013	0.39 ± 0.06	0.25	0.43	126	D	
2014	0.37 ± 0.04	0.26	0.40	72	C	
Totals:	0.41 ± 0.06	0.23	0.45	1457		

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899 **Table 2.** Principle Component Analysis loadings.

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	PC1	PC2	PC3
Conductivity	0.56	-0.08	-0.21
Secchi	0.24	0.75	-0.53
July-August Temperature	0.35	-0.64	-0.48
X2	0.56	0.09	0.24
Food	-0.44	-0.08	-0.63
Eigenvalues	2.82	1.00	0.86
Cumulative Proportion of Variance	56%	76%	94%

Year			
1999	-2.5	-0.6	0.2
2000	-0.4	-0.6	-0.3
2001	1.2	-1.4	1.8
2002	0.5	-0.7	0.6
2004	0.6	-0.6	0.1
2005	-0.8	-0.3	-0.3
2006	-2.1	-1.3	-1.5
2007	1.0	0.2	0.2
2010	-0.5	1.8	0.9
2011	-2.8	1.6	-0.1
2012	0.9	1.2	0.0
2013	1.6	0.4	0.4
2014	3.2	0.3	-2.0

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II.b Putting the Extreme Drought into a Long-Term Context: Life History Diversity

METHODS

Life history attributes of juvenile Delta Smelt were quantified using otolith microstructure to back-calculate hatch-dates and determine natal origins using strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$ at the core of the otolith using laser ablation multi-collector ICP-MS. Delta Smelt were collected during the Summer Towntnet Survey (STS), a long-term monitoring survey conducted by the California Department of Fish and Wildlife to determine the distribution and abundance of juvenile pelagic fishes in the upper San Francisco Estuary. The STS conducts bi-weekly surveys from June through August at x number of fixed stations in the upper estuary. For this study Delta Smelt were collected in 1999, 2001-2002, 2004-2007, and 2010-2014 (Table 1). Fish were measured for fork-length to the nearest millimeter onboard, and preserved in 95% ethanol.

Sagittal otoliths were dissected from the head using ultra-fine forceps 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. Hatch-date was estimated by subtracting mean age from the capture date, and reported as the calendar day from January 1 for each year.

945 Natal origins were determined using the strontium isotope ratios ($^{87}\text{Sr}:$ ^{86}Sr) of the otolith core
946 using laser ablation multicollector ICPMS at the UC Davis Interdisciplinary Center for Plasma
947 Mass Spectrometry (<http://icpms.ucdavis.edu>). A multi-collector inductively coupled plasma
948 mass spectrometer (*Nu Plasma HR* from Nu Instrument Inc.) was interfaced with a Nd:YAG 213
949 nm laser (New Wave Research UP213) for strontium isotope measurement by laser ablation
950 (LA-MC-ICP-MS technique). A laser beam of 40- μm diameter traversed across the otolith from
951 the core to the edge at 10- μm per second, with the laser pulsing at 10-Hz frequency and 5-10
952 J/cm^2 photon output. Helium was used as the carrier gas to maximize sensitivity and minimize
953 sample deposition at the ablation site, and was mixed with Argon gas between the laser sample
954 cell and the plasma source. Gas blank and background signals were monitored until ^{84}Kr and
955 ^{86}Kr stabilized after the sample change (i.e. exposing sample cell to the air) and were measured
956 for 30 seconds. The laser was typically fired for 90-120 seconds and background signals were
957 subtracted from the measured signals automatically. Strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) were
958 internally normalized by the measured $^{86}\text{Sr}/^{88}\text{Sr}$ ratio relative to assumed ratio of 0.1194, which
959 proportionally corrects for mass discrimination. The signal on mass 85 was monitored to correct
960 for any ^{87}Rb interference on ^{87}Sr . The analytical accuracy was determined by using the results of
961 replicate analyses of a aragonite coral standard at the beginning and end of several analytical
962 sessions. Replicate analyses yielded $^{87}\text{Sr}/^{86}\text{Sr} = 0.70919 \pm 0.000096$ ($n = 25$), consistent with
963 modern seawater values of 0.70918.

964
965 Strontium isotope ratios ($^{87}\text{Sr}:$ ^{86}Sr) of water samples collected among potential natal
966 freshwater rearing areas and across the low-salinity region of the upper estuary, encompassing
967 the known distribution of the species. Water samples were collected at IEP monitoring stations in
968 2011 using an acid rinsed polypropylene syringe from a bucket of water collected at the surface
969 of the water column. Water was filtered through a 0.45 μm syringe filter and the sample was
970 acidified (1mL of 3% nitric acid) to stop bacterial growth. At the UC Davis ICPMS lab, water
971 samples were initially screened for alkaline earth metals (such as strontium) and analytical
972 interferences (such as rubidium) on an Agilent 7500ce (Agilent Technologies, Inc.) Q-ICP-MS
973 (quadrupole inductively coupled plasma mass spectrometer.) After elemental screening, the
974 samples were transported to a class 100 (less than 100 particles per cubic foot of air) clean room
975 facility. Within this environment, an aliquot of each water sample was made at volume totaling

976 approximately 1 nanogram of total strontium. This volume (ranging 3 – 70 mL) was evaporated
977 to dryness and reconstituted in sub-boiling double-distilled nitric acid (8M) for Sr
978 chromatographic separation. Strontium was isolated from all other water constituents by rinsing
979 water samples through a micro-column packed with Sr spec resin (Eichrom Inc.) The purified
980 strontium was subsequently oxidized with concentrated sub-boiling double-distilled nitric acid to
981 remove organics from column and dried to a powder. This powder was reconstituted in 2% sub-
982 boiling double-distilled nitric acid and analyzed with the Nu Plasma HR (MC-ICP-MS) to
983 determine the $^{87}\text{Sr}:^{86}\text{Sr}$ ratio.

984
985 Samples were introduced into the Nu Plasma with a desolvating nebulizer system (DSN-100)
986 providing an order of magnitude sensitivity increase by evaporating most of the sample matrix
987 (water vapor) away. Ratios include 50-60 data points and each data point was integrated for 10
988 seconds. Baselines were measured for 30 seconds by ESA deflection (ion beams were defocused
989 away from detectors). Strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) were internally normalized as
990 described with the LA-MC-ICP-MS technique with the exception of the Krypton correction on
991 ^{86}Sr . In this case, $^{84}\text{Sr}:^{86}\text{Sr}$ was assumed to be .00675476 (natural abundance of these isotopes)
992 and is used to estimate subtraction of $^{84}\text{Krypton}$ and $^{86}\text{Krypton}$. Kr was subtracted until the
993 $^{84}\text{Sr}/^{86}\text{Sr}$ ratio equals the canonical value of .00675476 (while iterating the mass-bias correction.)
994 Replicate analyses of NIST SRM 987 (strontium carbonate) were conducted bracketing every six
995 samples normalizing for instrument drift over the course of the day and analytical artifact
996 between sessions. An in-house modern coral std was processed in parallel with each water
997 sample set and resulted in $^{87}\text{Sr}:^{86}\text{Sr}$ (n=8) = 0.709182 +/- 0.000017 (2SD). Water quality was
998 also collected using a YSI 6600. Water quality parameters included salinity (psu), electrical
999 conductivity (μs), and temperature $^{\circ}\text{C}$. To describe the relationship between strontium isotope
1000 ratios and salinity, we fit a smoothing spline to data. In addition, a conservative linear mixing
1001 model using three freshwater endmembers (North Delta- Cache-Lindsey Slough Complex
1002 $^{87}\text{Sr}:^{86}\text{Sr}$ = 0.70642, Sacramento River upstream of confluence with the North Delta $^{87}\text{Sr}:^{86}\text{Sr}$ =
1003 0.70583 and along the San Joaquin River near Jersey Point $^{87}\text{Sr}:^{86}\text{Sr}$ = 0.70721) was used with
1004 the $^{87}\text{Sr}:^{86}\text{Sr}$ = global ocean value of 070918.

1005 To construct and map of strontium isotopes ratios ($^{87}\text{Sr}:^{86}\text{Sr}$) the estuary was divided into
1006 polygons in Arc-GIS based on areas defined by **Feyrer et al. 2007**. Strontium isotope ratios for

1007 water samples were assigned to a polygon using GPS coordinates. When multiple samples
1008 occurred in the same polygon the average was used to assign the polygon an isotope value.
1009 Polygons not sampled were assigned an isotope value based on nearest neighbor extrapolation
1010 and evaluation of water quality variables, particularly salinity for adjacent polygon extrapolation.
1011 This resulted in a “static” spatial distribution map of strontium isotope ratios, terms an iso-scape
1012 for the estuary. Natal origins of Delta Smelt were determined using strontium isotope ratios
1013 from the otolith core and the iso-scape map for fish collected during the Summer Townt Survey
1014

1015 Life History Diversity

1016 Life history diversity was quantified using a combination of natal origins and 7-day hatch-
1017 date groups to assign fish to a unique cohort based on origin and hatch-date. The numbers of
1018 individuals assigned to each cohort was summed, and the Shannon-Weaver diversity index (H')
1019 and Shannon’s Equitability Index (EH) was calculated for each year.

1020

1021 RESULTS

1022 *The strontium isotope iso-scape*

1023 The strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$ of water samples collected in 2011 varied predictably
1024 across the freshwater – Low-Salinity Zone region of the estuary and were similar to data from
1025 2006 and 2007 (Hobbs et al. 2010) (Figure 1). Strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$ varied
1026 regionally within the estuary, in freshwater areas (psu <0.5) of the Delta isotope values never
1027 exceeded 0.7072. Waters entering the South Delta from the San Joaquin River at Mossdale
1028 averaged 0.70718 and varied little between years ($2\sigma = 0.0002$). Water entering the North Delta
1029 from the Sacramento River exhibited a wider range of variability, strontium isotope ratios
1030 ranging from 0.70583 to 0.70652. Sacramento River water was typically lower (less than
1031 0.7060) than the North Delta from Cache Slough to the Deepwater Ship Channel (0.70602-
1032 070653). During high flow conditions in 2011 strontium isotope ratios less than 0.7065 could be
1033 found as far west as Browns Island at the Confluence. Waters originating from the Sacramento
1034 River and North Delta can be drawn through the West and Central Delta from the Delta Cross
1035 Channel or through Three-Mile Slough. These waters with a strontium isotope ratio ~0.7065,
1036 mix with San Joaquin River water and tributaries (Consumnes and Mokolumne Rivers) to the
1037 east to create an iso-scape that ranges from 0.7066 to 0.7072. San Joaquin River water (100%

1038 pure) rarely makes up the full volume of the Central and South Delta and reaches the area awest
1039 of the Confluence (unpublished data from McWilliams and Associates, particle tracking model
1040 results from a wet year 1999 and below normal year 2012). Assuming this holds true for all flow
1041 conditions, isotopic ratios greater than 0.7072 would reflect some degree of mixing with low-
1042 salinity waters.

1043 Strontium isotopes exhibit a conservation mixing behavior, where the isotopic value of a
1044 mixture of two source waters with known isotope values and bulk strontium concentration can be
1045 accurately predicted with a relatively simple mixing model. We fit mixing model curves with
1046 different freshwater sources (Sacramento River at the entrance to the Delta, North Delta waters,
1047 and San Joaquin River water at Mossdale) with the global ocean strontium isotope of 0.70918.
1048 Modelled curve results were plotted along with water sampled collected in the estuary in 2011
1049 across a range of salinity values from 0.3psu to 5.4psu, and provided a good fit to empirical data
1050 (Figure 2). Few values fell outside the 95% confidence intervals, but in general the model
1051 predictions of strontium isotope ratios given a salinity value was within measurement error for a
1052 hand-held salinity meter typically used in the field to associate fish distribution with salinity
1053 zones. However, model fits for salinity values less than 0.5psu varied due to the differences in
1054 the freshwater source, thus the dynamic mixing that occurs within the Delta can make salinity
1055 predictions difficult. For example using a Sacramento River or North Delta source with isotope
1056 ratios ranging from 0.7058 to 0.7065 can result in different salinity predictions for very low
1057 levels of salinity, and when using the San Joaquin River ratio of 0.7072, considerable overlap
1058 can occur from salinities of 0.4 to 1psu. However, particle tracking models suggest pure San
1059 Joaquin River water rarely exits the Central Delta, thus we can reduce our uncertainty for natal
1060 origin salinity estimates from strontium isotope values assuming the San Joaquin River water did
1061 not contribute to isotope ratios found west of the confluence.

1062 Natal origins of Delta Smelt were defined as follows, the North Delta, including the Cache-
1063 Lindsey Slough area to the west, the Sacramento Deep-water Ship Channel down to the
1064 confluence with the San Joaquin River at Sherman Island ($^{87}\text{Sr}:^{86}\text{Sr} \leq 0.7065$). The Central and
1065 South Delta has strontium isotope ratios that overlapped low salinity areas ($<0.5\text{psu}$) ≥ 0.7066
1066 ≤ 0.7077 . The Low-Salinity Zone encompasses salinity habitats from 1 psu to 6 psu and can be
1067 further refined using strontium isotope ratios due to the high precision of MC-ICPMS (Table 1),

1068 however fish with low-salinity natal origins in this study were few (65 of 887 total fish
1069 examined), and thus fish with a natal strontium isotope ratio >0.7077 were assigned to the Low-
1070 Salinity Zone natal habitat.

1071 The natal origins of 887 Delta Smelt collected over 12 years were examined in this study
1072 (Table 2). The North Delta region of the upper San Francisco Estuary comprised 57% of the
1073 fish, and exhibited an increasing trend through time ($\tau = 0.46, p = 0.046$). The Central-South
1074 Delta made up 36% of the fish while the Low-Salinity Zone contributed only 7% of the
1075 individual analyzed (Figure 3). Delta Smelt exhibit a protracted spawning period with a hatch-
1076 date distribution for all years combined ranging from day 57 to day 174. The 5th and 95th
1077 percentiles of hatch-date were day 79 and day 151 which corresponded with mean water
1078 temperatures of 13°C and 18°C (Figure 4). Hatch-dates exhibited a decreasing trend through
1079 time ($\tau = -0.62, p = 0.0041$), with hatch-dates in 2013 and 2014 being 30 days earlier than
1080 1999 and 2001 (Figure 5). Day of year when water temperatures reached 12°C and 20°C did not
1081 exhibit a statistically significant trend through time, however, day of year when temperatures
1082 reached 20°C was approximately 30 days earlier than the years 1999-2007 (Figure 5).

1083 The diversity of Delta Smelt cohorts ranged from a low of 16, 7-day hatch-date/natal origin
1084 cohorts in 2005 to a high of 33 in 2011, with an overall average of 20.5 unique hatch-date/natal
1085 origin cohorts per year. The Shannon-Weaver Diversity Index ranged from a low of 2.5 in 2001
1086 and 2005 to a high of 3.2 in 2011, and the index of equitability, a measure of numerical evenness
1087 among cohorts was near 1 indicating a relative even spread of individuals among cohorts (Figure
1088 6). No trends through time were detected using the Mann-Kenall test ($\tau = -0.121, p = 0.63$).

1089 **DISCUSSION**

1090 Delta Smelt exhibited trends in the natal origins and hatch-date distributions from 1999 to
1091 2014 with more fish originating in the North Delta and fish hatching approximately a month
1092 early in the recent critical drought years 2013-2014 than the wetter period, early in the time-
1093 series (1999-2001). Water temperatures also warmed earlier in the year reaching a threshold
1094 temperature of 20 °C approximately 30 days earlier in 2013 and 43 days earlier in 2014, while
1095 the 12 °C threshold was actually 6 days later in 2013 and 11 days earlier in 2013 resulting in a
1096 significant shortening of the “hatching-window” during the critical drought period. A shortening

1097 of the hatching-window could limit the production of larvae and result in recruitment limitation
1098 and a poor adult year-class. This appeared to be an important driver in spring of 2012, when a
1099 large adult year-class produced during the anomalously wet year in 2011, experienced a
1100 shortened window with the 20 °C threshold occurring nearly 40 days earlier than 2010 and 2011.
1101 The abundance of post-larval Delta Smelt in 2012, as indexed by the 20-mm Survey was
1102 relatively high at 11.1 (mean 2002-2014 = 7.4), while the index of juveniles in the Summer
1103 Townet Survey was low at 0.9, suggesting recruitment failure occurred during the late spring in
1104 2012 when an unseasonably warm temperatures occurred, concomitant with the onset of the
1105 recent drought.

1106 To explore this pattern further, we examined the data from 2012 and 2013 Summer Townet in
1107 greater detail and include results in section x and summarize here. We calculated a regional
1108 index of relative abundance for each survey to explore spatial patterns of abundance change. In
1109 both 2012 and 2013 fish were more abundant in the North Delta regions including the Cache-
1110 Linsley Slough area and the Deep-water Ship Channel during the first survey in early June.
1111 Abundance declined precipitously in the North Delta between survey 1 and survey 2 when mean
1112 daily water temperatures exceeded 20 °C. Using the otolith natal strontium isotope ratios, few
1113 individuals arrived downstream at stations in the confluence and Suisun Bay regions, but it was
1114 apparent many fish likely died in the North Delta between Surveys 1 and 2 in both years.
1115 Survival from Survey 1 to Survey 2 in both years appeared to depend on growth rate and somatic
1116 body condition, with fish not achieving a growth rate of at least 0.35mm/day not surviving to
1117 Survey 2. This would suggest that recruitment failure has occurred in the North Delta in the late
1118 spring when water temperatures in this region exceeded 20 °C.

1119 Delta Smelt appear to be responding to the recent drought by moving further north,
1120 presumably in response to encroaching salinity. The proportion of the Delta Smelt originating in
1121 the North Delta and contributing to the population collected by the Summer Townet Survey has
1122 exhibited an increase over time. This has also been observed in the Fall Midwater Trawl Survey
1123 natal origin chemistry and by catch data during the Spring Kodiak Trawls. In 2009, additional
1124 survey stations were explored in the North Delta, along the Sacramento Deepwater Ship
1125 Channel, and have been consistently sampled since 2011. Since the onset of drought, the
1126 centroid of distribution for Delta Smelt has shifted upstream, when calculated using core stations

1127 only, and has shifted even further upstream when all stations, including those in Sacramento
1128 Deepwater Ship Channel are included. Moreover, the abundance of Delta Smelt collected in the
1129 Toe-Drain of the Yolo Bypass has increased significantly since 2012 (**Mahardja et al. 2015**).
1130 This shift north may be further jeopardizing the population by subjecting young to increasingly
1131 warm temperatures during the drought.

1132 While the life history diversity of Delta Smelt has not changed significantly during the recent
1133 drought, the shift northward may be compromising the resilience of the population. It is still
1134 unclear which environmental driver(s) is responsible for this distributional shift. The occurrence
1135 of mature adults in the upper reaches of the Sacramento Deepwater Ship Channel and the Tow-
1136 Drain suggests this shift is a behavioral response by adults, migration further north during the
1137 spawning migration. This could be a response to the Low-Salinity Zone distribution further
1138 upstream during the drought. Adult Delta Smelt spawning strategies may be tied to a
1139 geographically distance from the Low-Salinity Zone, for placing eggs in an optimal location to
1140 account for larval dispersal in the spring. While larvae appear to tolerate brackish conditions, as
1141 evidenced from fish with natal strontium isotope ratios consistent with rearing in salinities near 2
1142 psu and from culture studies (**Lindberg et al. 2013**), growth rates were lower for fish hatched in
1143 the Low-Salinity Zone. Fish exhibiting the migratory phenotype, being born in freshwater and
1144 rearing in the Low-Salinity Zone during the juvenile stage typically experienced faster growth
1145 rates, thus this is likely the optimal life history strategy.

1146 In summary, Delta Smelt exhibited changes in Life History attributes; natal origins and hatch-
1147 dates in response to environmental conditions associated with the recent drought, and may be
1148 undergoing a longer-term phenological shift in spawning and hatching earlier in the year and
1149 moving further North in the estuary in response to climate change. This change in phenology
1150 may pose further threats to Delta Smelt population resilience if their prey resources are not
1151 responding similarly to shifting environmental conditions. Their apparent volitional movement
1152 northward is also troubling considering the proposal for new freshwater export intakes along the
1153 lower Sacramento River. Increased freshwater exports from the North Delta, along with climate
1154 change may result in entrainment issues for the new facilities. It is becoming increasingly clear
1155 that Delta Smelt's persistence in the upper San Francisco Estuary is near the brink of extinction.

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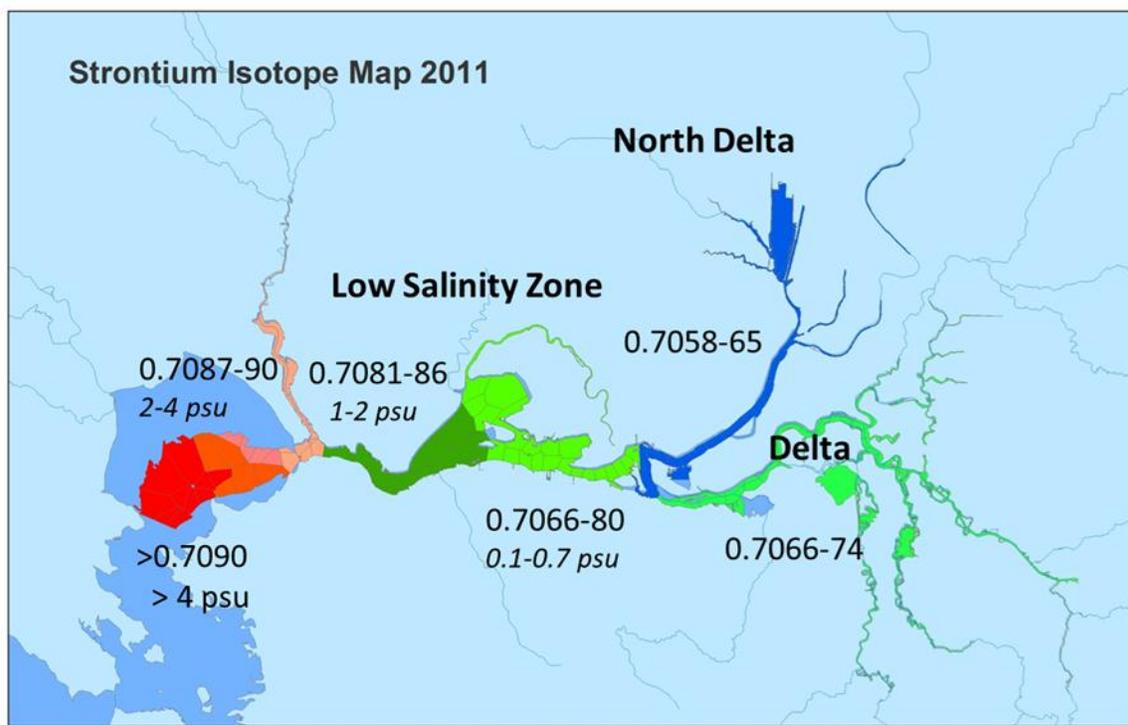
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Table 1. The samples size by year (n) and the mean and 2σ standard deviation of strontium isotope ratio (⁸⁷Sr:⁸⁶Sr) by natal regions (ND= North Delta, SD = South Delta and salinity <0.5psu, the Low-Salinity Zone (LSZ 0.5-6psu).

	<i>n</i>	ND	2σ	<i>n</i>	SD	2σ	<i>n</i>	LSZ	2σ	Total N
1999	22	0.7063	± 0.00014	23	0.7068	± 0.00026	2	0.7079	± 0.00002	47
2001	24	0.7064	± 0.00011	22	0.7069	± 0.00029	1	0.7078	±	47
2002	17	0.7063	± 0.00020	34	0.7068	± 0.00020	1	0.7080	±	52
2004	32	0.7063	± 0.00020	16	0.7067	± 0.00015	5	0.7080	± 0.00024	53
2005	33	0.7064	± 0.00016	30	0.7069	± 0.00027	1	0.7080	±	64
2006	12	0.7063	± 0.00015	9	0.7071	± 0.00023	21	0.7085	± 0.00024	42
2007	31	0.7061	± 0.00023	13	0.7069	± 0.00028	2	0.7079	± 0.00005	46
2010	31	0.7064	± 0.00012	19	0.7069	± 0.00033	5	0.7079	± 0.00019	55
2011	100	0.7063	± 0.00015	82	0.7071	± 0.00031	5	0.7085	± 0.00040	187
2012	80	0.7063	± 0.00010	14	0.7070	± 0.00037	10	0.7082	± 0.00025	104
2013	87	0.7063	± 0.00016	30	0.7070	± 0.00032	8	0.7082	± 0.00038	125
2014	37	0.7062	± 0.00019	24	0.7071	± 0.00033	4	0.7079	± 0.00017	65

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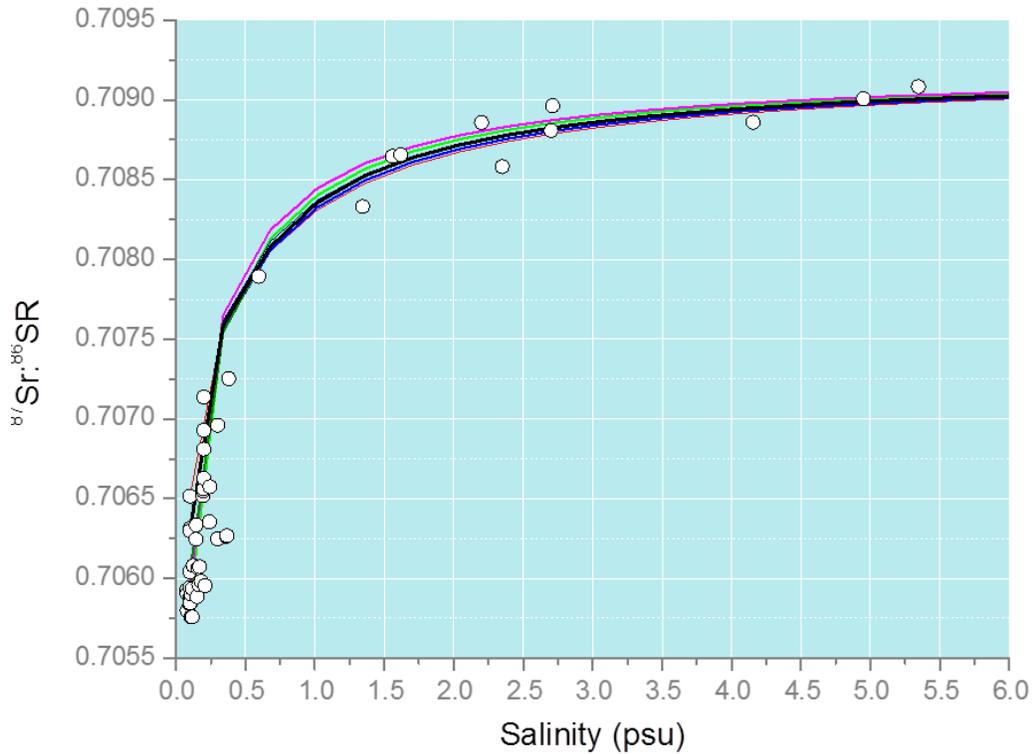


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1181 Figure 1. Map of strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) from water samples collected during the fall
1182 of 2011.

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1185

1186 Figure 2. Relationship between Strontium Isotope Ratios $^{87}\text{Sr}:^{86}\text{Sr}$ from water samples (circles)
 1187 and salinity (psu). Lines represent mixing curves from a linear mixing model with different
 1188 freshwater end-members in the North Delta $^{87}\text{Sr}:^{86}\text{Sr}$, 0.70581-0.70653 and $^{88}\text{Sr} = 0.9\text{-}1.4\text{ppm}$
 1189 with seawater $^{87}\text{Sr}:^{86}\text{Sr}$ 0.70918 $^{88}\text{Sr} = 9\text{ppm}$. Note: strontium isotope ratios >0.708 represent
 1190 salinity habitats greater than 1-psu and demarcate the transition from freshwater to the low-
 1191 salinity zone.

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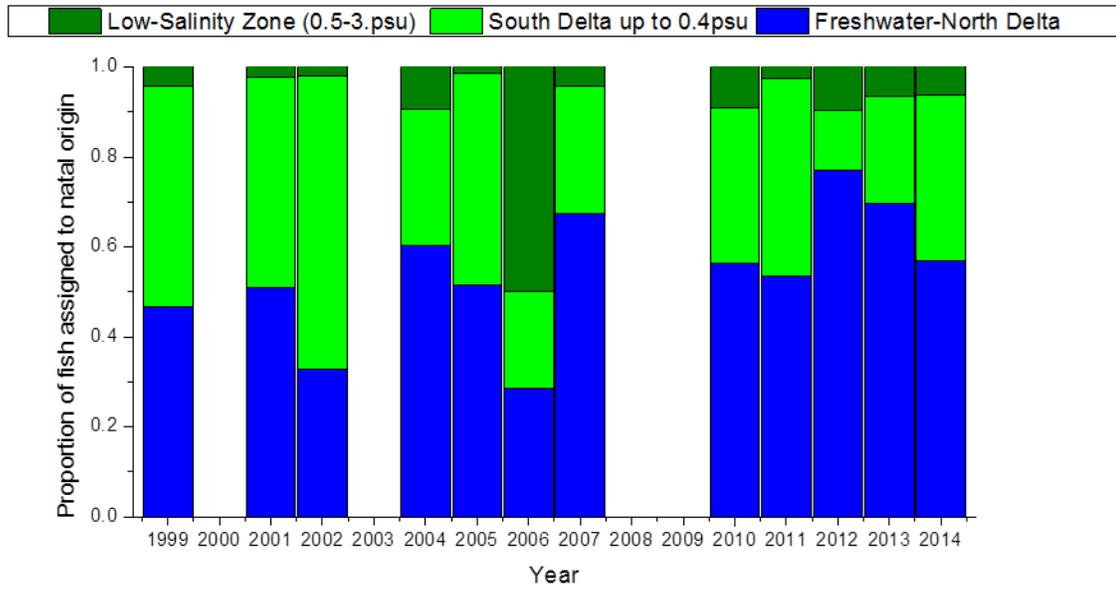
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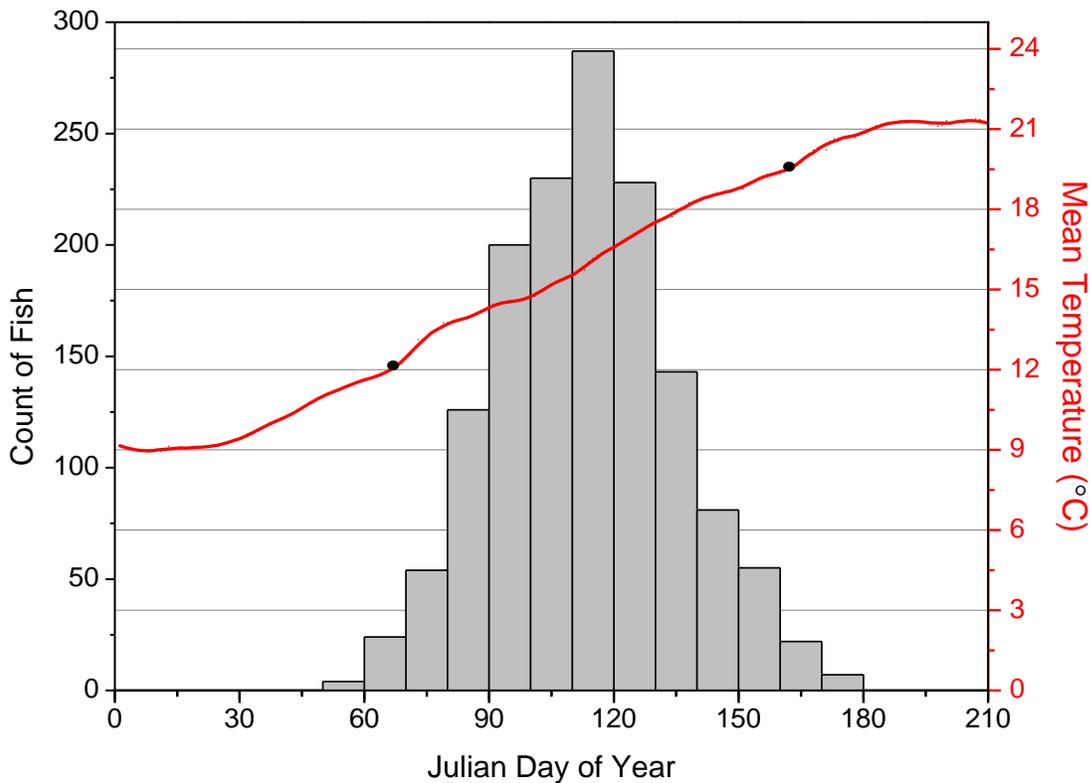
1199 Figure 3. The natal origins as proportion of fish collected in the Summer Towntnet Survey. Natal
 1200 origins were determined using otolith strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$

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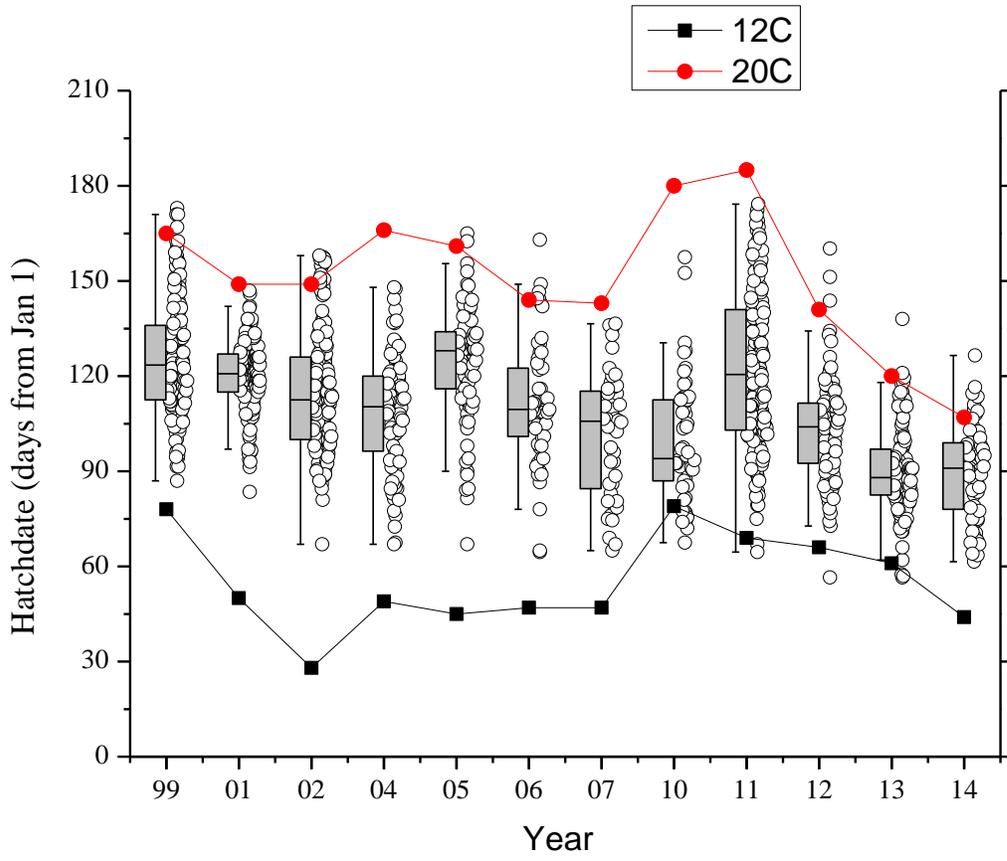
1205

1206 Figure 4. Histogram of Julian (calendar day of year) hatch-dates of Delta Smelt collected during
 1207 the Summer Townet Survey for all fish (N= 1461) aged between 1999 and 2014. In red, the
 1208 mean daily water temperature across the estuary for the corresponding years of sample
 1209 collections. A majority of fish hatched when mean water temperatures were between 12 °C and
 1210 20 °C (5% quartile = JD 79 and 95% = JD 151 which corresponded with a mean temperature of
 1211 14 and 19°C. Filled circles denote the 12 °C and 20 °C.

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1216 Figure 5. Boxplot of hatch-dates and day of year when mean water temperatures for the upper
 1217 estuary @ Rio Vista reached 12°C and 20 °C. Open circles represent individual fish hatch-dates.

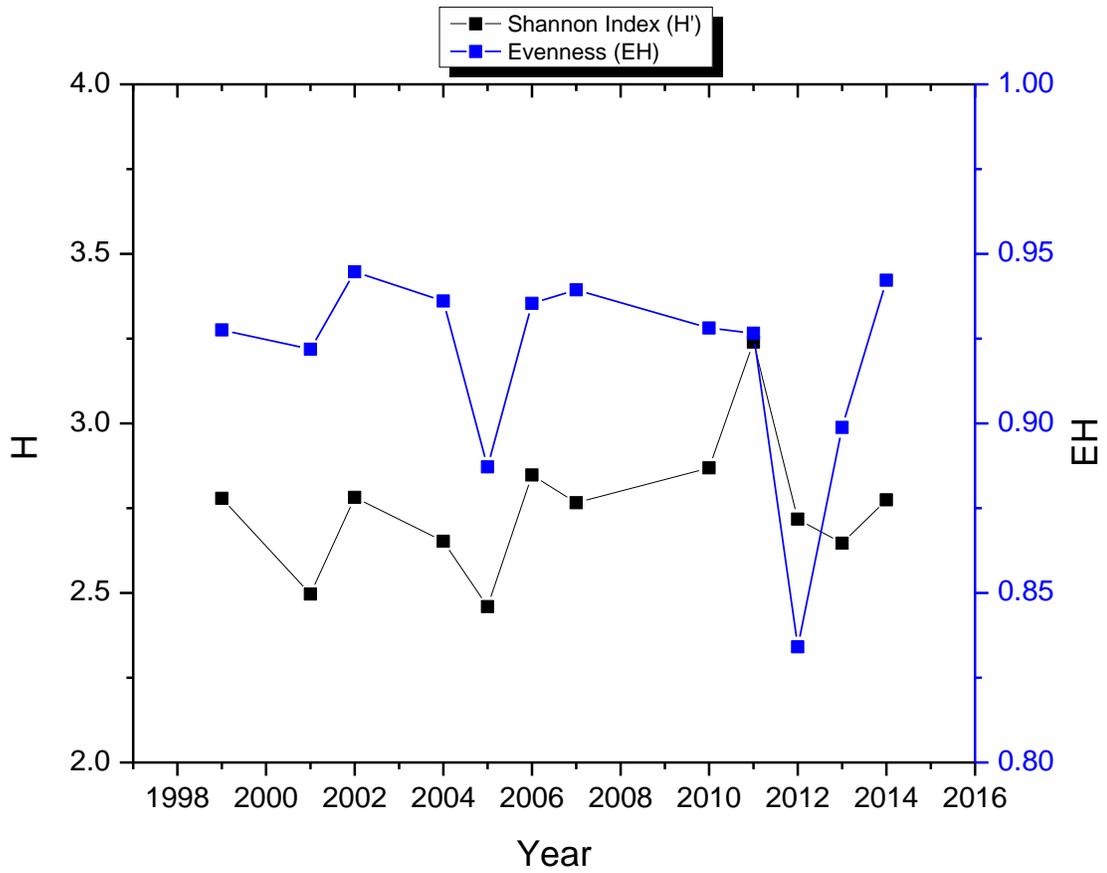
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1224 Figure 6. The Shannon Diversity Index (H') and Shannon's Equitability Index (EH) for Delta
 1225 Smelt Life Histories.

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1237 **III. Contrasts in Health Indices of Delta Smelt Reared in**
1238 **the Low Salinity Zone and Cache Slough Regions in the**
1239 **Summer of 2012 and 2013.**

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1241

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1265 **BACKGROUND**

1266 Due to a number of studies on the relationships of habitat quality and delta smelt abundance,
1267 the United States Fish and Wildlife Service (USFWS) formulated the USFWS Delta Smelt
1268 Biological Opinion Reasonable and Prudent Action Component 3 or Fall X2 Action (**USFWS**
1269 **2008**). Since the mechanism(s) underlying the relationships of habitat quality and abundance was
1270 uncertain, the USFWS proposed and the US Bureau of Reclamation initiated a scientifically-
1271 based adaptive management process to investigate the relationship. To determine the relationship
1272 of Fall X2 on habitat quantity and quality a comprehensive investigation involving a multitude of
1273 investigators was initiated in 2011 known as the Fall Low-Salinity Habitat Survey (FLaSH).
1274 Although the approach incorporated many of the important factors affecting abundance of delta
1275 smelt such as water quality, productivity, and the health of the fish, there was no examination of
1276 juvenile delta smelt prior to the critical Fall period.

1277 The abundance indices provided by the Summer Tow-net Survey can only explain a part of
1278 the juvenile recruitment potential from the summer. It is important to ascertain the quality of fish
1279 in summer. If the fall juvenile recruitments were of poor health they may not survive long,
1280 regardless of the actions taken in the fall. In addition, poor growing fish in the summer may
1281 result in smaller fish in the fall and potentially affect fecundity in the winter and spring.
1282 Although the IEP recognizes that size and recruitment are important contributors to abundance
1283 (Baxter et al, 2010, Feyrer et al. 2007, 2010), quality may be equally important to recruitment
1284 success. Moreover, little or no information is available on the health of delta smelt in the summer
1285 therefore the quality as measured by growth, health, and nutritional status of the fish entering the
1286 critical fall period from the summer is unknown. An examination of the juvenile rearing period
1287 in the summer may give insight as to how habitat quality contributes to the quality of recruitment
1288 in the fall.

1289 Due to the potential importance of summer conditions to fall recruitment of juvenile delta
1290 smelt we examined patterns in growth, hatch-date, somatic condition and natal origin at the
1291 highest spatial and temporal resolution available for the Summer Towntnet Survey. In addition we
1292 calculated a regional index of juvenile abundance at the region and survey scale to better track
1293 the changes in abundance and identify regions where recruitment failure is occurring during
1294 summer.

1295

1296 **METHODS**

1297

1298 Delta smelt were collected during the California Department of Fish and Wildlife
1299 (CDFW)“Summer Townet Survey (STN)” which samples at 41 fixed stations bi-weekly between
1300 June and August since 1959. CPUE at each station was calculated as the mean catch of Delta
1301 Smelt per volume of water sampled over the three replicate tows conducted at each station
1302 (Figure 1). We used all stations sampled in each survey, including core stations and non-core
1303 stations added in recent years. For further details on the sampling see the CDFW website:
1304 (<http://www.dfg.ca.gov/delta/projects.asp?ProjectID=TOWNET>).

1305 An index of regional abundance was calculated for each survey by summing the catch per unit
1306 of effort (CPUE) across stations within a region and then dividing by the number of stations for
1307 each survey (Figure 1). Regions were defined by CDFW and were based on major geographic
1308 areas of the estuary and included areas that were consistently freshwater habitats and areas that
1309 were consistently low-salinity habitats. Regions differed in total area and the number of
1310 sampling stations.

1311 To minimize lethal take of Delta Smelt a sub-sample of the total catch was preserved in liquid
1312 nitrogen from select surveys. In 2012, sub-samples were collected during surveys 1, 2, 5 and 6,
1313 while in 2013, sub-samples were collected in surveys 1-5 (Table X). Fish were individual
1314 wrapped in aluminum foil, given a unique fish identification number, flash frozen and stored in
1315 liquid nitrogen. In the laboratory each fish was thawed, photographed and measured for fork-
1316 length to the nearest millimeter, toweled dry and mass was recorded to the nearest 0.01-g on a
1317 Metler Toledo Model 1600 microbalance.

1318 Sagittal otoliths were dissected from the head using ultra-fine forceps (Dupont® SE140,
1319 stainless steel) and stored dry in tissue culture trays. Before mounting, the otoliths were
1320 “cleared” by soaking in 95% ethanol for 24 hours. Otoliths were mounted onto glass slides with
1321 Crystal Bond® thermoplastic resin in the sagittal plane, ground to the core on both sides with
1322 wet-dry sandpaper and polished with a polishing cloth and 0.3-micron polishing alumina on a
1323 MIT Corp. polishing wheel. Otoliths were digitized with a 12-Megapixel digital camera (AM
1324 Scope: www.amscope.com) at a magnification of 20X with an Olympus CH30 compound
1325 microscope. Digital images at 20X magnification were merged into a complete image of a
1326 transect from the core to the dorsal edge at a 90° angle from the primary axis of the otolith.

1327 Otolith increments were enumerated to estimate age and the distance from the core to each daily
1328 ring was measured using Image-J NIH software. Aging was conducted by two readers, and the
1329 mean, median, average percent error between age readers was assessed. If the age reading by the
1330 independent readers for an individual fish was greater than 10% average percent error, the
1331 sample was selected for processing of the second otolith for age analysis. If age discrepancy
1332 among readers was found for the second otolith, that sample was discarded. The instantaneous
1333 growth rate for individual fish was calculated by dividing the fork-length by the age estimate,
1334 where age was the number of otolith increments. Otolith increment counts have been shown to
1335 be an accurate measure of age from hatch (**Hobbs et al. 2007**). The hatch-date for each fish was
1336 calculated by subtracting the age from the capture date and was reported as the number of days
1337 from January 1 to facilitate plotting.

1338

1339 *Age and Growth*

1340

1341 Otolith increments were enumerated to estimate age using Image-J NIH software. Aging was
1342 conducted by a minimum of two readers, and the mean, median, average percent error between
1343 age readers was assessed. If the age reading by the independent readers for an individual fish
1344 was greater than 10% average percent error, the sample was selected for processing of the second
1345 otolith for age analysis. If age discrepancy among readers was found for the second otolith, that
1346 sample was discarded. The absolute growth rate AGR (g) for individual fish was calculated by:

1347

$$AGR (g) = \frac{FL_{catch} - FL_{hatch}}{Age_{mean}}$$

1348

1349 Where length-at-hatch was 5.2mm. Otolith increment counts have been shown to be an accurate
1350 measure of age from hatch (Hobbs et al. 2007).

1351

1352 *Natal Origins*

1353

1354 Otoliths were mounted on petrographic slides (20 per slide) for otolith microchemistry.
1355 Otolith strontium isotope ratios were quantified using methods previously developed (**Hobbs et**
1356 **al 2007; 2010**). Briefly, the strontium isotope profile from the core to the edge along a similar

1357 path used for aging was scanned using a laser beam of 55-microns moving at a speed of 10-
1358 microns per second. Laser profiles began at 100-micron in the core to ensure the analysis
1359 encompass the entire natal chemistry. The strontium isotope ratios were resolved using methods
1360 developed for Delta Smelt (**Hobbs et al. 2005**). The natal water source and life-history
1361 transitions were determined for each fish (e.g. migration to the Low-Salinity Zone) (**Hobbs et al**
1362 **2005; Hobbs et al 2010**).

1363
1364 Fish mass-length relationships are often non-linear and frequently modelled as a cubed
1365 function of length such as Fulton's condition factor. However, delta smelt mass-length
1366 distributions have been found to vary across distinct life-history stages (**Slater et al. 2014**). Fish
1367 collected in this survey ranged in lengths that transitioned across life-history stages. To create an
1368 index of fish somatic condition, we fit a generalized additive model (GAM) to mass (wet weight-
1369 grams) and fork-length (mm). The advantage of the GAM model is that it provides great
1370 flexibility in fitting non-linear relationships that change as a function of life history stages. We
1371 used the fitted residual value of individuals mass to length relationship from the GAM as an
1372 index of somatic condition. The disadvantage to this approach is that the model requires fitting
1373 to new data as subtleties in the mass-length relationship may change with additional data, thus
1374 our index is specific to the dataset in question.

1375 1376 **RESULTS**

1377 The majority of the fish collected for otolith analysis were collected during surveys 1 and 2.
1378 Delta smelt were more abundant at stations in the Deep-water Ship Channel (DSC) and Cache-
1379 Liberty Slough (CLS) complex during survey 1, with an index of 74.8 and 68.8 respectively,
1380 while fish were much less abundant at stations downstream (Table 3). Delta smelt abundance in
1381 the DSC and CLS declined to 31.6 and 25.7 respectively during survey 2, while abundance in the
1382 confluence increased slightly (Table 3). Abundance at stations in CLS increased to an index of
1383 38, while no fish were collected in the DSC and the index at the confluence increased slightly
1384 during survey 3. In survey 4, the abundance in the DSC increased from zero to 31.6, while the
1385 CLS declined to an index of 1.6 and abundance at the confluence declined to 1.2. Abundance in
1386 Suisun Bay increased from zero to 4.6 (Table 3). By survey 5 the abundance of delta smelt had
1387 decline to approximately 8% of the initial abundance in survey 1 (Table 3). Abundance in the

1388 DSC in surveys 5 and 6 were higher than all other areas of the delta making up 57 to 68% of the
1389 total catch index in the last two surveys.

1390 We analyzed otoliths from 99 of the 163 Delta Smelt encountered during surveys 1, 2, 5 and 6
1391 of the Summer Townet Survey in 2012 (Table 2). In survey 1, 69 delta smelt from 10 stations
1392 (Figure 1) were collected, and 42 individuals, (61% of total catch), were examined for otolith
1393 age, growth, and natal origins. Salinity in the Cache-Lindsey Slough confluence (721) and Deep
1394 Water Ship Channel stations (719, 796 and 797) ranged from 0.09 to 0.49-ppt (\bar{x} = 0.27, \pm 0.16 σ)
1395 and Stations in the lower Sacramento River (704 and 706) ranged from 0.08 to 0.34-ppt (\bar{x} =
1396 0.20, \pm 0.12 σ), and were collectively identified as the freshwater zone for survey 1. Salinity at
1397 stations from the confluence of lower Sacramento River to Suisun Bay and Montezuma Slough
1398 (513, 508 and 609) ranged from 0.96 to 2.94 (\bar{x} = 2.1, \pm 0.76 σ) and were identified as the low-
1399 salinity zone (Table 1.) Strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$ (SIR) of the natal core region varied
1400 by sampling stations, with fish collected at stations 721, 719 and 797 ranging from 0.7061 to
1401 0.7064, while fish collected at stations 796, 706, 704 and 513 ranged from 0.7063 to 0.7069, and
1402 fish collected at stations 508 and 609 exhibited much higher values ranging from 0.7078 to
1403 0.7085 (Figure 2A). SIR of waters in the North Delta from the deep water ship channel to the
1404 confluence of Cache-Lindsey Slough complex ranged from 0.7061-0.7066 (\bar{x} = 0.7063, \pm 0.0002
1405 2σ), while stations in the lower Sacramento River from stations 707-703 were slightly higher
1406 (0.7066-0.7069) (\bar{x} = 0.7065, \pm 0.0004 2σ), as a result of delta waters. SIR in Montezuma
1407 Slough and Suisun Bay ranged from 0.7071-0.7089) (\bar{x} = 0.7076, \pm 0.0018 2σ) reflecting the
1408 influence of low-salinity water. Otolith natal SIR generally matched SIR of the capture
1409 locations, except for the individuals collected at station 513, suggesting these fish originated in
1410 the Lower Sacramento River and moved to this station in Honker Bay. Delta smelt collected in
1411 Montezuma Slough were hatched in low-salinity waters. Growth rates varied significantly
1412 among individuals and were highly variable across stations. Growth rates of delta smelt
1413 collected from stations in freshwater ranged from 0.28-0.53 mm/day (\bar{x} = 0.39, \pm 0.07 σ) while
1414 individuals collected in low-salinity stations ranged from 0.33-0.52 mm/day (\bar{x} = 0.4, \pm 0.06 σ)
1415 (Figure 2B). No difference in growth was detected between stations in freshwater and low-
1416 salinity water. Somatic condition index (SCI) also varied considerably among individual delta
1417 smelt. Values below zero reflect individuals that had lower body mass relative to fish of that
1418 length. Delta smelt collected at stations 719, 721 were distributed around zero, while fish at

1419 stations 797, 796, 706 were above zero and all fish collected at station 513 were below zero,
1420 depicting poor condition of these individuals. SCI of delta smelt collected from stations in
1421 freshwater ranged from -0.03 to +0.10 (\bar{x} = 0.015, \pm 0.03 σ) while individuals collected in low-
1422 salinity stations ranged from -0.05 to + 0.02 (\bar{x} = -0.01, \pm 0.02 σ) (Figure 2C). No difference in
1423 SCI was detected between stations in freshwater and low-salinity water (STAT). Hatch-dates
1424 varied significantly among individuals and stations. Delta smelt collected in freshwater stations
1425 (704-797) had a broad distribution ranging from day 73 (March 13th) to day 122 (May 1st), with
1426 an average hatch-date of day 96 (April 5th) \pm 12 days, 1 σ , while fish collected in low-salinity
1427 stations (513-609) where generally hatched later in the year ranging from day 93 (April 2nd) to
1428 day 117 (April 26th), with an average hatch-date of day 108 (April 17th) \pm 8 days, 1 σ and
1429 subsequently younger than delta smelt in freshwater (Figure 2D).

1430 In survey 2, 69 delta smelt from 12 stations were collected, and 37 individuals, (54% of total
1431 catch) were examined for otolith age, growth, and natal origins (Table 1). Salinity in the Cache-
1432 Lindsey Slough confluence (721) and Deep Water Ship Channel stations (719 and 797) ranged
1433 from 0.08 to 0.34-ppt (\bar{x} = 0.20, \pm 0.12 σ) and Stations in the lower Sacramento River and
1434 confluence (704 and 804) ranged from 0.068 to 0.071-ppt (\bar{x} = 0.07, \pm 0.001 σ), and were
1435 collectively identified as the freshwater zone for survey 1. Salinity at stations from the
1436 confluence of lower Sacramento River to Suisun Bay and Montezuma Slough (513, 508, 520 and
1437 609) ranged from 0.73 to 4.49 (\bar{x} = 2.5, \pm 1.7 σ) and were identified as the low-salinity zone
1438 (Table 1.) Strontium isotope ratios $^{87}\text{Sr}:$ ^{86}Sr (SIR) of the natal core region varied by sampling
1439 stations, with fish collected at stations 721, 719 and 797 ranging from 0.7061 to 0.7064, fish
1440 collected at stations 704, 804, 508 and 513 ranging from 0.7063 to 0.7072, while fish collected
1441 at stations 508 and 609 exhibited much higher values ranging from 0.7076 to 0.7082 (Figure
1442 3A). Like survey 1, some fish at station 513 originated in the Deep Water Ship Channel area,
1443 while fish collected at other stations originated in the areas of collection. Growth rates of delta
1444 smelt collected from stations in freshwater ranged from 0.28-0.53 mm/day (\bar{x} = 0.39, \pm 0.07 σ)
1445 while individuals collected in low-salinity stations ranged from 0.33-0.52 mm/day (\bar{x} = 0.4, \pm
1446 0.06 σ) (Figure 3B). No difference in growth was detected between stations in freshwater and
1447 low-salinity water. Somatic condition index also varied considerably among individual delta
1448 smelt. SCI of delta smelt collected from stations in freshwater ranged from -0.07 to +0.05 (\bar{x} = -
1449 0.01, \pm 0.02 σ) while individuals collected in low-salinity stations ranged from -0.07 to + 0.07 (\bar{x}

1450 = $-0.012, \pm 0.04\sigma$) (Figure 3C). Hatch-dates varied significantly among individuals and stations.
1451 Delta smelt collected in freshwater stations (704-797) had a broad distribution ranging from day
1452 78 (March 18th) to day 134 (May 13st), with an average hatch-date of day 102 (April 11th) ± 13
1453 days, 1σ , while fish collected in low-salinity stations (513-609) where generally hatched later in
1454 the year ranging from day 91 (March 31st) to day 133 (May 12th), with an average hatch-date of
1455 day 111 (April 20th) ± 10 days, 1σ and subsequently younger than delta smelt in freshwater
1456 (Figure 3D).

1457 In survey 5, only 11 delta smelt from 6 stations were collected, and 6 individuals from 4
1458 stations, (55% of total catch) were examined for otolith age, growth, and natal origins (Table 1).
1459 Salinity in the Cache-Lindsey Slough confluence (721) and Deep Water Ship Channel stations
1460 (797) ranged from 0.06 to 0.36-ppt ($\bar{X} = 0.21, \pm 0.17\sigma$). The single station at the confluence
1461 (801) average salinity was 0.57-ppt and included with stations 721 and 797 as a freshwater zone
1462 for survey 5. Salinity at station 519 averaged 1.17 and thus was the only station representing
1463 catch of delta smelt in the low-salinity zone for survey 5 (Table 1.) Strontium isotope ratios
1464 $^{87}\text{Sr}:^{86}\text{Sr}$ (SIR) of the natal core region varied by sampling stations, with fish collected at stations
1465 721, and 719 ranging from 0.7061 to 0.7063, while the single fish collected at stations 801 was
1466 0.7064 and the single fish collected at station 519 exhibited was 0.7075, reflecting the natal
1467 origin in low-salinity water (Figure 4A). Growth rates of delta smelt collected from stations in
1468 freshwater ranged from 0.39-0.42 mm/day ($\bar{X} = 0.40, \pm 0.02\sigma$) while the single individual
1469 collected in low-salinity had a growth rate of 0.35 mm/day (Figure 4B). SCI of delta smelt
1470 collected from stations in freshwater ranged from -0.07 to +0.10 ($\bar{X} = +0.002, \pm 0.07\sigma$) while the
1471 single individual collected in low-salinity had an index of 0.03 (Figure 4C). Delta smelt
1472 collected in freshwater stations had hatch-dates ranging from day 81 (March 21st) to day 131
1473 (May 10th), with an average hatch-date of day 102 (April 11th) ± 21 days, 1σ , while the single
1474 fish collected in low-salinity zone had a hatch-date of day 119 (April 28th) (Figure 4D).

1475 In survey 6, only 14 delta smelt from 5 stations were collected, and all 14 fish were examined
1476 for otolith age, growth, and natal origins (Table 1). Salinity in the Cache-Lindsey Slough
1477 confluence (721) and Deep Water Ship Channel stations (797) and lower Sacramento River
1478 (704) ranged from 0.06 to 0.37-ppt ($\bar{X} = 0.26, \pm 0.15\sigma$). Salinity at station 519 and 610 ranged
1479 from 3.6 to 5.6-ppt and averaged 4.4-ppt $\pm 1.0\sigma$ (Table 1.) Strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$
1480 (SIR) of the natal core region varied by sampling stations, with fish collected at stations 721 and

1481 797 ranging from 0.7061 to 0.7065, while the two fish collected at stations 704 was 0.7062. Fish
1482 collected in the low-salinity zone had one fish with a natal SIR of 0.7062, while the two other
1483 fish had higher SIR of 0.7070 and 0.7079 (Figure 5A). Growth rates of delta smelt collected
1484 from stations in freshwater ranged from 0.34-0.39 mm/day (\bar{x} = 0.36, \pm 0.02 σ) while the fish
1485 collected in low-salinity zone ranged from 0.30-0.36 mm/day (\bar{x} = 0.34, \pm 0.03 σ) (Figure 5B).
1486 SCI of delta smelt collected from stations in freshwater ranged from -0.10 to +0.17 (\bar{x} = +0.017,
1487 \pm 0.08 σ) while fish collected in low-salinity zone ranged from -0.14 to + 0.017 (\bar{x} = -0.077, \pm
1488 0.08 σ) (Figure 5C). Delta smelt collected in freshwater stations had hatch-dates ranging from
1489 day 85 (March 25th) to day 112 (April 21st), with an average hatch-date of day 103 (April 12th) \pm
1490 10 days, 1 σ , while the fish collected in low-salinity zone had a hatch-dates ranging from day 87
1491 (March 27th) to day 159 (June 7th) (Figure 5D).

1492 Fish were combined by salinity habitat type at the collection station across the six surveys in
1493 2013 to further examine spatial and temporal variation in natal origin, growth rate, somatic
1494 condition index and hatch-date. Natal origins of delta smelt rearing in freshwater habitats
1495 (LSR, CLS & DCS) ranged from 0.7061 to 0.7069 and did not differ between surveys 1 and 2,
1496 while natal origins of fish collected in the Low-Salinity Zone were lower in survey 2 with many
1497 more individuals with a natal SIR below 0.7072 (Figure 7A). Growth rates of fish rearing in
1498 freshwater during survey 1 ranged from 0.28 to 0.53-mm/day (\bar{x} = 0.39, \pm 0.07 σ) and from 0.27
1499 to 0.51-mm/day (\bar{x} = 0.41, \pm 0.05 σ) in survey 2. There is a distinct shift in distribution of growth
1500 rates during survey 2, where fish with a growth rate below 0.35-mm/day in survey 1 were not
1501 observed in survey 2, except for a single individual. Meanwhile growth rates of fish collected in
1502 the low-salinity zone during survey 2 (\bar{x} = 0.43, \pm 0.04 σ) were higher than survey 1 (\bar{x} = 0.40, \pm
1503 0.06 σ) (Figure 7B). The somatic condition index for delta smelt collected during survey 1 (\bar{x} =
1504 +0.015, \pm 0.03 σ) was higher than survey 2 (\bar{x} = -0.013, \pm 0.02 σ) for freshwater reared fish and
1505 fish collected in the low-salinity zone during surveys 1 and 2 (Figure 7C). Hatch-date
1506 distributions for delta smelt reared in freshwater did not differ between survey 1 (\bar{x} = 96, \pm 12 σ)
1507 and survey 2 (\bar{x} = 102, \pm 13 σ), but were slightly earlier than fish collected in the low-salinity
1508 zones in survey 1 (\bar{x} = 108, \pm 8 σ) and survey 2 (\bar{x} = 112, \pm 10 σ) (Figure 7D). There were no
1509 differences in hatch-dates for delta smelt collected in the low-salinity zones between survey 1
1510 and 2.

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1516 Table 1. Station identification codes and the regions used for the regional CPUE recruitment index.

Carquinez	Suisun Bay	Montezuma Slough	Confluence	Central Delta	Cache-Liberty	Deepwater Ship Channel
323	405	606	508	812	711	795
340	411	609	513	815	713	796
	418	610	520	902	716	797
	501		704	906	719	
	504		706	910	721	
	519		707	912	723	
	602		801	914		
			804	915		
			809	918		
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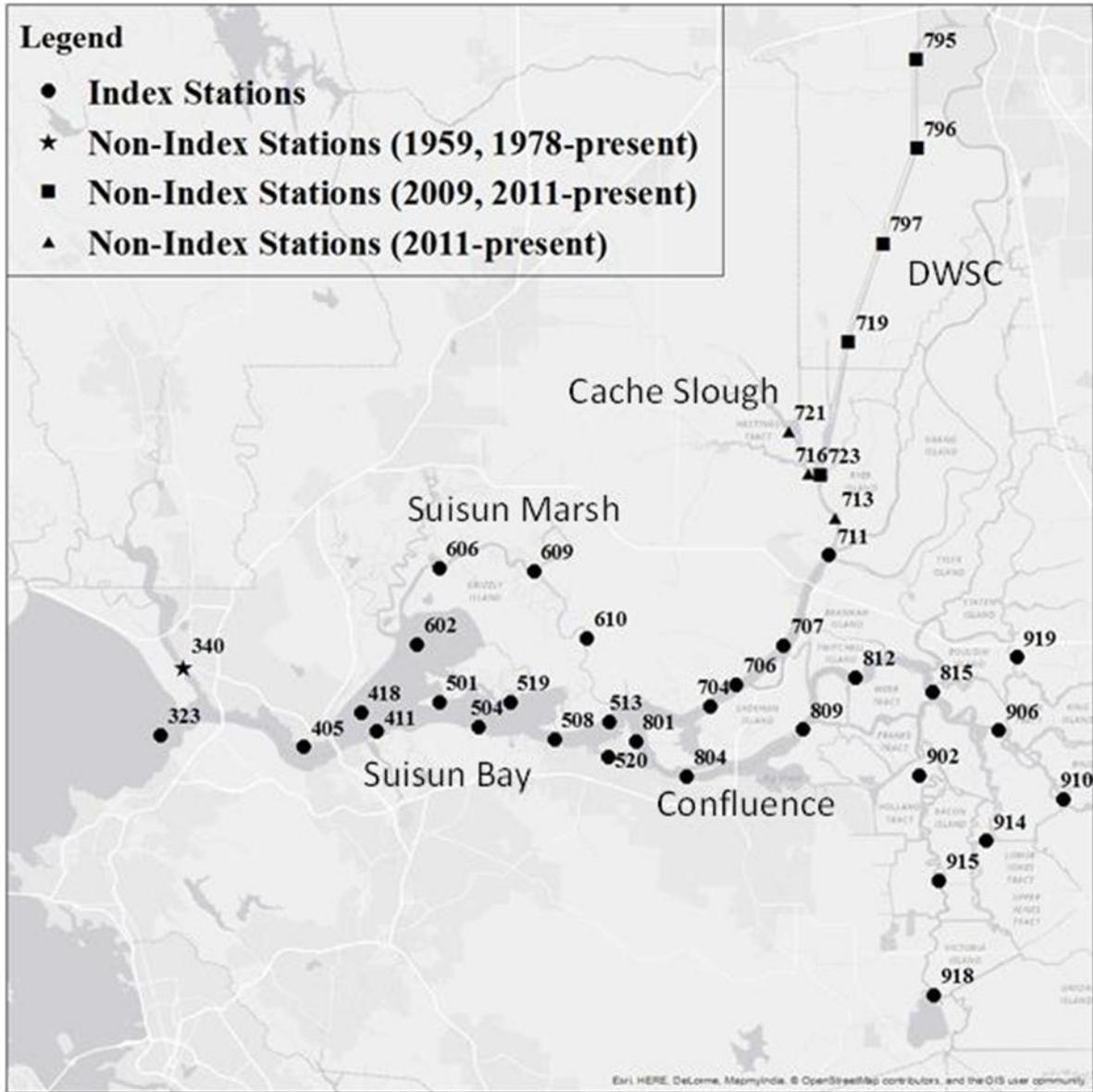
1530 Table 2. Summary of water quality, delta smelt catch and the numbers of individuals analyzed for otolith
 1531 growth and micro-chemistry for the 2012 Summer Towntnet Survey.

Survey	Station	Salinity Group	Salinity Top	Salinity Bottom	Median Temp	Delta Smelt Caught	Delta Smelt Examined	% of Catch
1	508	LowSalinity(1-6)	2.0	2.5	20.1	1	1	100%
1	513	LowSalinity(1-6)	1.0	1.6	20.0	4	4	100%
1	606	LowSalinity(1-6)	4.7	4.9	21.3	1	0	0%
1	609	LowSalinity(1-6)	2.8	2.9	20.5	7	5	71%
1	704	Fresh	0.3	0.3	21.6	5	4	80%
1	706	Fresh	0.1	0.1	22.1	1	1	100%
1	719	Fresh	0.2	0.2	22.4	12	8	67%
1	721	Fresh	0.1	0.1	20.5	16	9	56%
1	796	Fresh	0.5	0.5	22.5	2	2	100%
1	797	Fresh	0.3	0.3	22.7	20	8	40%
2	508	LowSalinity(1-6)	2.3	2.9	19.9	2	1	50%
2	513	LowSalinity(1-6)	0.7	1.0	19.2	15	9	60%
2	520	LowSalinity(1-6)	1.0	1.0	21.3	2	2	100%
2	606	LowSalinity(1-6)	6.0	6.0	20.6	1	0	0%
2	609	LowSalinity(1-6)	3.8	3.9	19.6	3	2	67%
2	704	Fresh	0.1	0.1	21.1	2	2	100%
2	719	Fresh	0.2	0.2	20.6	13	8	62%
2	721	Fresh	0.1	0.1	18.2	8	4	50%
2	796	Fresh	0.5	0.5	22.1	2	0	0%
2	797	Fresh	0.3	0.3	20.8	16	8	50%
2	804	Fresh	0.3	0.3	21.1	1	1	100%
2	809	Fresh	0.2	0.4	19.9	4	0	0%
5	519	LowSalinity(1-6)	3.1	3.3	21.0	1	1	100%
5	602	LowSalinity(1-6)	5.4	5.5	21.2	1	0	0%
5	721	Fresh	0.1	0.1	19.8	2	2	100%
5	797	Fresh	0.4	0.4	23.6	5	2	40%
5	801	LowSalinity(1-6)	0.5	0.6	20.6	1	1	100%
5	809	Fresh	0.4	0.4	20.0	1	0	0%
6	519	LowSalinity(1-6)	4.8	5.6	20.8	2	2	100%
6	610	LowSalinity(1-6)	3.6	3.6	19.7	1	1	100%
6	704	Fresh	0.1	0.1	22.0	2	2	100%
6	721	Fresh	0.1	0.1	20.4	1	1	100%
6	797	Fresh	0.3	0.4	22.8	8	8	100%

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1536 Figure 1. Map of the Summer Townet Survey stations.

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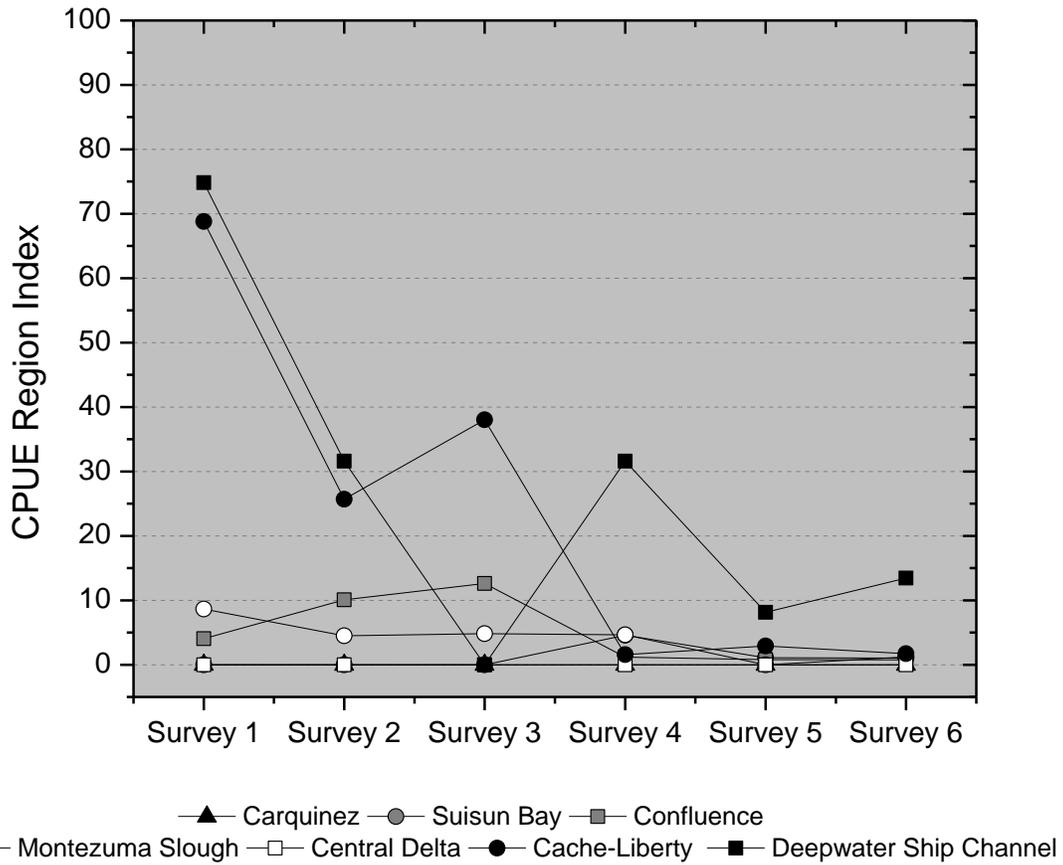
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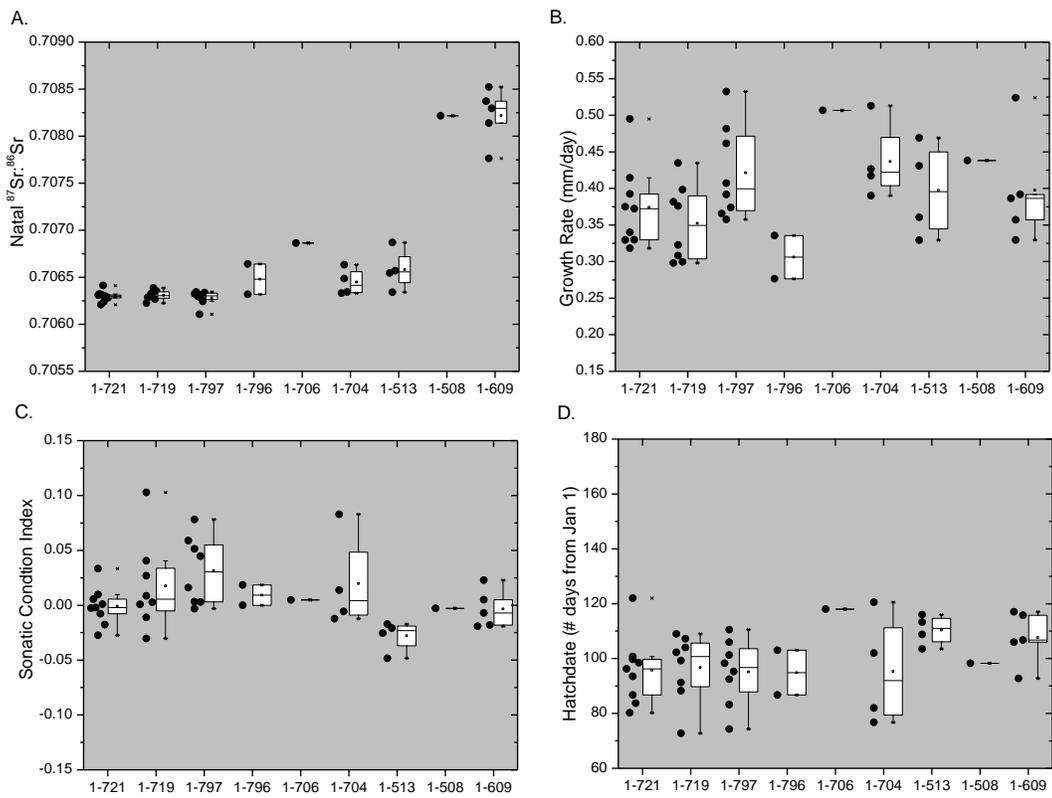
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Figure 2. Recruitment index (Sum station CPUE/# stations) over the 6 surveys of the 2012 Summer Towntnet Survey.

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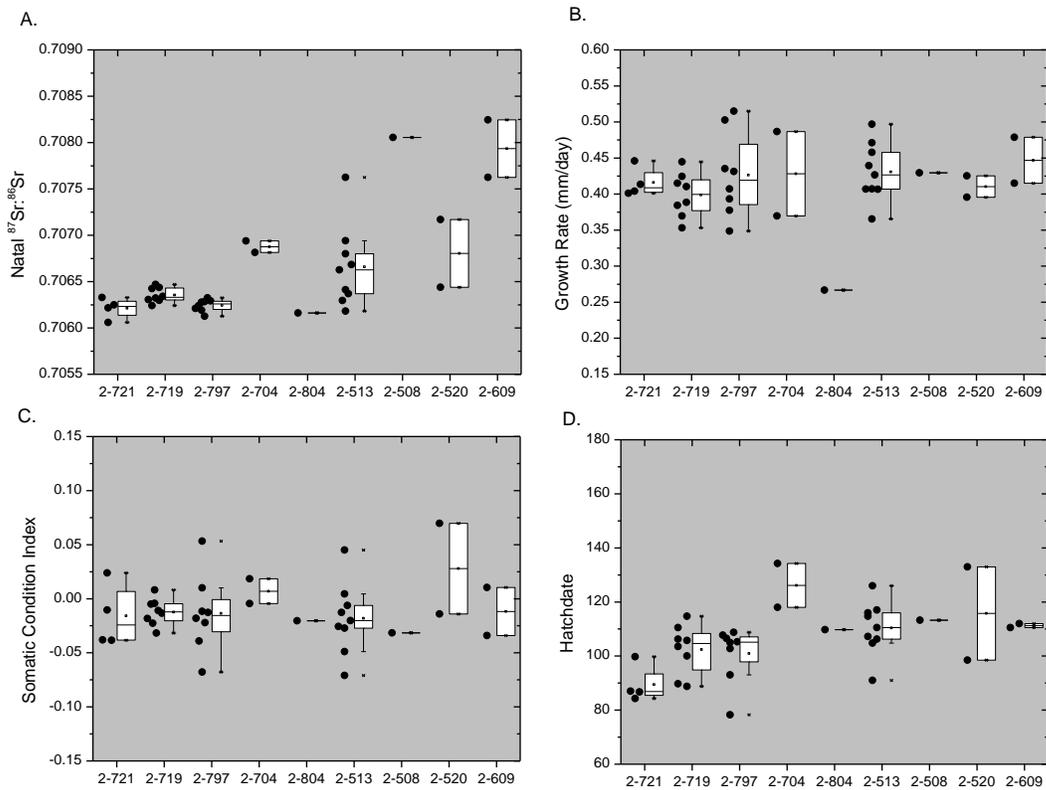
Table 3. Regional CPUE index for 2012 Summer Townet Survey

	CAR	SB	CON	MZ	CD	CLS	DSC
Survey 1	0	0	4.1	8.6	0	68.8	74.8
Survey 2	0	0	10.1	4.5	0	25.7	31.6
Survey 3	0	0	12.6	4.8	0	38.0	0
Survey 4	0	4.6	1.2	4.6	0	1.6	31.6
Survey 5	0	1.1	0.8	0	0	2.9	8.1
Survey 6	0	1.0	0.8	1.2	0	1.7	13.5



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1575 Figure 3. Survey 1 boxplots for each station. Black dots represent values for individual fish. A.
1576 Strontium isotope ratios of the natal cores, B. Growth rate C. Condition Index D. Hatch-date. Stations
1577 721 to 704 were freshwater while stations below 704 were low-salinity habitats.



1578

1579 Figure 4. Survey 2 results. Black dots represent values for individual fish. A. Strontium isotope ratios of
 1580 the natal cores, B. Growth rate C. Condition Index D. Hatch-date. Stations 721 to 704 and 804 were
 1581 freshwater while stations 503-609 were low-salinity habitat.

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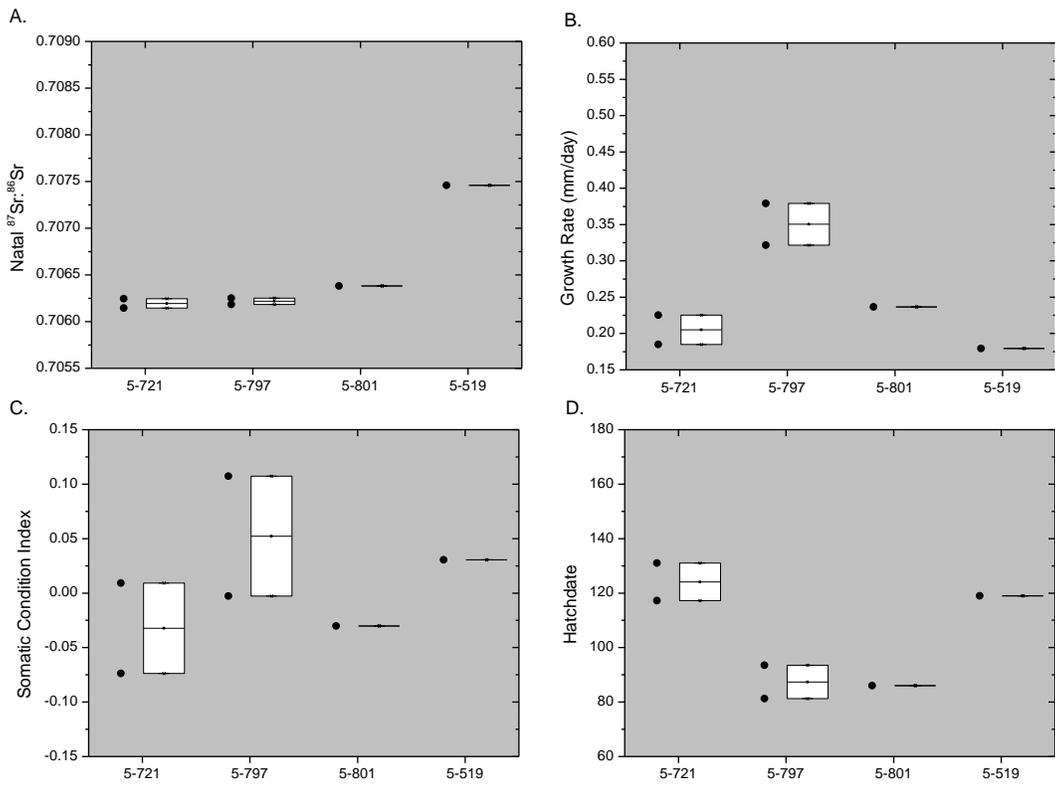
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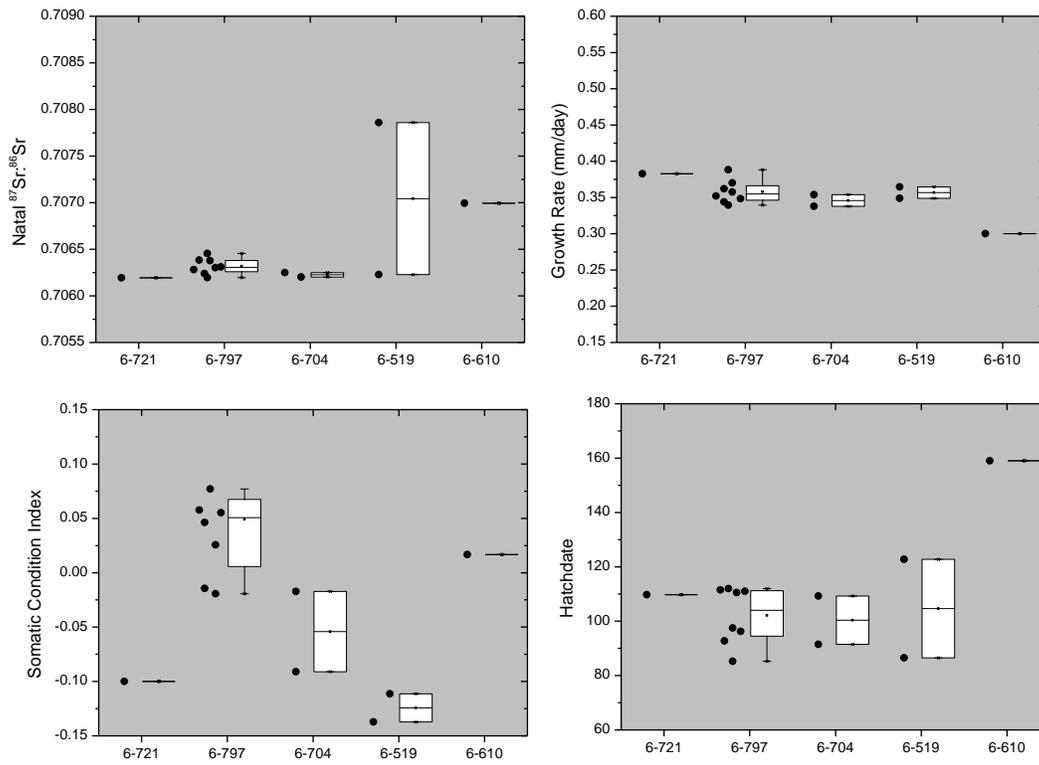
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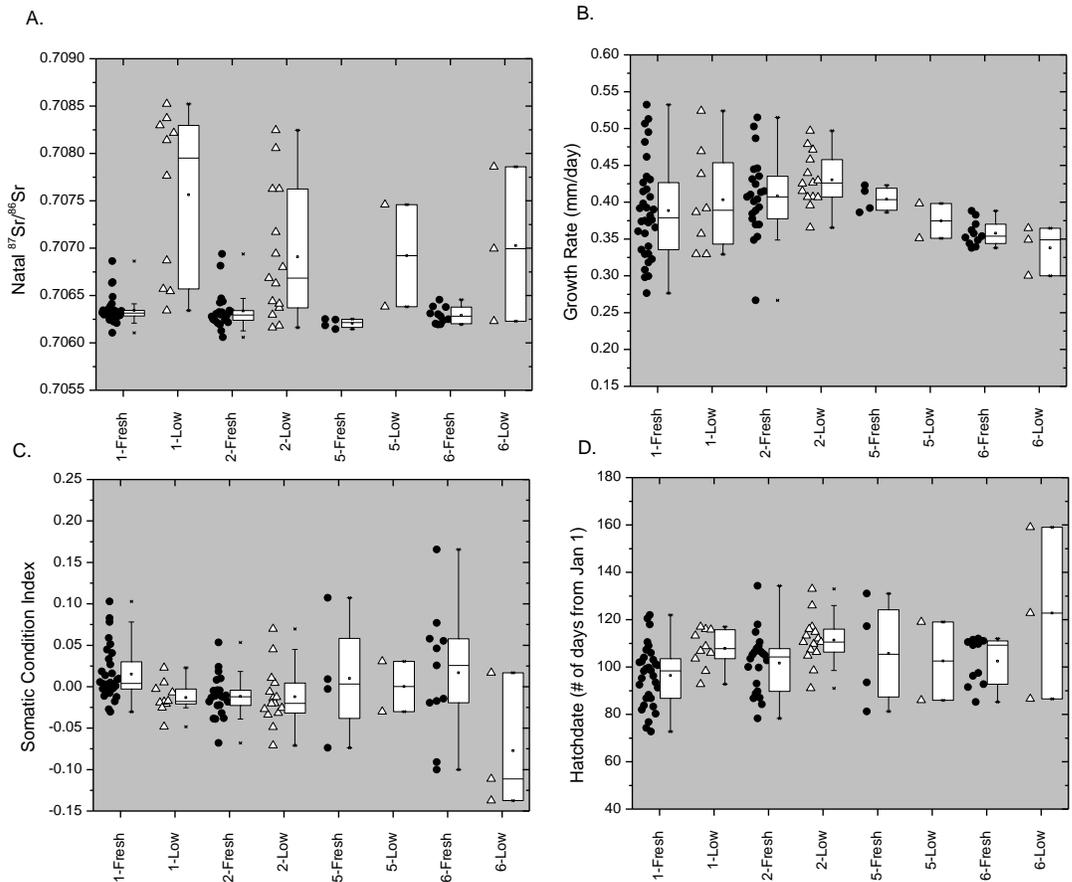
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 1590 Figure 5. Survey 5 results. Black dots represent values for individual fish. A. Strontium isotope ratios of
 1591 the natal cores, B. Growth rate C. Condition Index D. Hatch-date.



1592

1593 Figure 6. Survey 6 results. Black dots represent values for individual fish. A. Strontium isotope ratios of
 1594 the natal cores, B. Growth rate C. Condition Index D. Hatch-date.

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1597 Figure 7. Box plots for surveys 1-6, with freshwater solid black circles, low-salinity zone (1-6-ppt),
 1598 open triangles depicting the salinity habitats where fish were collected. A. Strontium isotope ratios of the
 1599 natal cores, B. Growth rate C. Condition Index D. Hatch-date.

1600

1601 **The Summer Towntnet Survey 2013**

1602

1603 We analyzed 122 fish for age, growth and natal history out of a total of 167 Delta Smelt
 1604 encountered during the Summer Towntnet Survey in 2013 (73% of total catch) (Table 4). In
 1605 survey 1 (June 10th -13th), 62 delta smelt from 10 stations were collected, and a total of 53
 1606 individuals, (85% of total catch), were examined for otolith age, growth, condition and natal
 1607 origins. Salinity in the Cache-Lindsey Slough confluence (721 & 723) and Deep Water Ship
 1608 Channel stations (719, 796 and 797) was fresh, ranging from 0.07 to 0.24-ppt while stations
 1609 downstream of 704 including 801 and 809 on the San Joaquin River had much higher salinity,
 1610 ranging from 0.36 to 4.81-ppt and were considered the low-salinity zone (Table 4). Temperatures

1611 were similar across the stations, with stations 801 and 809 being about a degree cooler. (Table
1612 4). Strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$ (SIR) of the natal core region varied across sampling
1613 stations, with fish collected in the freshwater stations 719, 721, 723 and 797 ranging from 0.7059
1614 to 0.7065, reflecting the isotope ratios of freshwater typically observed in the North Delta
1615 (*Cache-Liberty Deepwater Ship Channel area*) (Figure 9A). Fish collected downstream of
1616 station 706 varied greatly in their natal SIR (0.706 to 0.708) reflecting fish born in the North
1617 Delta and fish born in low-salinity habitats (Figure 3A). Growth rates varied significantly
1618 among individuals and were highly variable across stations. Growth rates of delta smelt
1619 collected from stations in freshwater ranged from 0.28-0.53 mm/day ($\bar{x} = 0.41, \pm 0.07\sigma$) while
1620 individuals collected in low-salinity stations ranged from 0.28-0.45 mm/day ($\bar{x} = 0.39, \pm 0.05\sigma$)
1621 (Figure 9B). No difference in growth was detected between stations in freshwater and low-
1622 salinity water. Somatic condition index (SCI) varied considerably among individual delta smelt.
1623 Fish collected in freshwater ranged from -0.06 to 0.07 and means were not different than fish
1624 collected in the low-salinity zone, which ranged from -0.11 to 0.08 (Figure 9C). Hatch-dates
1625 varied significantly among individuals and stations. Delta smelt collected in freshwater had a
1626 broad distribution ranging from day 57 to day 118, with an average hatch-date of day 94 ± 15
1627 days, 1σ , while fish collected in low-salinity were generally hatched earlier in the year ranging
1628 from day 57 (April 2nd) to day 97 (April 26th), with an average hatch-date of day 82 ± 10 days, 1
1629 σ and subsequently older than delta smelt in freshwater (Figure 9D).

1630 In survey 2 (June 24th – 27th), 25 delta smelt from 8 stations were collected, and 21
1631 individuals, (84% of total catch) were examined for otolith age, growth, and natal origins (Table
1632 4). Salinity in the Cache-Lindsey Slough confluence and Deep Water Ship Channel stations were
1633 fresh, ranging from 0.08 to 0.29-ppt while stations downstream of 704 including 809 on the San
1634 Joaquin River had higher salinity, ranging from 0.42 to 6.68-ppt and were considered the low-
1635 salinity zone (Table 4). Temperature in the low salinity zone ranged from 20.5 to 21.6°C while
1636 in freshwater temperatures ranged from 20.1 to 21.1°C. Strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$ (SIR)
1637 of the natal core region varied across sampling stations, with fish collected in the freshwater
1638 stations 719, 721 & 797 ranging from 0.7061 to 0.7065, reflecting the isotope ratios of
1639 freshwater typically observed in the North Delta (*Cache-Liberty Deepwater Ship Channel area*)
1640 (Figure 10A). Fish collected downstream of station 706 varied greatly in their natal SIR (0.7061
1641 to 0.7089) reflecting fish born in the North Delta and fish born in low-salinity habitats (Figure

1642 10A). Growth rates varied significantly among individuals and salinity habitats in survey 2.
1643 Growth rates of delta smelt collected from stations in freshwater ranged from 0.40-0.49 mm/day
1644 (\bar{X} = 0.45, \pm 0.03 σ) while individuals collected in low-salinity stations ranged from 0.29-0.45
1645 mm/day (\bar{X} = 0.39, \pm 0.04 σ) (Figure 10B). Somatic condition index (SCI) varied considerably
1646 among individual delta smelt. Fish collected in freshwater ranged from -0.05 to 0.06 and means
1647 were not different than fish collected in the low-salinity zone, which ranged from -0.07 to 0.12
1648 (Figure 10C). Hatch-dates were similar for fish collected in freshwater and low-salinity habitats
1649 during survey 2. Delta smelt collected in freshwater had hatch-dates ranging from day 73 to day
1650 110, with an average hatch-date of day 89 ± 15 days, 1 σ , while fish collected in low-salinity
1651 ranged from day 77 (April 2nd) to day 93 (April 26th), with an average hatch-date of day 83 ± 5
1652 days, 1 σ (Figure 10D).

1653 In survey 3 (July 8th – 11th), 20 delta smelt from 6 stations were collected, and 16 individuals,
1654 (80% of total catch) were examined for otolith age, growth, and natal origins (Table 4). Salinity
1655 in the Cache-Lindsey Slough confluence and Deep Water Ship Channel stations were fresh,
1656 ranging from 0.07 to 0.36-ppt while stations below the confluence had much higher salinity,
1657 ranging from 7.29 to 11.04-ppt and were considered the low-salinity zone. Salinity in Suisun Bay
1658 and marsh region increased considerably from survey 2 to 3 (Table 4). Temperature in the low
1659 salinity zone ranged from 20.5 to 22.1°C, while in freshwater temperatures ranged from 21.5 to
1660 23.6°C and were on average 2°C higher than survey 1 and 2. Catch distribution shifted
1661 downstream bayward of the confluence in survey 3. Strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$ (SIR) of
1662 the natal core region varied across sampling stations. Only one fish was collected in freshwater
1663 (721) and its corresponding natal isotope ratio was 0.7064 (Figure 11A). Fish collected
1664 downstream of the confluence varied greatly in their natal SIR (0.7061 to 0.7077) reflecting both
1665 fish born in the North Delta and fish born in low-salinity habitats (Figure 11A). The growth
1666 rate of the individual collected in freshwater was relatively high (0.48 mm/day) while individuals
1667 collected in low-salinity stations ranged from 0.34-0.48 mm/day (\bar{X} = 0.40, \pm 0.04 σ) (Figure
1668 11B). Somatic condition index (SCI) varied considerably among individual delta smelt. The fish
1669 collected in freshwater had a positive index of 0.05, while fish collected in the low-salinity zone,
1670 which ranged from -0.11 to 0.06. The mean SCI for fish in the LSZ was $-0.02 \pm 0.04\sigma$ (Figure
1671 11C). The hatch-date of the fish collected in freshwater was day 78 while fish from the LSZ had
1672 hatch-dates ranging from day 74 to day 110, with an average hatch-date of day 88 ± 9 days, 1 σ ,

1673 while fish collected in low-salinity ranged from day 77 (April 2nd) to day 93 (April 26th), with an
1674 average hatch-date of day 83 ± 5 days, 1σ (Figure 11D).

1675 In survey 4 (July 22nd – 25th), 44 delta smelt from 6 stations were collected, and 20
1676 individuals, (45% of total catch) were examined for otolith age, growth, and natal origins. A
1677 large catch even occurred at station 519 (N= 33), however, we only examine 9 fish from this
1678 catch. (Table 4). Salinity in the Cache-Lindsey Slough confluence , Deep Water Ship Channel
1679 down to station 704 on the lower Sacramento River near Rio Vista were fresh, ranging from 0.10
1680 to 0.20-ppt while stations below the confluence had much higher salinity, ranging from 7.73 to
1681 11.82-ppt and were considered the low-salinity zone in survey 4. Temperature in the low salinity
1682 zone ranged from 19.8 to 20.4°C while in freshwater temperatures warm, ranging from 20.6 to
1683 23.3°C. Strontium isotope ratios $^{87}\text{Sr}:$ ^{86}Sr (SIR) of the natal core region varied across sampling
1684 stations. Fish collected in freshwater had natal SIR value ranging from 0.7060 to 0.7064
1685 reflecting natal origins in freshwater, while fish collected in the LSZ ranged from 0.7060 to
1686 0.7076 identifying fish that were born in freshwater and had moved into the LSZ and fish that
1687 were born and resided in the LSZ through survey 4 (Figure 12A). The growth rate of the
1688 individual collected in freshwater ranged from 0.35 to 0.44 mm/day (\bar{x} = 0.39, $\pm 0.03\sigma$) while
1689 individuals collected in the LSZ ranged from 0.35-0.49 mm/day (\bar{x} = 0.39, $\pm 0.04\sigma$) and were not
1690 different from fish collected in freshwater (Figure 12B). Somatic condition index (SCI) varied
1691 considerably among individual delta smelt but not by habitat. Fish collected in freshwater ranged
1692 from -0.06 to 0.08, while fish collected in the low-salinity zone, which ranged from -0.04 to
1693 0.06. (Figure 12C). The hatch-date of fish collected in freshwater ranged from 75 to 114 with an
1694 average hatch-date of day 94 ± 17 days, 1σ while fish from the LSZ had hatch-dates ranging
1695 from day 72 to day 118, with an average hatch-date of day 90 ± 12 days, 1σ (Figure 12D).

1696 In survey 5 (August 5th – 8th), only 3 delta smelt from 3 stations were collected and examined
1697 for otolith age, growth, and natal origins. (Table 4). Salinity in the Deep Water Ship Channel
1698 station was fresh 0.35-ppt while stations 519 and 602 had much higher salinity (4.76 and 8.74,
1699 respectively) in survey 4. Temperature in the freshwater habitat was cooler than the previous 2
1700 surveys and was 20.9 °C, while temperature in the LSZ sites was relatively cool at 19.2 and 19.6
1701 °C. The fish collected at 797 and 602 had natal SIR values consistent with originating in
1702 freshwater (0.7063 and 0.7065 respectively) while the fish collected at station 519 had natal SIR
1703 values indicative of originating in the LSZ (Figure 13A). The growth rate of the fish collected

1704 at station 797 was 0.33mm/day, fish collected at station 602 had a growth rate of 0.36 mm/day
1705 and the fish collected at station 519 had a growth rate of 0.35 mm/day. (Figure 13B). Somatic
1706 condition index (SCI) for the three fish was generally poor, with the fish collected at station 797
1707 was -0.03, fish collected at 602 was -0.01 and fish collected at station 519 was -0.11 (Figure
1708 13C). The hatch-date of the fish collected at station 797 was 93, fish collected at station 602 was
1709 111 and fish collected at station 519 was 91(Figure 13D).

1710 In survey 6 (August 19th – 21st), 14 delta smelt from 7 stations were collected and 9 fish were
1711 examined for otolith age, growth, and natal origins. (Table 4). Only a single station had
1712 freshwater (719) 0.23-ppt, and salinity had intruded as far upstream as station 704 (2.57-ppt)
1713 during survey 6. Salinity on the San Joaquin River side of the confluence was 2.2-2.92-ppt and
1714 salinities bayward of the confluence ranged from 6.99 to 12.47-ppt (Table 1). Temperature at
1715 station 719 was warm at 25.1°C , while temperatures elsewhere were relatively cool ranging
1716 from 19.0 to 21.7 °C (Table 4). Natal SIR values of the five fish collected at station 719 were
1717 between 0.7063 and 0.7064 indicative of natal origins in freshwater while fish at the other
1718 stations ranged from 0.7062 to 0.7072. A single fish from station 802 had a natal signature from
1719 the LSZ (Figure 14A). Growth rates of the fish collected at station 719 ranged from 0.29 to
1720 0.34mm/day, while fish collected at the LSX stations had a growth rates from 0.31 to 0.36
1721 mm/day (Figure 14B). Somatic condition index (SCI) for fish collected at station 719 ranged
1722 from -0.02 to 0.05, while fish collected at the LSZ stations ranged from -0.05 to 0.02 (Figure
1723 14C). The hatch-date of the fish collected at station 719 ranged from 87 to 138, representing a
1724 new cohort of fish not seen in previous surveys, while fish in the LSZ stations ranged from 74 to
1725 121 with some late hatched fish as well (Figure 14D).

1726 Fish were combined by salinity habitat type at the collection station across the six surveys
1727 in 2013 to further examine spatial and temporal variation in natal origin, growth rate, somatic
1728 condition index and hatch-date. Natal SIR varied across salinity habitats and surveys. Fish
1729 collected in freshwater habitats consistently had natal $^{87}\text{Sr}/^{86}\text{Sr}$ values less than 0.7065, which is
1730 consistent with water $^{87}\text{Sr}/^{86}\text{Sr}$ values of the North Delta region. Fish collected in low and high-
1731 salinity habitats varied more than fish collected in freshwater habitats and consisted of fish with
1732 freshwater natal origins (<0.7065) and values from 0.7066 to 0.7090 consistent with fish
1733 inhabiting low-salinity habitats, thus fish in the LSZ consisted of migratory fish from freshwater
1734 and fish which were natal to the LSZ (Figure15A). Growth rate also varied considerably among

1735 salinity habitats and across surveys. Growth rates tended to vary within habitat and surveys
1736 greatly, however growth rate was low for fish collected in the LSZ during survey 2, which were
1737 primarily fish originating in the LSZ. Growth rates were also lower during surveys 5 and 6.
1738 Between survey 2 and survey 4 we saw very few fish with growth rates less than 0.35mm/day,
1739 which was consistently with values observed in 2012 (Figure 15B). Somatic condition index
1740 varied among individuals but no meaningful trend was found between salinity habitats or surveys
1741 (Figure 15C). Hatch-dates varied across the surveys, but did not appear to vary between salinity
1742 habitats (Figure 15D).

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1744 **DISCUSSION**

1745 Delta Smelt abundance for the spawning population in spring of 2012 (2011 year-class) had
1746 one of the highest indices in the last 20 years (Fall Midwater Trawl Survey Index = 343).
1747 Meanwhile the 20-mm Survey index of 2012, which captured the offspring from the 2011 year-
1748 class, was also one of the highest indices (11.1) since 2000. During the 2012 and 2013 Summer
1749 Townet Survey we observed a decline in CPUE index between survey 1 and survey 2. The
1750 majority of Delta Smelt captured during these two surveys occurred in the Deepwater Ship
1751 Channel (DSC) and the Cache-Liberty Slough (CLS) complex, where we observed the largest
1752 absolute decline in CPUE. Survival of Delta Smelt that remained in the DSC and CLS between
1753 surveys 1 and 2 appeared to be growth rate dependent as Delta Smelt found in the DSC and CLS
1754 during survey 2 had growth rates that were greater than 0.35-mm/day, while 28% of the Delta
1755 Smelt found there during survey 1 had growth rates below 0.35-mm/day. However, the decline
1756 in CPUE cannot be attributed solely to growth related mortality. The otolith strontium isotope
1757 ratios provided evidence of fish migrating from the North Delta to the Low-Salinity Zone as
1758 Delta Smelt collected in the Low-Salinity Zone (LSZ) during survey 2 had natal origins in the
1759 DSC and CLS. Exploration of the strontium isotope ratios of the entire otolith profile (from core
1760 to edge) confirmed that all but one fish found in the LSZ that had been hatched in the DSC and
1761 CLS had higher isotope values near the edge of the otolith confirming their move to low-salinity
1762 habitats. Meanwhile, Delta Smelt CPUE in the LSZ increased 400% during this time period,
1763 however, the percentage of CPUE change may not be the most accurate measure of abundance
1764 change when the CPUE is very low, as a few individuals could account for such a large relative
1765 change in CPUE. Growth rates of Delta Smelt that had migrated to the LSZ between survey 1

1766 and 2 were greater than 0.35 mm/day providing further evidence supporting the idea that fish
1767 growing slower than 0.35 mm/day in the DSC had died.

1768 Interestingly, the somatic condition index of fish remaining in the DSC and CLS from survey
1769 1 to 2 exhibited a slight decrease in condition, suggesting conditions for Delta Smelt were poor.
1770 Very few individuals were from surveys 5 and 6 and did not make direct comparisons of somatic
1771 condition to surveys 1 and 2, but somatic condition index of 5 of the 7 fish collected in these
1772 later surveys were higher than fish collected in survey 2, suggesting survival to the late summer
1773 in the DSC and CLS may have been contingent on somatic condition. These region has been
1774 identified as a contaminant hotspot in the Delta. Hammock et al. (2015) found high incidence of
1775 contaminant stress in Delta Smelt collected in the DSC and CLS regions; the same individual
1776 fish examined in this report. Weston et al. (2014) repeatedly detected acute toxicity to *Hyalella*
1777 *azteca* following storms in both western Cache Slough and Ulati Creek, and attributed the
1778 toxicity largely to pyrethroids in urban runoff. In a two-year study, Werner et al. (2000) found
1779 that of the 24 sites sampled throughout the delta, Ulati Creek most frequently showed acute
1780 toxicity to *Ceriodaphnia dubia* (6 of 21 monthly samples were acutely toxic). Kuivila and Moon
1781 (2004) detected high concentrations of the pesticides Molinate and Thiobencarb in Cache
1782 Slough, and suggested that mixtures of pesticides could have chronic health effects on Delta
1783 Smelt, particularly juveniles.

1784 Water temperatures were extremely high in the summer of 2012, where temperatures in
1785 freshwater ranged from 20.5 °C to 22.7 °C during survey 1 and 18.2 °C to 22.1 °C during survey
1786 2, and were generally higher than 2013. Delta Smelt are sensitive to high water temperatures and
1787 not frequently encountered at temperatures above 25 °C in field surveys and exhibit mortality
1788 around 27 °C in lab experiments (Komoroske et al 2014). However, these field and laboratory
1789 assessments of Delta Smelt sensitivity to temperature do not account for longer term effects on
1790 growth or somatic condition. In addition, they do not include other factors such as food
1791 abundance, turbidity or contaminants. Elevated water temperatures can have large influence on
1792 the metabolic rate of fish and may have a significant effect on Delta Smelt inhabiting food
1793 limited habitats. Slater et al. (in prep) examined Delta Smelt diets and stomach fullness of fish
1794 analyzed in this report and showed Delta Smelt stomach fullness of fish rearing in freshwater had
1795 a slightly lower mean stomach fullness in August compared to June. However, with water

1796 temperatures 2-3 °C higher in freshwater the metabolic demand would be much higher and food
1797 supplies and stomach fullness may suggest the DSC and CLS were poor rearing habitats during
1798 the summer of 2012 and may account for the rapid decline of Delta Smelt following the high
1799 abundance index in 2011 when outflow was high and water temperatures much cooler than 2012.

1800 Detailed analysis of Delta Smelt from the 2012 Summer Townet Survey revealed patterns
1801 suggesting high mortality between survey 1 and survey 2 was associated with poor rearing
1802 habitat with warm water temperatures, likely less prey availability or nutritional quality and
1803 significant contaminant stress. The intersection of these stressors resulted in a significant decline
1804 in the Delta Smelt abundance index from 2011 to 2012 and provides a key example of how
1805 recruitment failure during the summer may be the primary factor driving the population
1806 dynamics of Delta Smelt. Moreover patterns were similar for 2013, when the abundance index
1807 of Delta Smelt was reduced, thus the role of density dependence in the recruitment mortality may
1808 be a persistent impact on Delta Smelt rearing in the North Delta every year. In recent years the
1809 proportion of adult Delta Smelt found in the SKT survey, and the proportion of fish originating
1810 from the North Delta from otolith chemistry suggests the population may be moving into a
1811 persistently poor nursery area. Future studies should be focused on what environmental drivers
1812 are associated with this shift in distribution to the North Delta.

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1823 Table 4. Summary of water quality, delta smelt catch and the numbers of individuals analyzed
 1824 for otolith growth and micro-chemistry for the 2013 Summer Towntet Survey.

Survey	Station	Salinity Group	Salinity ppt	Temperature °C	Total Catch	N	% of Catch
1	519	LowSalinity(1-6)	4.8	20.7	1	1	100%
1	609	LowSalinity(1-6)	3.1	20.0	17	17	100%
1	610	LowSalinity(1-6)	3.4	20.0	2	2	100%
1	704	LowSalinity(1-6)	0.8	19.1	7	7	100%
1	706	Fresh	0.1	20.8	1	1	100%
1	707	Fresh	0.1	21.6	2	0	0%
1	719	Fresh	0.2	21.0	10	9	90%
1	721	Fresh	0.1	20.0	8	8	100%
1	723	Fresh	0.1	21.0	4	4	100%
1	797	Fresh	0.2	21.2	8	5	63%
1	801	Fresh	3.0	18.8	1	1	100%
1	809	Fresh	0.4	18.6	4	0	0%
2	508	LowSalinity(1-6)	4.5	20.5	2	2	100%
2	606	LowSalinity(1-6)	6.7	21.6	7	7	100%
2	609	LowSalinity(1-6)	4.6	21.0	3	3	100%
2	610	LowSalinity(1-6)	4.2	21.3	3	3	100%
2	719	Fresh	0.2	20.9	2	1	50%
2	721	Fresh	0.1	20.1	1	1	100%
2	797	Fresh	0.3	21.1	4	4	100%
2	809	Fresh	0.4	20.2	3	0	0%
3	418	LowSalinity(1-6)	11.0	20.5	1	1	100%
3	501	LowSalinity(1-6)	7.4	22.1	2	2	100%
3	519	LowSalinity(1-6)	7.3	21.0	11	10	91%
3	602	LowSalinity(1-6)	9.2	20.3	4	3	75%
3	721	Fresh	0.1	21.5	1	1	100%
3	797	Fresh	0.4	23.6	1	0	0%
4	418	LowSalinity(1-6)	11.8	20.4	1	1	100%
4	519	LowSalinity(1-6)	7.7	20.2	33	9	27%
4	602	LowSalinity(1-6)	10.4	19.8	2	2	100%
4	704	Fresh	0.2	22.6	1	1	100%
4	719	Fresh	0.2	23.3	6	6	100%
4	721	Fresh	0.1	20.6	1	1	100%
5	519	LowSalinity(1-6)	4.8	19.6	1	1	100%
5	602	LowSalinity(1-6)	8.7	19.2	1	1	100%
5	797	Fresh	0.3	20.9	1	1	100%
6	418	LowSalinity(1-6)	12.5	19.8	2	0	0%
6	519	LowSalinity(1-6)	7.0	21.7	1	1	100%
6	602	LowSalinity(1-6)	10.2	19.0	3	0	0%
6	704	LowSalinity(1-6)	2.6	20.7	1	1	100%
6	719	Fresh	0.2	25.1	5	5	100%
6	801	LowSalinity(1-6)	2.9	20.9	1	1	100%
6	804	LowSalinity(1-6)	2.2	20.8	1	1	100%

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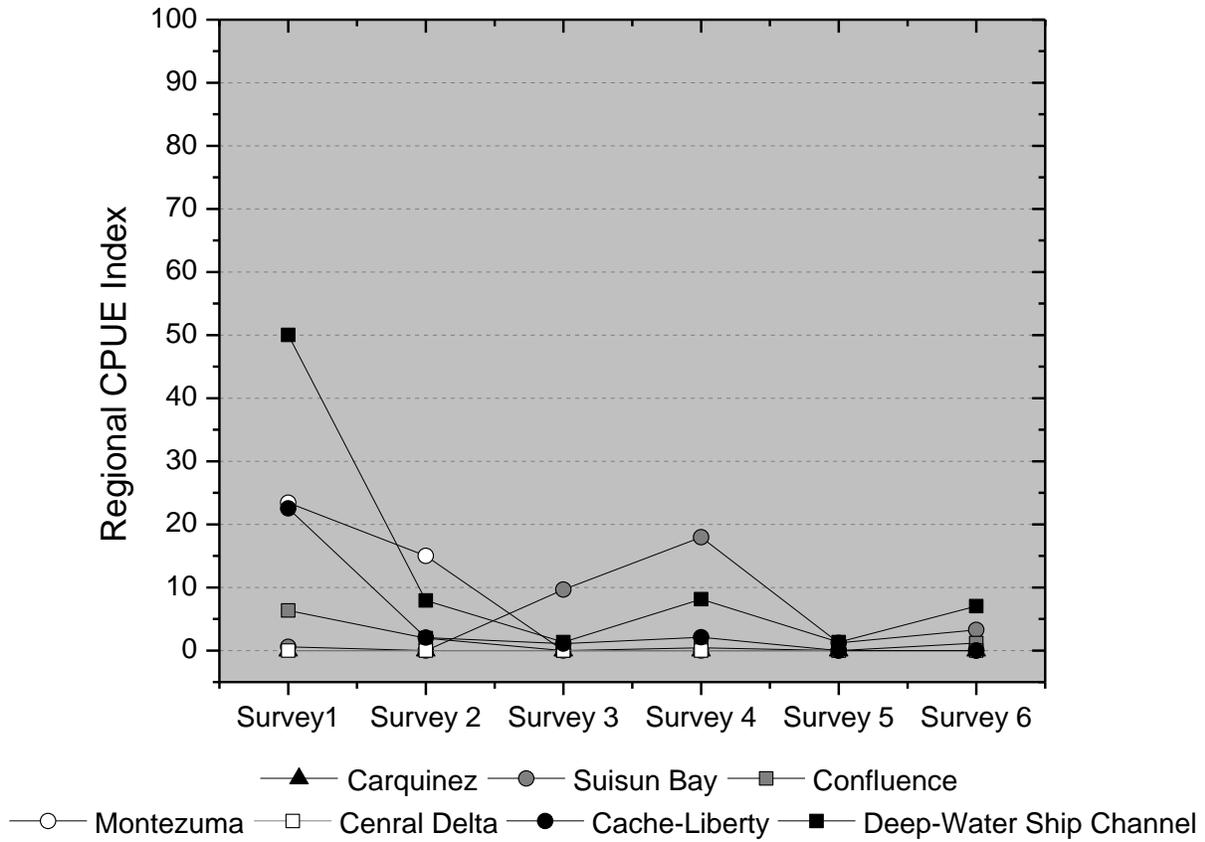
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1833 Figure 8. Recruitment index (Sum station CPUE/# stations) over the 6 surveys of the 2013
1834 Summer Towntnet Survey.

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1842 Table 5. Regional CPUE index for 2013 Summer Townet Survey

	CAR	SB	CON	MZ	CD	CLS	DSC
Survey 1	0	0.6	6.3	23.4	0	22.5	50.0
Survey 2	0	0	2.0	15.0	0	2.0	7.9
Survey 3	0	9.7	0	0	0	1.1	1.3
Survey 4	0	18.0	0.4	0	0	2.1	8.1
Survey 5	0	1.2	0	0	0	0.0	1.3
Survey 6	0	3.3	1.2	0	0	0.0	7.0

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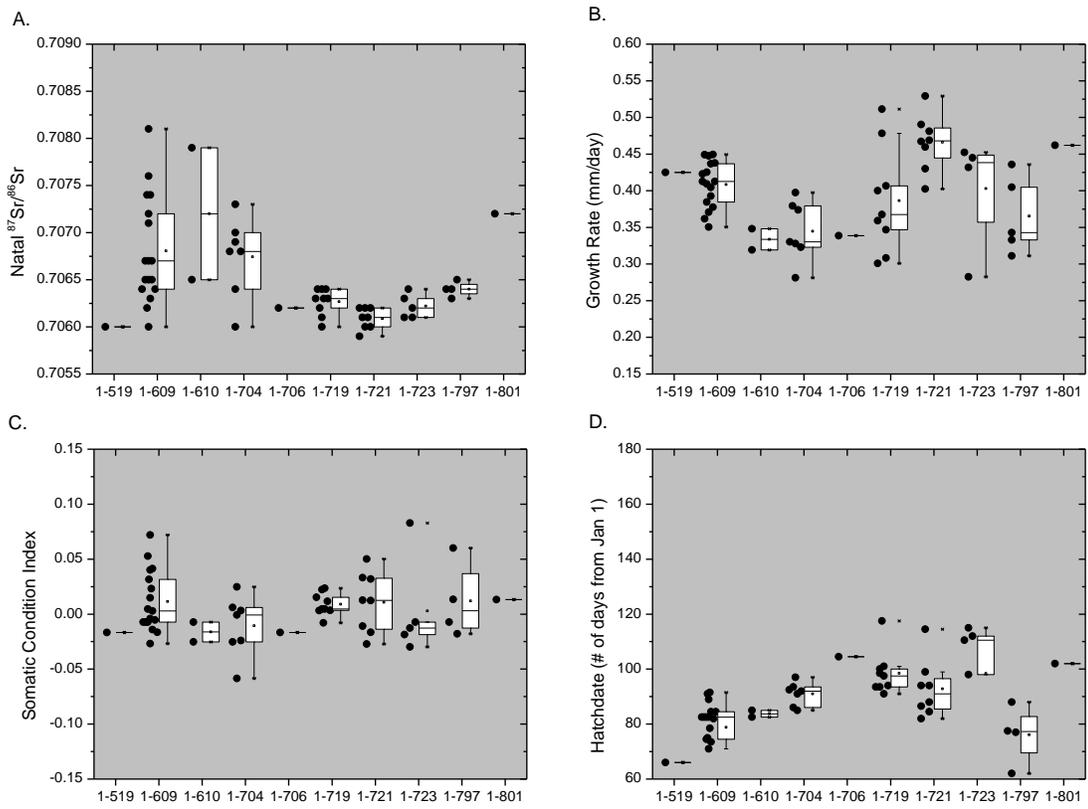
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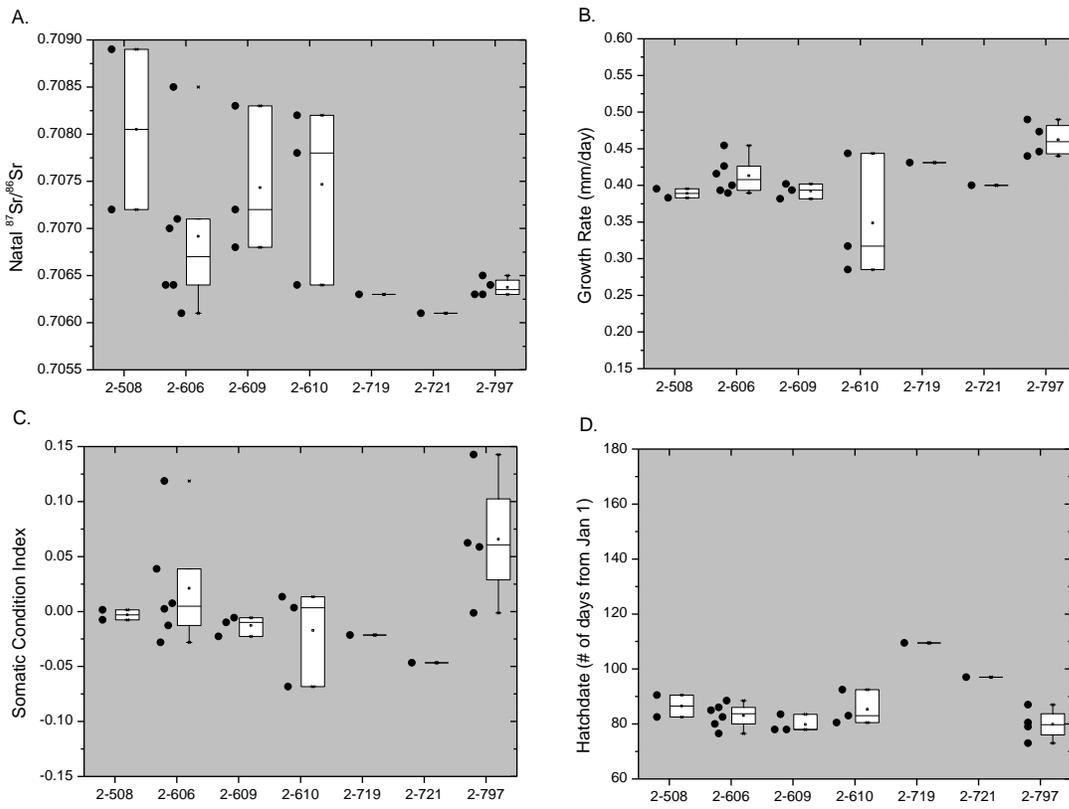


1858

1859 Figure 9. Survey 1 2013, boxplots for each station. Black dots represent values for individual
 1860 fish. A. Strontium isotope ratios of the natal cores, B. Growth rate C. Condition Index D. Hatch-
 1861 date. Stations 721 to 704 were freshwater while stations below 704 were low-salinity habitats.

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1863



1864

1865 Figure 10. Survey 2 2013, boxplots for each station. Black dots represent values for individual
 1866 fish. A. Strontium isotope ratios of the natal cores, B. Growth rate C. Condition Index D. Hatch-
 1867 date. Stations 719, 721 and 797 were freshwater, while 508, 606, 609 and 610 were low-salinity
 1868 habitats.

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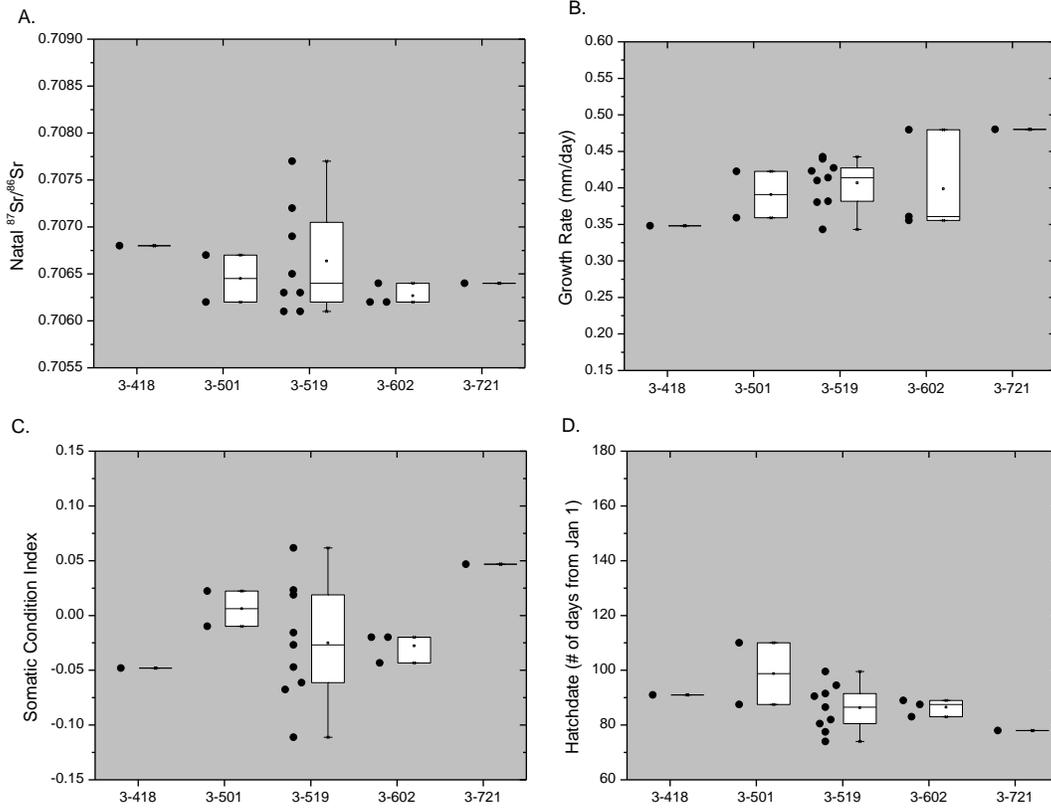
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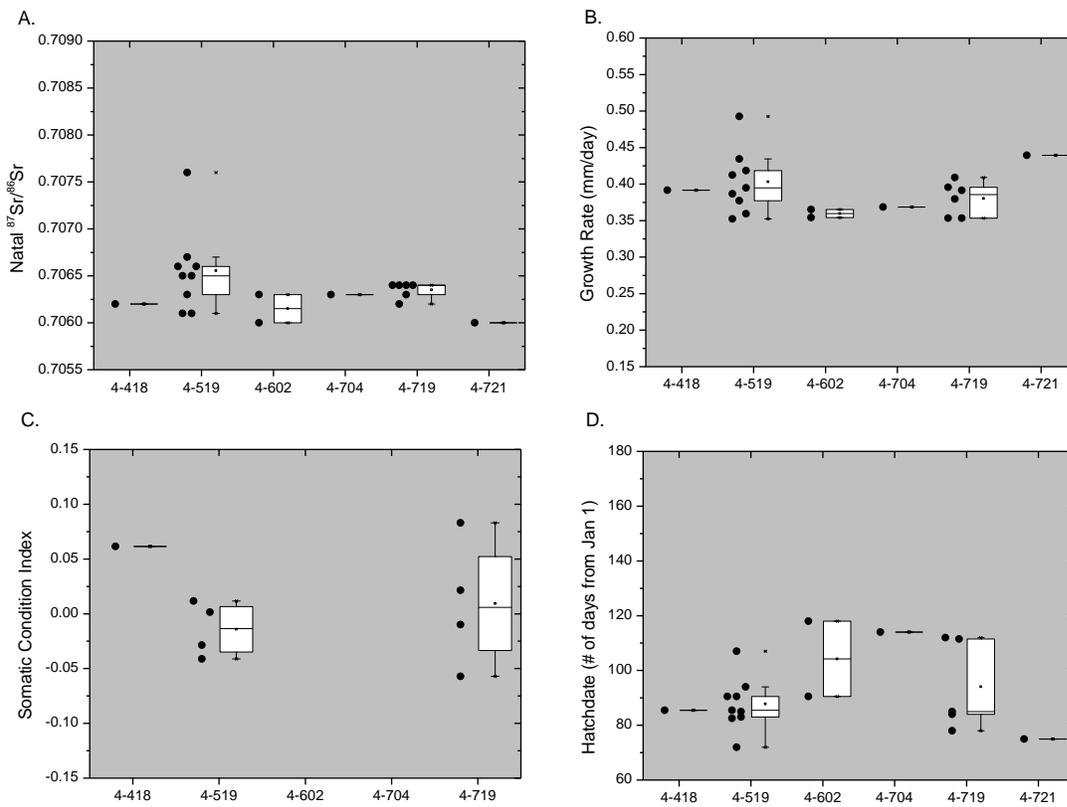
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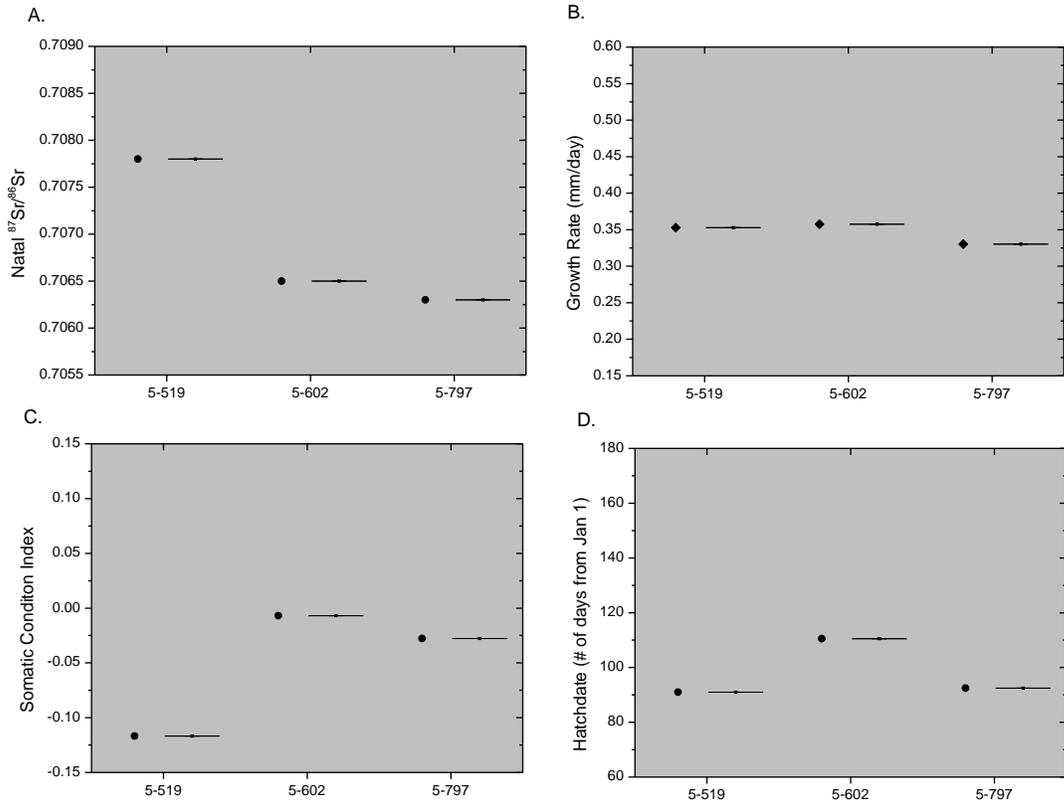


1879 Figure 11. Survey 3 2013, boxplots for each station. Black dots represent values for individual
1880 fish. A. Strontium isotope ratios of the natal cores, B. Growth rate C. Condition Index D. Hatch-
1881 date. Station 721 was freshwater and stations 418, 501, 519 and 602 were low-salinity habitats.



1882

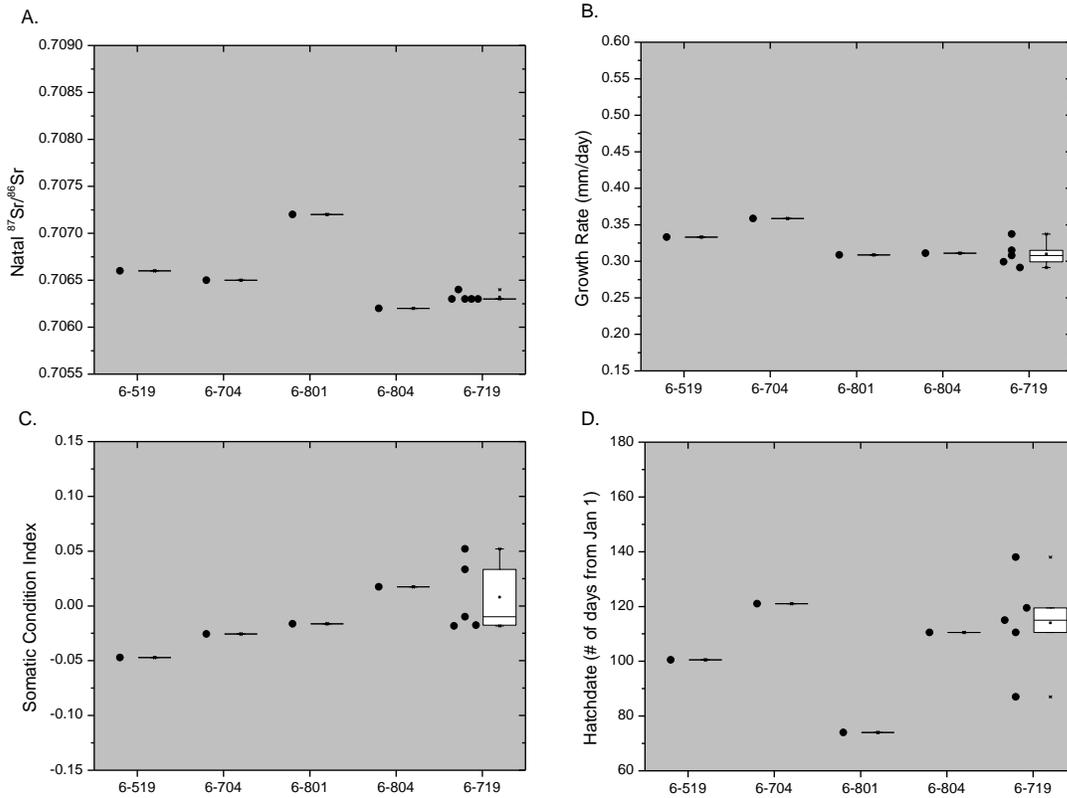
1883 Figure 12. Survey 4 2013, boxplots for each station. Black dots represent values for individual
 1884 fish. A. Strontium isotope ratios of the natal cores, B. Growth rate C. Condition Index D. Hatch-
 1885 date. Stations 704, 719 and 721 were freshwater and stations 418, 519, and 602 were low-salinity
 1886 habitats.



1887

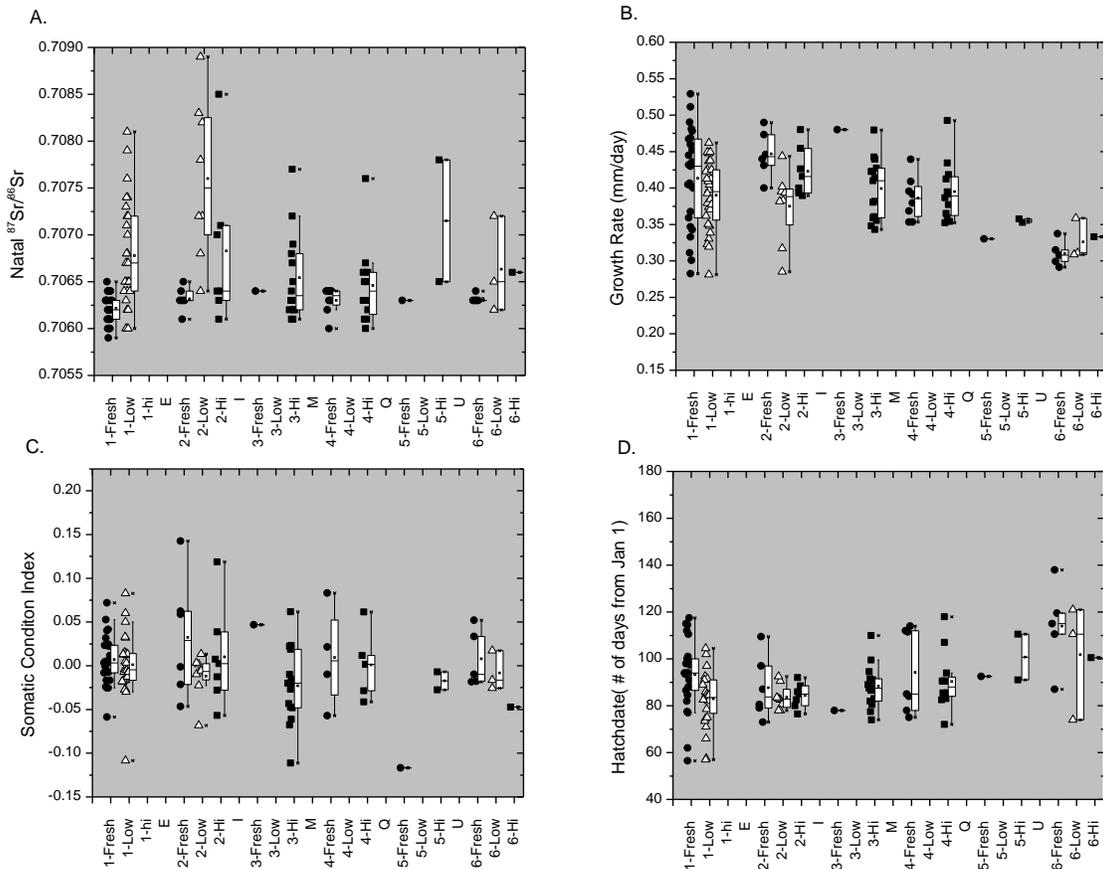
1888 Figure 13. Survey 5 2013 boxplots for each station. Black dots represent values for individual
 1889 fish. A. Strontium isotope ratios of the natal cores, B. Growth rate C. Condition Index D. Hatch-
 1890 date. Note only 3 fish were analyzed from survey 5. Station 797 was freshwater and stations
 1891 519, and 602 were low-salinity habitats.

1892



1893

1894 Figure 14. Survey 6 2013, boxplots for each station. Black dots represent values for individual
 1895 fish. A. Strontium isotope ratios of the natal cores, B. Growth rate C. Condition Index D. Hatch-
 1896 date. Station 719 was freshwater and stations 519, 704, 801 and 804 were low-salinity habitats.



1897

1898 Figure 15. Box plots for surveys 1-6 2013, with freshwater ● solid black circles, low-salinity
 1899 zone (1-6-ppt), open triangles △ and high-salinity zone (>6-ppt) ■ solid black squares
 1900 depicting the salinity habitats where fish were collected. A. Strontium isotope ratios of the natal
 1901 cores, B. Growth rate C. Condition Index D. Hatch-date.

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1909 **Life History Diversity of Delta Smelt from the Otolith**
1910 **Analysis of the Spring Kodiak Trawl (2005-2006 and**
1911 **2010-2011 Year Classes)**

1912 Prepared by:

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1916 Prepared for:

1917 U.S. Department of the Interior/ Bureau of Reclamation Contract Number R13AP0022

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1922

1923 &

1924 The Interagency Ecological Program

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1932

1933 **INTRODUCTION**

1934 In the Fall of 2011, a large scale multidiscipline study was launched by the Interagency
1935 Ecological Program (IEP) to investigate the effects of freshwater outflow on the habitat
1936 conditions and response of Delta Smelt (*Hypomesus transpacificus*) to higher than normal
1937 outflow in 2011(**Brown et al. 2014**). High outflow years provide positive benefits to many
1938 estuarine species, including species of management importance such as the Delta Smelt
1939 (**Sommer et al. 2007; Feyrer et al 2007; Nobriga et al 2008; IEP-MAST 2015**). However; the
1940 ecological mechanisms associated with the effects of overall improved habitat conditions and
1941 Delta Smelt abundance are not well understood. The IEP's Management Analysis and Synthesis
1942 Team (IEP-MAST) recently completed a review of Delta Smelt biology and developed a
1943 conceptual model framework for assessing habitat attributes effects on the Delta Smelt life cycle.
1944 Using the conceptual model framework, hypothesis regarding direct links between habitat
1945 attributes and Delta Smelt responses were examined for a pair of years when low outflow years
1946 where followed by high outflow years (2005, 2010 low outflow and 2006, 2011 high outflow
1947 years) known as the Fall Low-Salinity Habitat Study (FLaSH) (**Brown et al. 2014**). For a
1948 majority of the hypotheses, either poor support was found or data was lacking. However; there
1949 was general support for improved habitat conditions in 2011 resulting in higher survival from the
1950 larvae to juvenile and from juvenile to sub-adult life stages (**IEP-MAST 2015**).

1951 California Department of Fish and Wildlife's Fall Midwater Trawl Survey (FMWT) Delta
1952 Smelt annual abundance index was highest in the wet year of 2011, relative to 2005-2006 and
1953 2010-2011, but did not exhibit a similar increase in the wet year of 2006 (**Brown et al. 2014**).
1954 The abundance of larvae and early juveniles was high in 2005 and 2006, but juvenile and sub-
1955 adult indices were low suggesting mortality was higher in these years compared to 2010 and
1956 2011. Thus, habitat attributes that support high survival through-out the year, and thus all life
1957 stages of Delta Smelt, are important drivers of adult abundance. Identifying the reason(s) for
1958 low abundance in a wet year may give important insights into key habitat attributes and
1959 environmental drivers that could be managed in a way that would improve the likelihood of
1960 abundance increases in all wet years. Moreover, habitat conditions in preceding wet years may
1961 have important implications for the response of a population to the environmental conditions
1962 present during a wet year. For example, the 2010 year-class, which produced the abundant 2011

1963 year class, was one of the lowest adult indices. Understanding the habitat attributes and
1964 environmental drivers during these years may also provide key insights into the dynamics of the
1965 Delta Smelt population. Thus even in low abundance years, the delta smelt may retain the life
1966 history diversity to provide a resilient response during years of ideal habitat attributes.

1967 Delta Smelt geographic range distribution varies seasonally and with life stages in response to
1968 changing abiotic conditions such as salinity, temperature, turbidity and with the onset of maturity
1969 and changing food densities (**Dege and Brown 2004, Bennett 2005, Sommer et al. 2011, Merz**
1970 **et al. 2011**). In late fall and winter, a majority of adult smelt move into fresh water for
1971 spawning, primarily the North Delta near the Cache Slough Complex and the Deepwater Ship
1972 Channel (**Sommer and Meija 2013; Murphy and Hamilton 2013**). However, Delta Smelt
1973 have been consistently found in Montezuma Slough during the spawning season, and thus they
1974 may also spawn in Suisun Marsh (**Murphy and Hamilton 2013**). In spring, young smelt move
1975 into brackish water, primarily in Suisun Bay and Suisun Marsh and through the central and south
1976 Delta towards the Central Valley Project and State Water Project (**Dege and Brown 2004;**
1977 **Nobriga et al. 2008, Feyrer et al. 2007**). This migratory behavior historically allowed them to
1978 avoid unfavorable conditions in the upper Delta during periods of low inflow and high water
1979 temperatures and to feed on abundant zooplankton in the low salinity zone.

1980 Delta Smelt have also been found year-round in fresh water (**Sommer et al. 2011a, Merz et**
1981 **al. 2011, Sommer and Meija 2013**). With the advancement of otolith microchemistry, many
1982 estuarine species have been observed to have both resident freshwater populations and migratory
1983 populations (**Gillanders et al.2015**). This life history strategy has been called “Partial
1984 Anadromy”, and has been hypothesized to occur as a “Bet-Hedging” survival strategy. Having
1985 both resident and migratory phenotypes, a population can persist in a dynamic habitat by
1986 spreading the risk of catastrophic mortality between two environments. (**Chapman et al. 2011**)
1987 In an estuary with a Mediterranean climate, inter-annual variability in precipitation and
1988 freshwater flow to the estuary can be great, thus spreading risk across the freshwater and
1989 brackish habitats would likely afford a species protection from extinction during poor conditions.

1990 The factors that influence an individual to exhibit a resident or migratory phenotype are not
1991 yet understood, but likely occur sometime in the early life stages. The hypothesized mechanisms

1992 can be physical and behavioral. Young fishes living in a flowing environment, like the tidal
1993 reaches of freshwater habitats at the head of an estuary experience complex hydrology. Larval
1994 behaviors, to some extent, would facilitate residency or migration (**Secor 1999**). Other
1995 phenotypic traits, such as body size or growth are also likely to influence behaviors and interact
1996 with the hydrology. For example, a young fish experiencing a poor feeding environment may
1997 have to forage longer distances to find food, which may facilitate transport downstream in an
1998 estuary with a strong residual flow downstream towards brackish water. In this case, slow
1999 growth may be associated with a migratory phenotype. However, migration from freshwater to
2000 brackish water can be energetically costly, and predation mortality along the migratory corridor
2001 may be high, thus migratory phenotypes may select for faster growing young fish. Ultimately,
2002 freshwater flows to the estuary would create habitats of varying quality and would likely interact
2003 with different selection pressures to shape the phenotypic response of the population.

2004 For the purpose of this report, we quantified life history attributes of Delta Smelt year-classes
2005 (2005, 2006, 2010, and 2011) collected by the IEP's Spring Kodiak Trawl Survey (SKT) during
2006 survey years 2006, 2007, 2011, and 2012. This survey was conducted from January through
2007 May and provides data on the distribution and abundance of adult life stages prior to and during
2008 spawning. We chose these year classes for consistency with the IEP-MAST study of Fall Low-
2009 Salinity Habitat (FLaSH) comparing a pair of dry years followed by wet years (2005, 2010 dry
2010 and 2006, 2011 wet).

2011 *Conceptual Model*

2012 Our conceptual model for this study is based on otolith data demonstrating that Delta Smelt
2013 exhibit a life history strategy termed "Partial Anadromy" whereby individuals express different
2014 life-history phenotypes (contingents) based on natal origins and/or migration history (Figure 1).
2015 Delta smelt can exhibit complex movement histories, with fish born in freshwaters (North Delta,
2016 near the Cache-Liberty-Deepwater Ship Channel) and remaining in freshwater through adulthood
2017 (Freshwater Residents), or rearing in low-salinity habitat from hatch through adulthood
2018 (Brackishwater Origin) and individuals migrating from fresh into brackish waters (Migrants).
2019 Individuals expressing different life history phenotypes may be an adaptive strategy providing
2020 population resilience for a species living in a dynamic habitat like the Sacramento-San Joaquin

2021 Delta. Inter-annual variability in freshwater outflow and associated habitat attributes may result
2022 in selection of contingents best suited to the environmental conditions in a given year.
2023 Environmental conditions (e.g. food availability, predation pressure) select for rapid growth of
2024 fishes, particularly during their early life stages (Houde 1987; Sogard 1997; Jonsson et al. 2011).
2025 However, studies have also found the highest predation pressure can occur on the fastest growing
2026 individuals of a cohort, thus selection pressures may dampen growth variability (Gleason and
2027 Bengsten 1996). Environmental conditions in the Delta and Low Salinity Zone (1-6 ppt) may
2028 result in variable growth rates among contingents. Inter-annual variability of environmental
2029 conditions and habitat attributes may result in different contingents comprising the adult
2030 population of Delta Smelt, which may provide key insights into the linkages between habitat
2031 attributes and Delta Smelt life history diversity and abundance. For example, lower outflow
2032 years results in a smaller area of low-salinity habitat (**IEP-MAST 2015**), which may result in
2033 slower growth and fewer migrant phenotypes.

2034 *Hypotheses*

- 2035 1. Contingent composition will not vary among study years.
 - 2036 a. The 2011 year class will have a more diverse composition.
- 2037
- 2038 2. Growth rates will not vary among study years.
 - 2039 a. The 2011 year class will have faster growth rates.
- 2040
- 2041 3. Growth rates will not vary among contingents.
 - 2042 a. Growth rates will be fastest among more abundant contingent.

2043

2044 **METHODS**

2045 *Environmental Data*

2046 Data for freshwater outflow was retrieved from the IEP's DAYFLOW model
2047 (<http://www.water.ca.gov/dayflow/>). Daily freshwater flows (OUTFLOW) in total acre-feet was
2048 used to describe inter-annual differences during study years. Daily water temperature data was

2049 retrieved from CDEC (<http://cdec.water.ca.gov/>) for the Rio Vista station (RIV). Data for the
2050 study years were averaged daily (15-min intervals over 24 hours).

2051 Fish were collected during the spawning season (Jan-May) by the CDFW SKT Survey, thus
2052 study year sample collections represent fish from the previous calendar year year-class of Delta
2053 Smelt. Throughout this report we refer to the SKT surveys 2006, 2007, 2011 and 2012, which
2054 represent the Delta Smelt birth years (year-classes) 2005, 2006, 2010 and 2011 respectively. The
2055 SKT survey uses a 7.6-m wide by 1.8-m depth Kodiak trawl towed between two boats at the
2056 surface for 10-minutes per tow among 39 fixed sampling stations located from the Napa River in
2057 the West to the San Joaquin River in the South and the Sacramento Deep Water Ship Channel to
2058 the North, encompassing the known distribution of adult Delta Smelt (Figure 2). Delta Smelt
2059 were measured for fork-length and a sub-sample archived for gonad staging. In SKT survey
2060 years 2006, 2007 and 2011 each fish was given a unique identification number and archived for
2061 otolith analysis by dissecting the head and placing it into 95% ethanol onboard. In 2012, fish
2062 were frozen in liquid nitrogen and dissected in the laboratory, where fork lengths were measured.
2063 For otolith analysis, a subsample of 200 fish was targeted per study year. Subsamples were
2064 chosen in direct proportion to the catch distribution by stratifying the catch between sample
2065 stations west of the Sacramento-San Joaquin River confluence (station 704) and upstream of this
2066 station. This was done to minimize sample bias towards regions with higher catch.

2067

2068 *Otolith Growth*

2069 Otoliths were dissected from the head and stored dry in ThermoScientific Cell Culture Plates.
2070 Before mounting, the membrane remains surrounding the otoliths were removed by soaking in
2071 95% ethanol for a minimum of 24 hours. Once the membrane was removed, otoliths were
2072 mounted onto microscope glass slides with Crystal Bond® thermoplastic resin in the sagittal
2073 plane. Otoliths were sanded sulcus side up until the outermost rings were visible, turned and
2074 sanded to core rings were visible with wet-dry sandpaper (Buehler 800 and 1200 grit) and
2075 polished with a polishing cloth and 0.3-micron polishing alumina. Otoliths were digitized with a
2076 12 Megapixel digital camera attached to an Olympus CH30 compound microscope at a
2077 magnification of 20X, using AM Scope software (www.amscope.com) Otolith increments were

2078 enumerated and the increment width and radial distance (μm) from the core to each daily ring
2079 was measured using Image-J NIH software (<http://imagej.nih.gov/ij/>).

2080

2081 *Growth Statistical Analyses*

2082

2083 Otolith increment widths (30-day increments) were modelled using a series of mixed effects
2084 regression models following the statistical approach outlined in **Morrongiello and Thresher**
2085 **(2015)** (Table 2). Fixed intrinsic predictors of 30-day increment growth were fish Age, Sex, and
2086 Age-at-Capture. Fixed extrinsic predictors included year class Cohorts, water temperatures and
2087 the life history phenotypes. Adjacent otolith increment measurements within a fish are more
2088 correlated to each other than to those of other fish because of individual-specific differences in
2089 growth rates. The fish sampled are also seen as a random draw of all possible fish in a
2090 population, therefore we included a random intercept for FishID which induces a correlation
2091 among increment measurements within a fish and allows each individual to have an independent
2092 model intercept (i.e. from the model's overall intercept). We included a random intercept for
2093 the Month, for which the 30-day increment occurred, which induces a correlation among
2094 increments from different fish deposited at the same proximate time of year. The Month random
2095 intercepts pool the effects of different extrinsic sources of growth variation after effects on
2096 intrinsic factors (Age, Sex and Age at Capture) are explicitly accounted for. These coefficients
2097 provide temporally resolved estimates of whether conditions were good or poor for growth in a
2098 given year and compared to the long-term average. We also explored whether the addition of
2099 random Age slopes for FishID, Month and FishID improve model performance.

2100

2101 All analyses were performed using the lme4, AICcmodavg, and effects package in R 3.0.2 (R
2102 Development Core Team 2013). 30-day growth increments, Age, and Age at Capture were
2103 natural log-transformed to satisfy linear model assumptions and all predictor variables were
2104 mean-centered to facilitate model convergence and interpretation of interaction terms. Analyses
2105 of random effects were performed by fitting the desired model structure using restricted
2106 maximum likelihood estimates of error (REML). Models with increasing fixed effect
2107 complexity were fitted using maximum likelihood estimates of error. We assessed the relative
2108 support for each candidate set of models using Akaike's information criterion (AIC). AIC values

2109 were rescaled as the difference between each model and the model with lowest AIC. Best
2110 models were then reanalyzed using REML to produce unbiased parameter estimates (**Zuur et al.**
2111 **2009**).

2112

2113 *Otolith Strontium Isotope Ratios*

2114

2115 Otoliths were mounted on petrographic slides (20 per slide) for otolith microchemistry.
2116 Otolith strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$ were quantified using methods previously developed
2117 (**Hobbs et al. 2005; 2010**). Otolith strontium isotope ratios ($^{87}\text{Sr}:^{86}\text{Sr}$) were measured at the UC
2118 Davis Interdisciplinary Center for Plasma Mass Spectrometry (<http://icpms.ucdavis.edu>). A
2119 multi-collector inductively coupled plasma mass spectrometer (*Nu Plasma HR* from Nu
2120 Instrument Inc.) was interfaced with a Nd:YAG 213 nm laser (New Wave Research UP213) for
2121 strontium isotope measurement by laser ablation (LA-MC-ICP-MS technique). A laser beam of
2122 40- μm diameter traversed across the otolith from the core to the edge at 10- μm per second, with
2123 the laser pulsing at 10-Hz frequency and 5-10 J/cm^2 photon output. Helium was used as the
2124 carrier gas to maximize sensitivity and minimize sample deposition at the ablation site, and was
2125 mixed with Argon gas between the laser sample cell and the plasma source. Gas blank and
2126 background signals were monitored until ^{84}Kr and ^{86}Kr stabilized after the sample change (i.e.
2127 exposing sample cell to the air) and were measured for 30 seconds. The laser was typically fired
2128 for 90-120 seconds and background signals were subtracted from the measured signals
2129 automatically. Strontium isotope ratios ($^{87}\text{Sr}:^{86}\text{Sr}$) were internally normalized by the measured
2130 $^{86}\text{Sr}:^{88}\text{Sr}$ ratio relative to assumed ratio of 0.1194, which proportionally corrects for mass
2131 discrimination. The signal on mass 85 was monitored to correct for any ^{87}Rb interference on ^{87}Sr .
2132 The analytical accuracy was determined by using the results of replicate analyses of an aragonite
2133 coral standard at the beginning and end of several analytical sessions. Replicate analyses yielded
2134 $^{87}\text{Sr}:^{86}\text{Sr} = 0.70918 \pm 0.0001$ ($n = 87$), consistent with modern seawater values of 0.70918. In
2135 addition accuracy was assessed by examining cultured Delta Smelt otoliths reared at the Fish
2136 Conservation and Culture Laboratory located at the Skinner Fish Facility in Byron California.
2137 Replicate analyses yielded $^{87}\text{Sr}:^{86}\text{Sr} = 0.70728 \pm 0.0001$ ($n = 87$), consistent with known value of
2138 0.70725. Data reduction was conducted off-line using Matlab 9.0 software. The strontium
2139 isotope profile from the core to the edge along the transect path used for otolith increment

2140 measurement was scanned using a laser beam of 40-microns moving at a speed of 10-microns
2141 per second. Laser profiles began at ~100-micron before the core to ensure the analysis
2142 encompasses the entire natal chemistry. Life history contingent membership was based on the
2143 strontium isotope ratio profile from the core to the edge of the otolith. Life history profiles were
2144 compared to the strontium isotope isoscape to distinguish freshwater residence from the
2145 migratory and brackish origin phenotypes. Analytical resolution of the laser ablation MC-
2146 ICPMS using laboratory standards was used to determine the certainty of contingent membership
2147 assignment.

2148

2149 *The Strontium Isotope Isoscape*

2150

2151 Water samples were collected at each SKT station in 2012 using an acid rinsed polypropylene
2152 syringe from a bucket of water collected at the surface of the water column. Water was filtered
2153 through a 0.45 µm syringe filter and the sample was acidified (1mL of 3% nitric acid) to stop
2154 bacterial growth. At the UC Davis ICPMS lab, water samples were initially screened for
2155 alkaline earth metals (such as strontium) and analytical interferences (such as rubidium) on an
2156 Agilent 7500ce (Agilent Technologies, Inc.) Q-ICP-MS (quadrupole inductively coupled plasma
2157 mass spectrometer.) After elemental screening, the samples were transported to a class 100 (less
2158 than 100 particles per cubic foot of air) clean room facility. Within this environment, an aliquot
2159 of each water sample was made at volume totaling approximately 1 nanogram of total strontium.
2160 This volume (ranging 3 – 70 mL) was evaporated to dryness and reconstituted in sub-boiling
2161 double-distilled nitric acid (8M) for Sr chromatographic separation. Strontium was isolated from
2162 all other water constituents by rinsing water samples through a micro-column packed with Sr
2163 spec resin (Eichrom Inc.) The purified strontium was subsequently oxidized with concentrated
2164 sub-boiling double-distilled nitric acid to remove organics from column and dried to a powder.
2165 This powder was reconstituted in 2% sub-boiling double-distilled nitric acid and analyzed with
2166 the Nu Plasma HR (MC-ICP-MS) to determine the $^{87}\text{Sr}:^{86}\text{Sr}$ ratio.

2167

2168 Samples were introduced into the Nu Plasma with a desolvating nebulizer system (DSN-100)
2169 providing an order of magnitude sensitivity increase by evaporating most of the sample matrix
2170 (water vapor) away. Ratios include 50-60 data points and each data point was integrated for 10

2171 seconds. Baselines were measured for 30 seconds by ESA deflection (ion beams were defocused
2172 away from detectors). Strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) were internally normalized as
2173 described with the LA-MC-ICP-MS technique with the exception of the Krypton correction on
2174 ^{86}Sr . In this case, $^{84}\text{Sr}:^{86}\text{Sr}$ was assumed to be .00675476 (natural abundance of these isotopes)
2175 and is used to estimate subtraction of $^{84}\text{Krypton}$ and $^{86}\text{Krypton}$. Kr was subtracted until the
2176 $^{84}\text{Sr}/^{86}\text{Sr}$ ratio equals the canonical value of .00675476 (while iterating the mass-bias correction.)
2177 Replicate analyses of NIST SRM 987 (strontium carbonate) were conducted bracketing every six
2178 samples normalizing for instrument drift over the course of the day and analytical artifact
2179 between sessions. An in-house modern coral std was processed in parallel with each water
2180 sample set and resulted in $^{87}\text{Sr}:^{86}\text{Sr}$ (n=8) = 0.709182 +/- 0.000017 (2SD).

2181
2182 Water quality was also collected using a YSI 6600. Water quality parameters included
2183 salinity (psu), electrical conductivity (μs), and temperature $^{\circ}\text{C}$. To describe the relationship
2184 between strontium isotope ratios and salinity, we fit a smoothing spline to data. In addition, a
2185 conservative linear mixing model using three freshwater endmembers (North Delta- Cache-
2186 Lindsey Slough Complex $^{87}\text{Sr}:^{86}\text{Sr}$ = 0.70642, Sacramento River upstream of confluence with
2187 the North Delta $^{87}\text{Sr}:^{86}\text{Sr}$ = 0.70583 and along the San Joaquin River near Jersey Point $^{87}\text{Sr}:^{86}\text{Sr}$
2188 = 0.70721) was used with the $^{87}\text{Sr}:^{86}\text{Sr}$ = global ocean value of 070918.

2189
2190 *Life History Phenotype-Contingent Composition*

2191
2192 Contingent composition was determined for each region sub-sampled. The proportion of each
2193 life history contingent comprising the sub-sample was expanded to the total catch of Delta Smelt
2194 in each region. The total composition of each contingent was summed across regions.

2195 *year class*

2196

2197 **RESULTS**

2198 *The strontium isotope iso-scape*

2199 The strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$ varied predictably across the freshwater – Low-Salinity
2200 Zone region of the estuary. Water samples collected in 2012 exhibited a similar $^{87}\text{Sr}:^{86}\text{Sr}$ -

2201 salinity trend to previous years and fit well with the mixing model results (Figure 3). Strontium
2202 isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$ in freshwaters never exceeded 0.7072 and $^{87}\text{Sr}:^{86}\text{Sr}$ of low-salinity (<0.5
2203 psu) was never below 0.7072. However, salinity values between 0.3 and 0.6 psu with the sole
2204 freshwater source endmember of the North Delta values had similar values to San Joaquin River
2205 $^{87}\text{Sr}:^{86}\text{Sr}$ 0.7072 (not shown). Thus we used the $^{87}\text{Sr}:^{86}\text{Sr} = 0.7080$ as a conservative value
2206 delineating the freshwater region and the low-salinity zone. A fish with a $^{87}\text{Sr}:^{86}\text{Sr}$ profile >
2207 0.7080 would indicate at least some rearing in low-salinity habitat.

2208 We examined otoliths for a total of 733 fish collected in the FLaSH study years during the
2209 Spring Kodiak Trawl Survey. We identified three major life history types, including fish that
2210 were born and reared for the entire life in freshwater “Freshwater Residents”- FWR, fish born
2211 and reared for the majority of life in low-salinity habitat “Brackish-Origin”-BO, and fish that
2212 were born in freshwater and had migrated to the low-salinity zone at some point before capture
2213 “Migrants”- MIG (Figure 4). We also observed significant variability with regards to the time of
2214 migration among the migratory type. However for this study we focus only on the major life
2215 history phenotypes “contingents”.

2216 The percentage of life history contingents varied among regions of the estuary and between
2217 years of the study. All fish collected in the low-salinity zone region were either brackish origin
2218 fish or migratory phenotypes (Table 1). No freshwater resident fish were found in the low-
2219 salinity zone, but brackish origin fish were found in freshwater, presumably migrating upstream
2220 to spawn. In each year, a majority of the catch occurred in freshwater (61-70%). We attempted
2221 to sub-sample fish from the catch distribution to provide a representative and robust estimate of
2222 the percentage of contingents (Appendix A). In three of the four study years we were able to
2223 accomplish this; however, for the SKT 2011 our sub-sample was significantly skewed towards
2224 freshwater catches due to biased sample archival (Table 1). In that year samples were archived
2225 by CDFW staff, thus we could not adequately match the catch distribution (Table 1). Therefore
2226 we provide both a percentage of each contingent based on our sub-sample (Sub-sample %) and
2227 by expanding the percentages to total catch (Expanded %) and did not attempt a statistical test on
2228 these data.

2229 The migratory contingent made up the majority of the Delta Smelt catch in each study year
2230 (61% - 93%- sub-sample; 68% - 92% expanded) Table 1, Figure 5. The freshwater contingent

2231 was found in all study years, but was highly variable between years, making up only 1% of the
2232 catch for SKT 2007 and 46%- sub-sample and 32% expanded for SKT 2011 (Table 1). The
2233 Brackish Water contingent was only observed in SKT 2007 and made up 18% of the catch in that
2234 year (Table 1). The composition of contingents did vary over the study years, but we did not
2235 observe higher diversity during the wetter years as hypothesized (H1) SKT 2007 and SKT 2012
2236 (2006 and 2011 year classes) (*See outflow in Appendix B*). The composition among wet years
2237 was different, with the 2006 year class comprised of a significant percentage of brackish origin
2238 fish (Figure 5).

2239 Freshwater residents comprised a larger percentage of the catch for SKT 2011 and SKT 2012
2240 (20-32%) compared to SKT 2006 and SKT 2007 (1-8%) (Table 1). Seasonal mean water
2241 temperatures at Rio Vista were cooler in 2010 and 2011 compared to 2005 and 2006 (Figure 6)
2242 and a significant correlation between the percentage of freshwater residents and cool spring
2243 temperatures was found (Figure 7).

2244 *Growth*

2245 The hierarchical structure of the mixed effect model allows us to partition growth variance
2246 among intrinsic and extrinsic sources of growth variation. Intrinsic growth factors included the
2247 Age, Sex and the Age-at-Capture. While intrinsic factors are important explanatory variables in
2248 partitioning variance, they can obfuscate growth comparisons of other factors such and
2249 environmental variability. A random intercept for each fish (FishID) allows for and quantifies
2250 the magnitude of individual-specific deviations from average growth, but still assumes that age-
2251 dependent growth responds similarly across all individuals. Including Age as a random slope for
2252 each fish (FishID) is equivalent to the time-series based dendrochronological method of
2253 detrending each individual's increments to remove age-related trends prior to further analysis.
2254 However, in our model this information is retained for further interpretation.

2255 First we fit all possible random effects and interactions and used AICc to determine the best
2256 fitting random effects structure. The random effects model (M2d:Appendix D), including a
2257 random slope and intercept for Age and FishID and random slope and intercept for Age and
2258 calendar month of increment formation had the best fit to the data and the additional variance
2259 explained in the full fixed + random effects model was 21.4% (Table 3). Next we fit additional

2260 models of complexity for the fixed effects, Year class, Age-at-Capture, Life History Phenotype
2261 and Sex. The best fitting model (M2d2) a Year class and Age-at-capture effect (Table 4). To
2262 evaluate temperature effects, we compared the best fit model with a model with temperature
2263 exchanged for the Year class effect; accounting for inter-annual variability in mean temperature.
2264 This model did further explain variance in growth (Table 45). The fixed effects component of the
2265 mixed effects model accounted for 63% of the variance in otolith increment growth ($R^2_{LMM(m)}$)
2266 and the fixed plus random effects explained 85% of the variance in otolith increment growth
2267 ($R^2_{LMM(c)}$) (Table 5).

2268 Incremental growth was influenced by the Age (Figure 8) and calendar month of increment
2269 formation (Figure 9). Age and calendar month of increment formation were correlated and
2270 explained the majority (93%) of the variance for random effects (Table 5). Age-at-capture had
2271 the strongest effect on increment growth, while Age and Year class had significant effects with a
2272 strong Age:Year class interaction term (Table 5). This interaction effect is the result of elevated
2273 otolith increment growth for the 2011 Year class, when fish were born later and thus younger
2274 relative to the calendar month of growth. However, since we accounted for the random effects of
2275 Age and Month of increment formation, growth of the 2011 Year class was higher than other
2276 year classes examined (Figure 9).

2277 **DISCUSSION**

2278 In this study, the contingent population structure varied, but was not related to freshwater
2279 outflow as hypothesized (wet years 2006 and 2011), rather the proportion of freshwater resident
2280 fish appeared to be associated with lower summer water temperatures at Rio Vista. Summer
2281 water temperatures may be a driver of spatial distribution for Delta Smelt and temperatures in
2282 freshwaters may limit their use of this habitat. Long-term changes in summer time distributions
2283 have been observed for Delta Smelt, where they no longer reside in the Central or South Delta
2284 during summer months when water temperatures exceeded $\sim 22^\circ\text{C}$ (Nobriga et al. 2008). In
2285 2005 and 2006 daily mean water temperatures at Rio Vista exceeded 22°C during the summer
2286 and we found fewer freshwater resident fish in these years. In addition, survival of Delta Smelt
2287 from Spring-Summer (20-mm Survey-Summer Towner Survey), when Delta Smelt are migrating
2288 from freshwater larval nursery areas to the Low-Salinity Zone, was lower in 2005 and 2006

2289 compared to 2010 and 2011 (**IEP-MAST 2015**), thus warm temperatures in freshwater may be a
2290 driver of Delta Smelt recruitment success.

2291 The abundance of the freshwater contingent did not appear to coincide with higher adult
2292 abundance index for Delta Smelt. The contribution of the freshwater contingent was similar
2293 between 2010 and 2011, however only the 2011 year class experienced much greater abundance
2294 (Appendix C). Interestingly, the total catch in the Spring Kodiak Trawl did not fluctuate from
2295 year to year as great as the abundance index (Appendix A). The index is calculated using only a
2296 core set of 39 stations, with stations 719 and 799 not included in the abundance index. In the
2297 four years of FLaSH study, these non-index stations made up a majority of the total catch of
2298 Delta Smelt (SKT 2006-61%, SKT 2007-54%, SKT 2011-55% and SKT 2012-25%) (Appendix
2299 A). We found the fish caught at these stations to be comprised of a large number of freshwater
2300 resident fish (35% of the sub-sampled catch from these stations). In other IEP surveys additional
2301 stations in the Sacramento Deep-Water Ship Channel have been added, and Delta Smelt have
2302 been caught as far up as Washington Lake at the turning basin of the Sacramento Deepwater
2303 Ship Channel. The long-term trend in the spatial distribution from IEP surveys has shifted from
2304 the Central and South Delta to the North Delta, thus a significant proportion of the population
2305 may now occur outside of core index stations. While the Spring Kodiak Trawl Survey index
2306 may continue to represent the long-term trend in relative abundance using only core stations, this
2307 may significantly hamper our ability to fully understand the drivers of Delta Smelt abundance.

2308 The majority of the Delta Smelt examined in this study were found to have migrated from
2309 freshwater habitats to the Low-Salinity Zone, suggesting this life history strategy continues to be
2310 the dominant behavior. In 2006, we found a large number of fish that appear to have been born
2311 in low-salinity habitats (Figure 5). These fish may have been born in freshwater and were
2312 transported to the Low-Salinity Zone rapidly post-hatch, or maternal contribution of Low-
2313 Salinity Zone strontium to the offspring may be obfuscating our natal origin identifications.
2314 While we cannot rule out the latter, it is unlikely this is the case, as Delta Smelt have a very
2315 small volume of yolk to derive maternal contributions and the otolith core at hatch is very small.
2316 Recent laboratory rearing experiments have confirmed that Delta Smelt can successfully hatch
2317 and rear in low-salinity, thus it is likely this is a viable life history strategy. However, the spatial
2318 distribution of ripe female (Stage 4) Delta Smelt from the Spring Kodiak Trawl Survey shows a

2319 large proportion of these fish residing downstream of the confluence in low-salinity water. It is
2320 possible these fish can make relatively rapid upstream movements to freshwater to spawn
2321 (Bennett et al 2014). If they do readily spawn in low-salinity habitats, the limited numbers of
2322 fish with low-salinity natal origins might suggest this is not a very successful strategy, and may
2323 be a significant loss to the population. Indeed, at times, roughly half the ripe females are found
2324 in the Low-Salinity Zone. Interestingly, we did observe brackish water origin fish in freshwater,
2325 thus they too migrate back into freshwater to spawn. We did observe any freshwater resident
2326 fish captured in low-salinity waters, thus the strontium isotope signatures appears to be a robust
2327 indicator of salinity history.

2328 Growth rates did not respond as predicted to higher freshwater outflow. Growth rates did
2329 vary between year classes, with the 2011 year class exhibiting higher growth rates, particularly
2330 during the fall, but growth was slower for the 2006 year class. The elevated growth rates in 2010
2331 and 2011 corresponded with lower water temperatures, however; substituting temperature effects
2332 for year class did not improve model fit. Regardless, this evidence suggests Delta Smelt benefit
2333 from cooler water temperatures, particularly during the summer months when temperatures peak.
2334 Laboratory studies have recently shown that Delta Smelt are particularly sensitive to warm water
2335 temperature, expressing a molecular stress response 4-6°C below the thermal maximal
2336 temperature, ~20-22°C (Komoroske et al 2015). Bennett (2005), found that Delta Smelt
2337 spawning and successful hatching was strongly cued to temperature and found poor survival for
2338 larvae above 20°C, thus the biological response of Delta Smelt to warm water temperatures is
2339 strong. Elevated growth rates also appeared to be associated with lower temperatures seasonally.
2340 Growth rates were fastest during the spring months in all years (March-May) (Figure 9). Growth
2341 is typically fast in the early life stages of fish, however we accounted for the ontogenetic effect
2342 of Age and thus life stage in our growth models, thus faster growth in spring was likely
2343 associated with cool water temperature.

2344 Climate change predictions for the Sacramento-San Joaquin Delta suggest the Delta Smelt will
2345 reach a significant level of thermal stress, restriction of reproductive timing and habitat loss by
2346 2020 (Brown et al. 2013). The recent drought (2012-2015) has likely reduced this time frame,
2347 and it is likely that Delta Smelt are currently exhibiting these responses to warm water
2348 temperatures. Air and water temperatures have increased significantly in the last two years and

2349 Delta Smelt abundance has hit all-time lows. The hatch-date distributions and growth rates have
2350 also shifted nearly a full month earlier than historic average and growth rates of young fish have
2351 declined (Hobbs unpublished data). Data from this study suggests, the significant increase in
2352 abundance for the 2011 year class was likely the result of both increased freshwater flows to the
2353 estuary and cool temperatures in 2010 and 2011. A large body of evidence now exists
2354 supporting the role of temperature in modulating the abundance of Delta Smelt, and likely other
2355 native fishes in the San Francisco Estuary. Climate predictions for the estuary do not portend an
2356 optimistic future for the Delta Smelt. Moreover, ongoing efforts to restore tidal marsh habitats in
2357 the Delta are likely to increase temperatures further, as the flooding of shallow polders will only
2358 increase water temperatures during the summer months. In light of the affects, we recommend
2359 the creation of a thermal management plan for the Delta. Integrating thermal refuge into the
2360 efforts to restore tidal marsh habitat may be one effective means to reduce water temperatures.

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2376 Table 1. Delta Smelt catch, sub-samples analyzed for strontium isotope ratios $^{87}\text{Sr}:^{86}\text{Sr}$, and the
 2377 percentage of life history contingents among regions for the sub-sample and expanded to total
 2378 catch. FWR= Freshwater Resident fish, MIG= Migratory fish and B) = Brackish Origin fish.
 2379 Spring Kodiak Trawl (SKT) begins in January and thus the study year represent the previous
 2380 year class of fish (e.g. SKT 2006 is the 2005 year class)

Station	SKT 2006					SKT 2007				
	Catch	Sub-Sample	FWR	MIG	BO	Catch	Sub-Sample	FWR	MIG	BO
Low-salinity Zone	170 (30%)	76 (41%)	0%	100%	0%	211 (30%)	47 (32%)	0%	66%	34%
Freshwater	405 (70%)	108 (59%)	12%	88%	0%	495 (70%)	102 (68%)	1%	89%	12%
		Sub-sample %	7%	93%	0%		Sub-sample %	1%	81%	18%
		Expanded %	8%	92%	0%		Expanded %	1%	81%	18%
Station	SKT 2011					SKT 2012				
	Catch	Sub-Sample	FWR	MIG	BO	Catch	Sub-Sample	FWR	MIG	BO
Low-salinity Zone	141 (32%)	18 (9%)	0%	100%	0%	466 (39%)	81 (40%)	0%	100%	0%
Freshwater	304 (68%)	182 (91%)	47%	53%	0%	740 (61%)	119 (60%)	32%	68%	0%
		Sub-sample %	46%	61%	0%		Sub-sample %	19%	81%	0%
		Expanded %	32%	68%	0%		Expanded %	20%	80%	0%

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2395 Table 2. Description of model parameters

Parameter	Code	Description
Fixed Effects		
Age	Age	Age (months) when otolith increment was formed
Sex	Sex	Male or Female
Age-at-capture	agecap	Age (months) at the time of capture. Measure of potential selectivity on growth.
Cohort	fCohort	Yearclass (birthyear)
Temperature	Temp	Mean temperatures from 15-min water temperatures (°C) at Rio Vista CDEC station
Life History Phenotype	fLHS	Freshwater resident or migratory (reared in low-salinity habitat) types from otolith 87Sr:86Sr
Random Effects		
FishID	fishid	Unique fish identification for each fish
Month	fMonth	Month when otolith increment was formed. Quantifies seasonal growth variability
Age	Age	Random Age slope on each FishID, Month, Life History Phenotype

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2413 Table 3. Random effects model selection

	df	Δ_AICc	Res.LL	$R^2_{LMM(m)}$	$R^2_{LMM(c)}$
M2d	17	0	39.03	0.635	0.850
M4i	18	2.02	39.03	0.635	0.850
M4h	18	474.71	-197.32	0.513	0.762
M2c	15	500.78	-213.39	0.524	0.770
M4g	16	501.65	-212.81	0.522	0.771
M4c	16	501.65	-212.81	0.522	0.771
M4f	18	1240.62	-580.28	0.050	0.963
M4e	18	1240.62	-580.28	0.050	0.963
M2b	15	1256.14	-591.07	0.039	0.963
M4d	16	1257.73	-590.85	0.038	0.962
M4b	16	1771.53	-847.75	0.163	0.988
M4a	14	1802.08	-865.05	0.159	0.989
M3d	17	2924.12	-1423	0.161	0.162
M3c	15	2920.07	-1423	0.161	0.162
M3b	15	2926.99	-1426.5	0.178	0.178
M3a	13	2922.95	-1426.5	0.178	0.178
2414 M2a	13	1813.44	-871.74	0.157	0.988

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2429 Table 4. Full Model (Intrinsic, extrinsic fixed factors) + random effects

Model	Fixed Effects	df	Δ_AICc	Res.LL	$R^2_{LMM(m)}$	$R^2_{LMM(c)}$
M2d2	Age * Cohort + Age-at-capture	16	0	42.36	0.633	0.849
M2d4	Age * Cohort + Lifehistory Phenotype	17	8.38	39.18	0.643	0.841
M2d0	Age * Cohort + Sex+ Age-at-capture	17	8.69	39.03	0.721	0.801
M2d3	Age + Cohort + Age-at-capture	13	46.58	16.04	0.541	0.705
M2d7	Age + Lifehistory Phenotype + Age-at-capture	11	47	13.81	0.512	0.652
M2d6	Age * Lifehistory Phenotype + Age-at-capture	12	48.32	14.16	0.485	0.521
M2d5	Age + Cohort + Lifehistory Phenotype	14	55.32	12.68	0.452	0.513
M2d1	Age + Cohort + sex +Age-at-capture	14	55.34	12.67	0.444	0.456
M2d2a	Age * Cohort + Age-at-capture	16	0	42.36	0.633	0.849
M2d2b	Age * Temperature + Age-at-capture	16	58.5	9.07	0.562	0.729

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2448 Table 5. Parameter estimates and test statistics for random and fixed effects from best fitting
2449 model

Random effects:

Groups		Variance	Std.Dev.	Correlation
Intercept	FishID	0.001	0.038	
Slope	Age	0.108	0.329	0.74
Intercept	Month	0.054	0.232	
Slope	Age	0.925	0.962	0.99
Residual		0.039	0.197	

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Fixed Effects:

	Estimate	Std.Error	t-value
(Intercept)	4.953	0.072	69.04
Age	-0.865	0.295	-2.94
Cohort 2006	-0.011	0.014	-0.79
Cohort 2010	0.001	0.015	0.1
Cohort 2011	0.047	0.014	3.46
Age-at-capture	-0.651	0.066	-9.88
Age:Cohort 2006	0.085	0.054	1.57
Age:Cohort 2010	0.329	0.057	5.75
Age:Cohort 2011	0.325	0.052	6.18

ANOVA	Df	SS	MS	F-value
Age	1	0.198	0.198	5.13
Cohort	3	0.450	0.150	3.88
Age-at-capture	1	4.284	4.284	110.82
Age:Cohort	3	2.664	0.888	22.97

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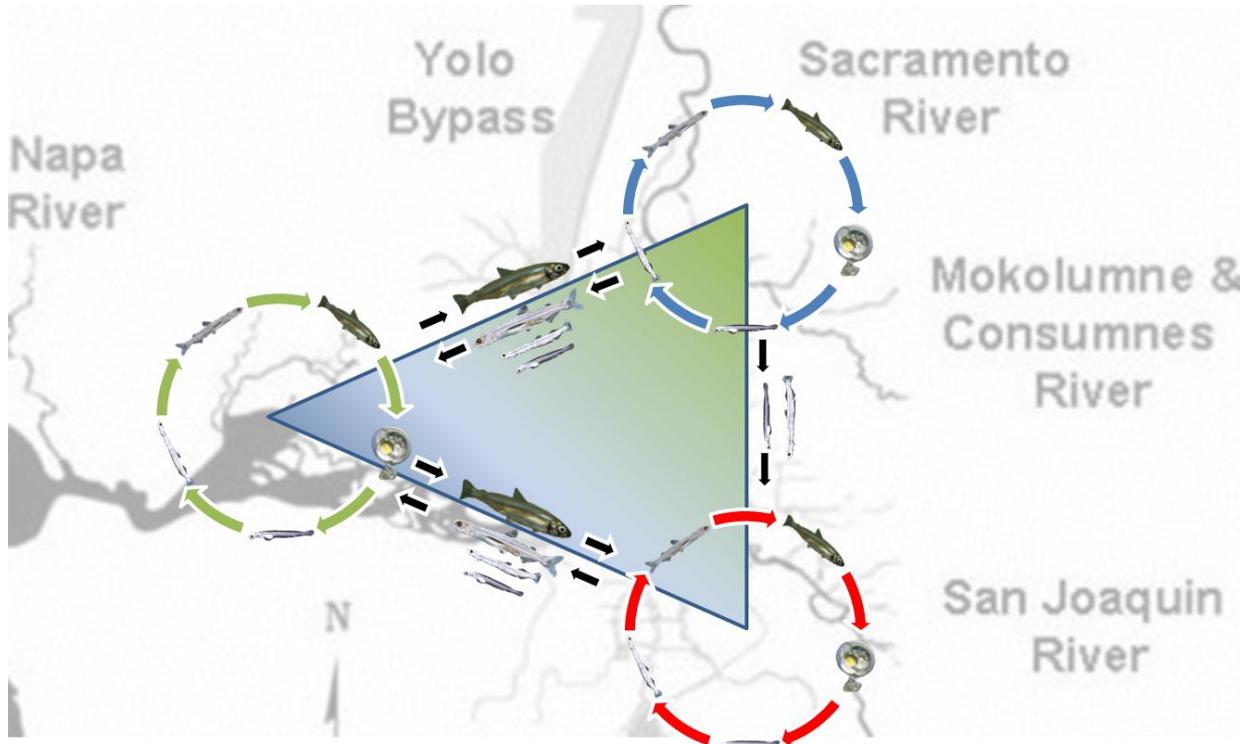
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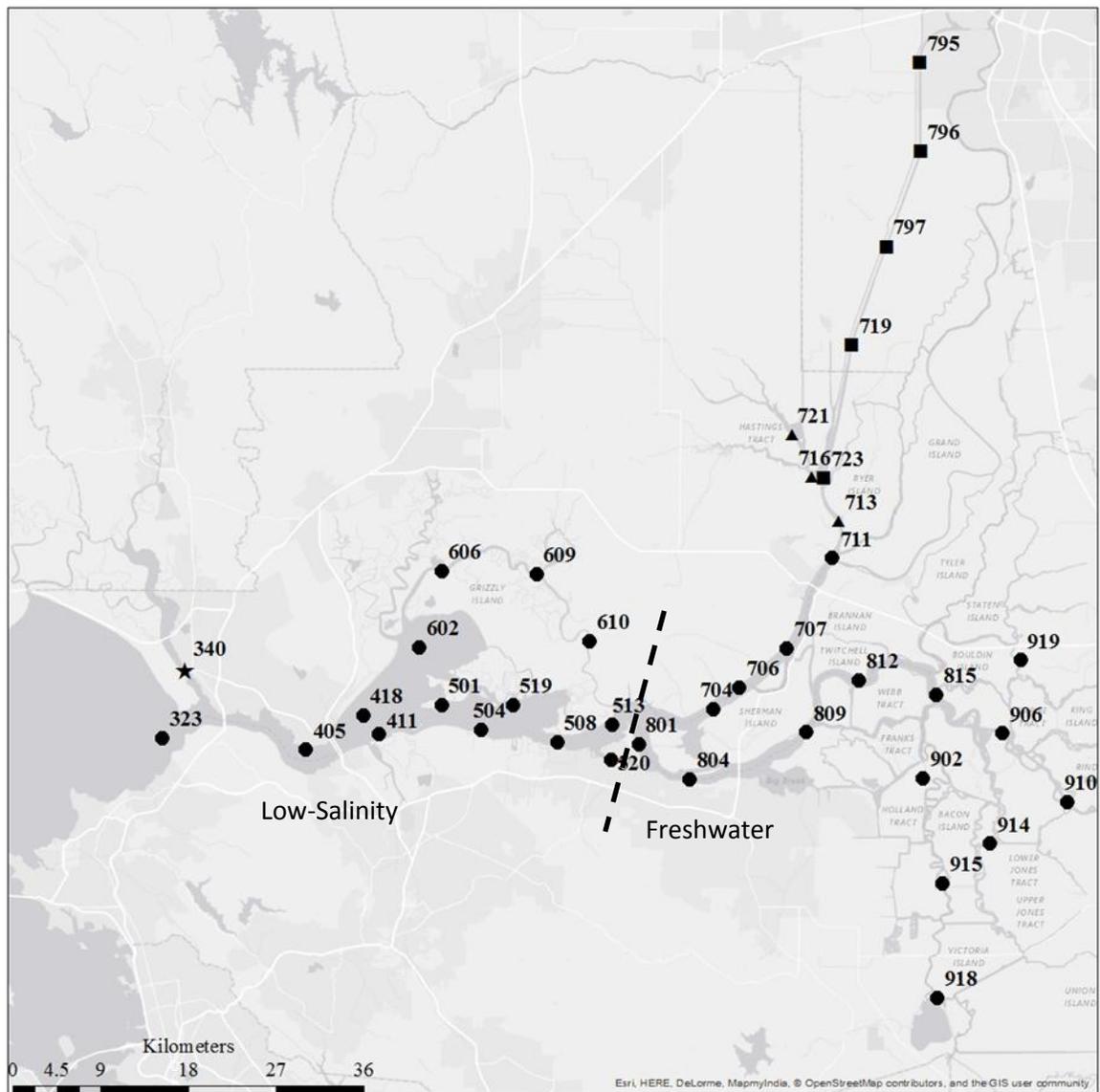
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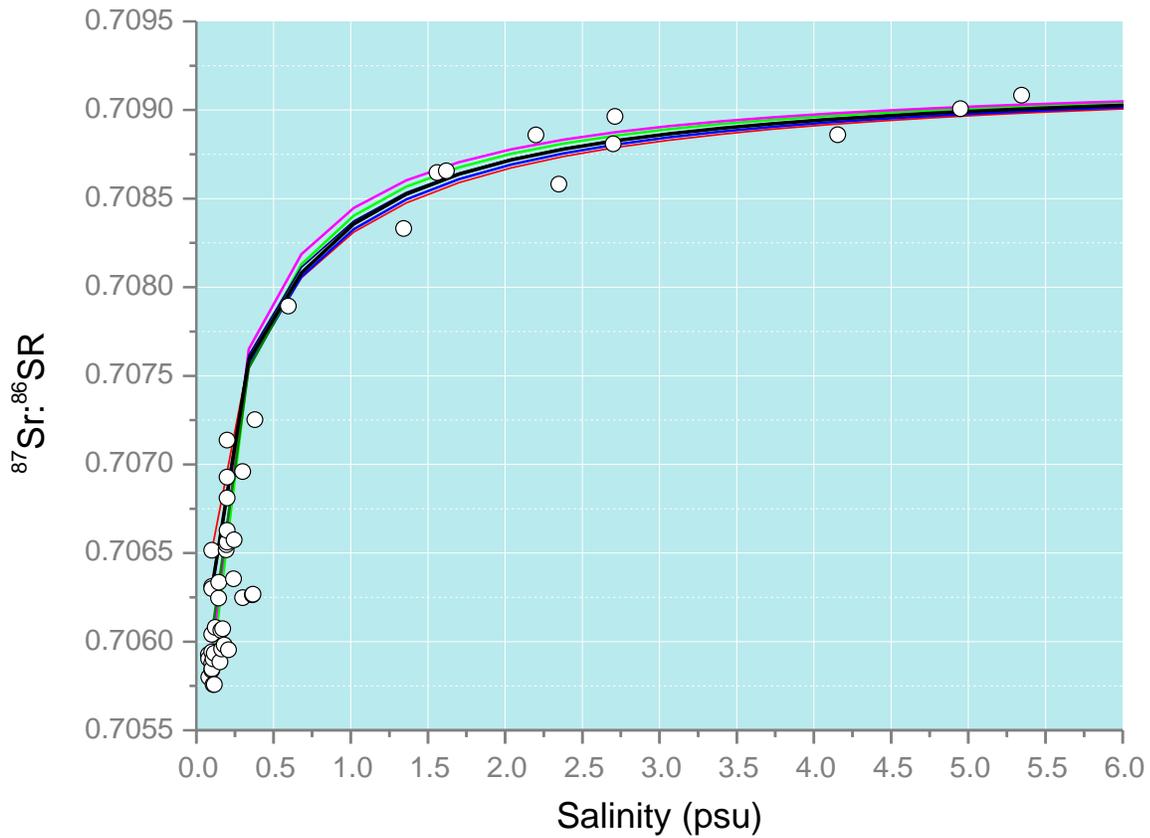
2463 Figure 1. Conceptual model of the life-history diversity of delta smelt Delta Smelt born in the
2464 North Delta and residing there to complete the life cycle (blue arrows), residing in the Central-
2465 South Delta (red), born and residing in the Low-Salinity Zone-LSZ (green). Note fish born in
2466 the LSZ have been found to migrate into freshwater to spawn. Delta Smelt migrate from
2467 freshwater to the LSZ (black) at different sizes.



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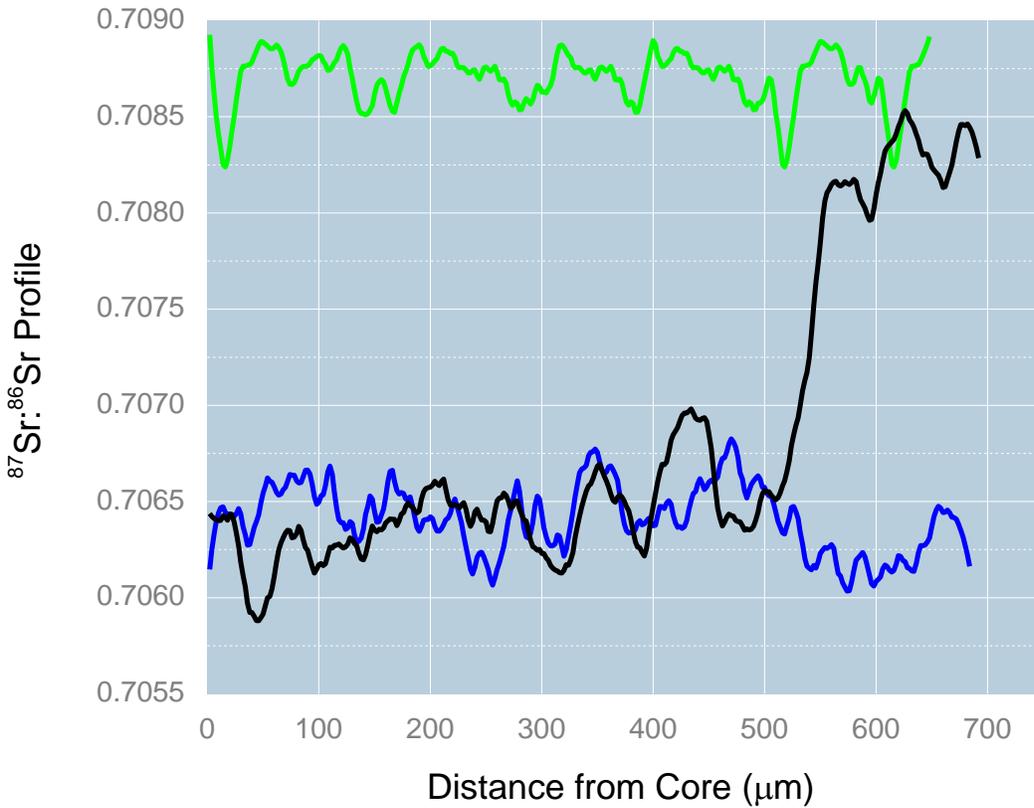
2469 Figure 2. Map of upper San Francisco Estuary. Closed circles represent CDFW Spring Kodiak
 2470 Trawl survey station locations (*not all stations are sampled by the SKT survey*), other symbols
 2471 newer stations added since 2009. Stations were divided into two regions, upstream freshwater
 2472 stations and downstream low-salinity zone stations (dashed line).

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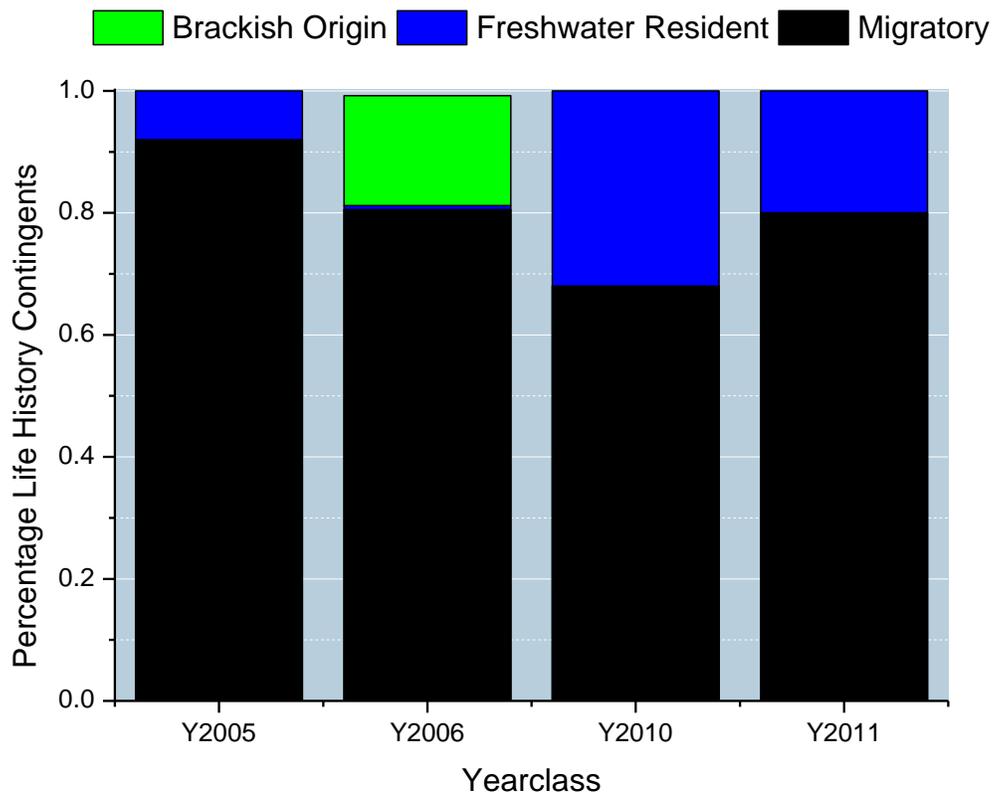
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2475 Figure 3. Relationship between Strontium Isotope Ratios $^{87}\text{Sr}:^{86}\text{Sr}$ from water samples (circles)
 2476 and salinity (psu). Lines represent mixing curves from a linear mixing model with different
 2477 freshwater end-members in the North Delta $^{87}\text{Sr}:^{86}\text{Sr}$, 0.70581-0.70653 and $^{88}\text{Sr} = 0.9\text{-}1.4\text{ppm}$
 2478 with seawater $^{87}\text{Sr}:^{86}\text{Sr}$ 0.70918 $^{88}\text{Sr} = 9\text{ppm}$. *Note: strontium isotope ratios >0.708 represent*
 2479 *salinity habitats greater than 1-psu and demarcate the transition from freshwater to the low-*
 2480 *salinity zone.*



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2482 Figure 4. Example profiles of strontium isotope ratios ($^{87}\text{Sr}:^{86}\text{Sr}$) for the three primary life
 2483 history phenotypes of adult Delta Smelt collected during (2012). Black = migratory phenotype,
 2484 Red = freshwater resident phenotype and Blue = Brackish Origin fish. Note: reproducibility
 2485 error on standard reference materials (cultured Delta Smelt otolith) is 0.0001-2 σ SD.

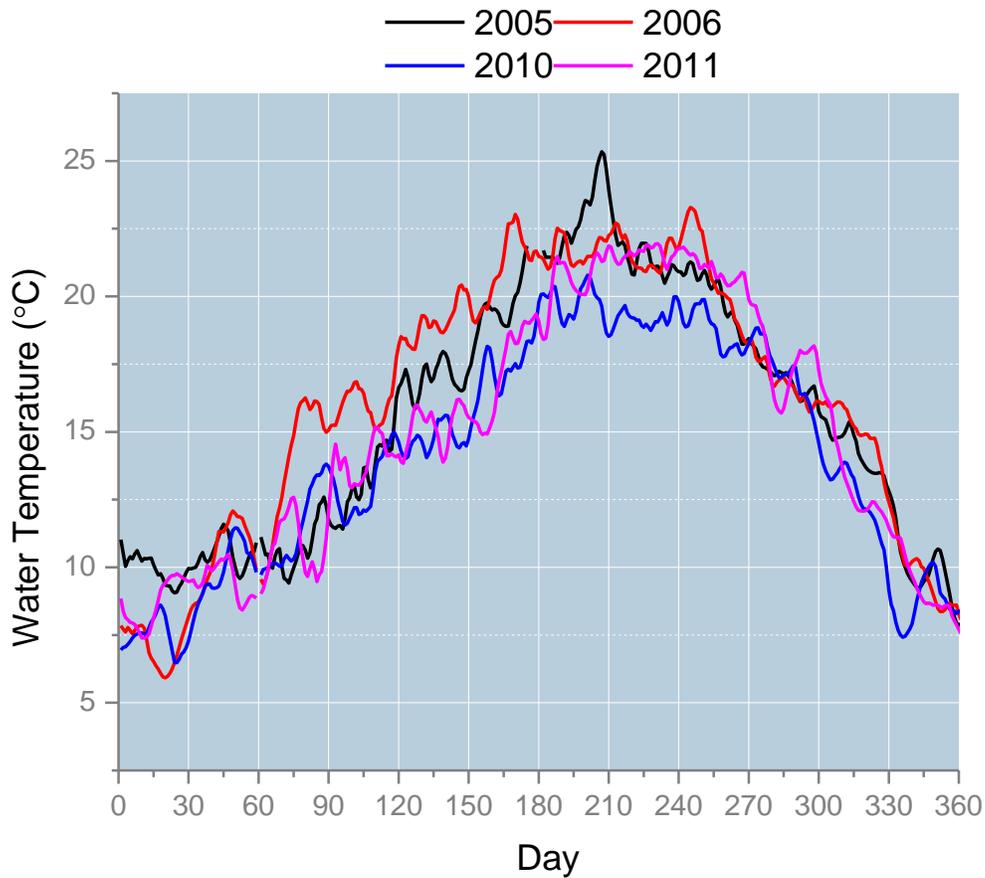


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2487 Figure 5. The percentage of adult Delta Smelt life history contingents for year classes 2005,
 2488 2006, 2010, and 2011.

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	2005	2006	2010	2011
Winter	10.4	10.5	9.6	9.6
Spring	16.4	18.7	15.0	15.5
Summer	21.4	21.4	19.2	21.0
Fall	13.4	13.5	12.5	13.1

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2494 Figure 6. Continuous daily water temperatures (Celsius) at the USBR- Rio Vista continuous
 2495 monitoring station (RIV) and seasonal mean daily water temperatures. Data available at
 2496 <http://cdec.water.ca.gov/cdecstation>

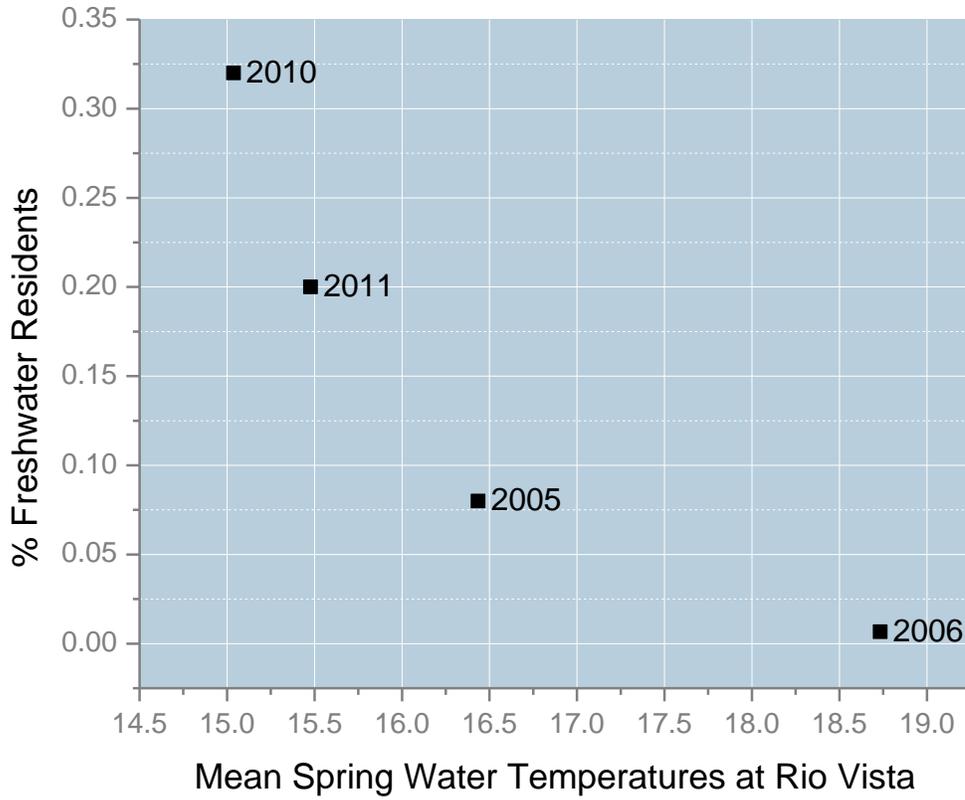
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2503 Figure 7. Relationship between the percentages of Freshwater Residents in the CDFW Spring
2504 Kodiak Trawl catch and spring (March-May) mean temperatures (Celsius) from the Rio Vista
2505 CDEC stations (RIV) for year classes 2005, 2006, 2010 and 2011

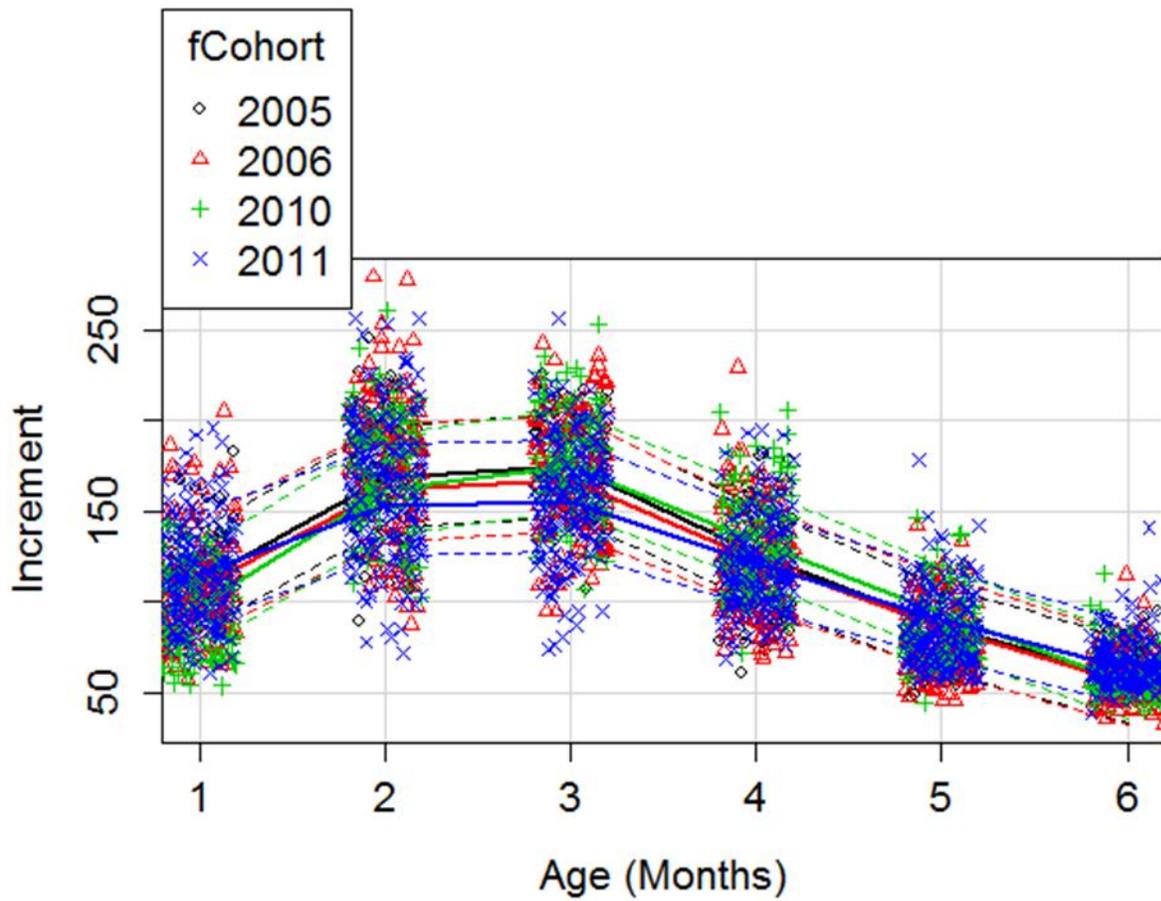
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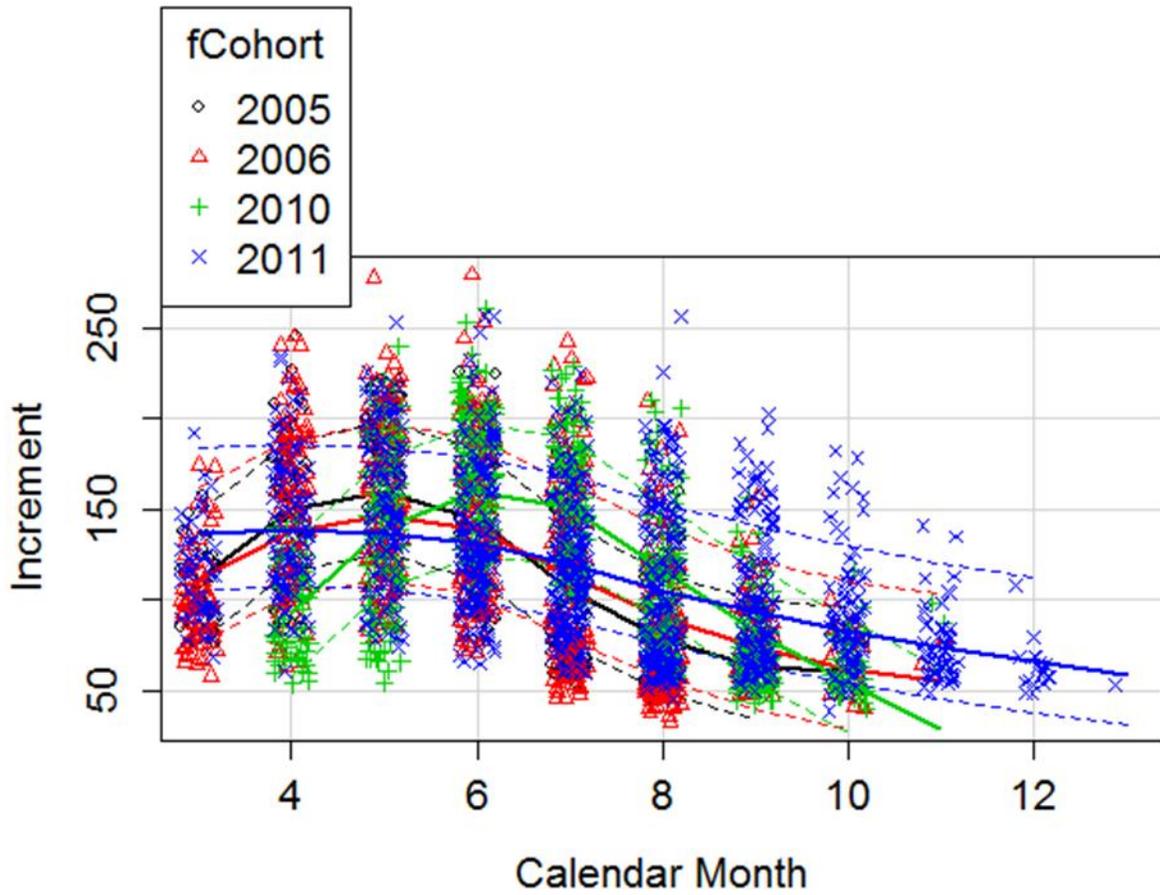
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2513 Figure 8. Scatterplot of otolith increment widths (μm) and monthly ages for the four year classes
 2514 of the FLaSH Study. Lines represent smoothed response curves with dashed lines representing
 2515 the 95% confidence intervals for each year class. Symbols for individual fish were jittered for
 2516 visual display.



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2518

2519 Figure 9. Scatterplot of otolith increment width (μm) during the calendar months of increment
 2520 formation for the FLaSH Study year classes. Lines represent smoothed response curves with
 2521 dashed lines representing the 95% confidence intervals for each year class. Symbols for
 2522 individual fish were jittered for visual display.

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2529 Appendix A. Delta Smelt catch per station and SKT Survey year and the numbers of fish
 2530 identified as freshwater resident phenotype (FWR), migratory phenotype (MIG) and brackish
 2531 water origin (BWR). Table divided into freshwater region and low-salinity region at station 704.

2532

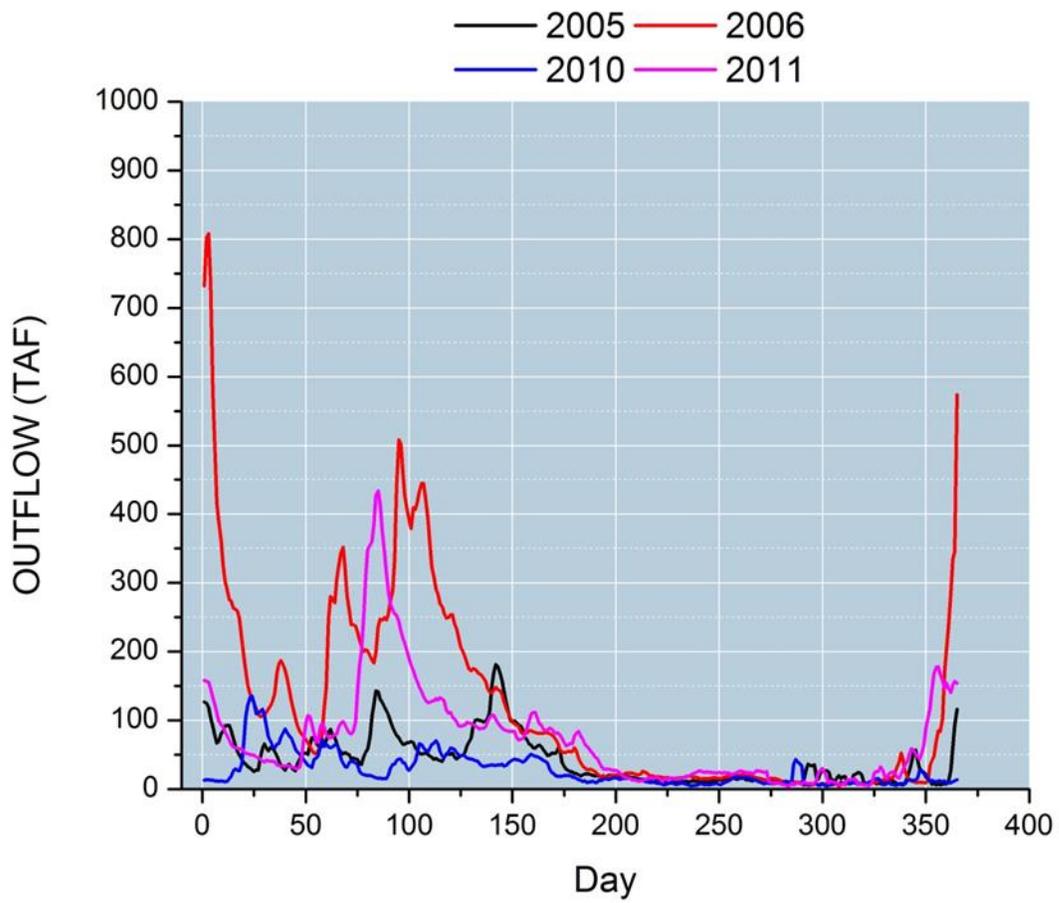
Station	SKT 2006				SKT 2007				SKT 2011				SKT 2012			
	Catch	FWR	MIG	BO												
340	51	0	15	0	0	-	-	-	0	-	-	-	2	0	2	0
405	2	0	2	0	0	-	-	-	0	-	-	-	2	-	-	-
411	5	0	1	0	0	-	-	-	0	-	-	-	9	0	2	0
418	2	0	2	0	0	-	-	-	0	-	-	-	1	0	1	0
501	14	0	7	0	0	-	-	-	2	-	-	-	18	0	7	0
504	5	0	2	0	0	-	-	-	0	-	-	-	8	0	1	0
508	5	0	4	0	1	0	1	0	0	-	-	-	14	0	4	0
513	3	0	1	0	8	0	2	0	1	-	-	-	25	0	4	0
519	8	0	2	0	23	0	4	2	7	-	-	-	160	0	25	0
520	2	0	1	0	0	-	-	-	0	-	-	-	24	0	2	0
602	1	0	1	0	3	0	0	1	9	0	2	0	21	0	2	0
606	56	0	34	0	135	0	19	8	45	0	4	0	47	0	20	0
609	12	0	3	0	37	0	5	5	76	0	12	0	126	0	9	0
610	4	0	1	0	4	-	-	-	1	-	-	-	9	0	2	0
704	1	0	1	0	52	0	9	2	10	2	7	0	23	0	4	0
706	0	-	-	-	16	0	2	0	4	0	4	0	40	0	10	0
707	1	0	1	0	3	0	1	0	16	3	12	0	22	0	7	0
711	0	-	-	-	1	-	-	-	0	-	-	-	2	1	1	0
712	0	-	-	-	0	-	-	-	1	-	-	-	0	-	-	-
713	0	-	-	-	3	0	0	1	2	0	2	0	43	1	4	0
715	21	0	15	0	14	0	3	0	4	1	3	0	57	2	2	0
716	13	0	5	0	14	0	2	2	10	3	7	0	203	10	22	0
719	114	0	13	0	313	1	49	4	245	76	50	0	301	24	25	0
799	239	12	55	0	70	0	18	0	0	-	-	-	0	-	-	-
801	1	-	-	-	0	-	-	-	0	-	-	-	11	0	5	0
804	2	1	-	-	3	0	3	0	0	-	-	-	6	0	1	0
809	3	0	3	0	6	0	2	3	4	1	3	0	27	-	-	-
812	0	-	-	-	0	-	-	-	1	0	1	0	3	-	-	-
815	1	-	-	-	0	-	-	-	0	-	-	-	0	-	-	-
902	3	0	1	0	0	-	-	-	0	-	-	-	0	-	-	-
906	0	-	-	-	0	-	-	-	1	0	1	0	0	-	-	-
910	0	-	-	-	0	-	-	-	2	0	2	0	0	-	-	-
914	1	-	-	-	0	-	-	-	2	0	2	0	0	-	-	-
919	2	0	1	0	0	-	-	-	1	0	2	0	0	-	-	-
920	1	-	-	-	0	-	-	-	0	-	-	-	0	-	-	-
921	0	-	-	-	0	-	-	-	1	-	-	-	0	-	-	-
922	2	-	-	-	0	-	-	-	0	-	-	-	0	-	-	-
923	0	-	-	-	0	-	-	-	0	-	-	-	2	-	-	-

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2534 Appendix B. Freshwater outflow from the DAYFLOW model for study years. Figure. Outflow
 2535 Total Acre-Feet from DAYFLOW for 2005, 2005, 2010 and 2011.

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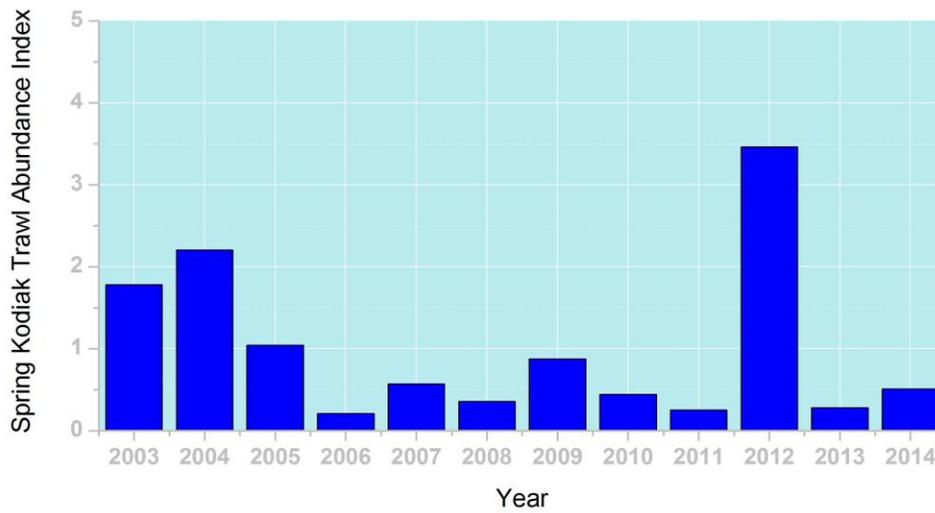
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2547 Appendix C. Spring Kodiak Trawl Survey Index.

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Random Effects Models	
M2a<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (1 fishid) + (1 fMonth), data)	
M2b<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fishid) + (1 fMonth), data)	
M2c<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (1 fishid) + (c.(log(Age)) fMonth), data)	
M2d<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fMonth), data)	
M3a<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (1 fishid) + (1 fLHS), data)	
M3b<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fishid) + (1 fLHS), data)	
M3c<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (1 fishid) + (c.(log(Age)) fLHS), data)	
M3d<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fLHS), data)	
M4a<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (1 fishid) + (1 fMonth), data)	
M4b<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fLHS) + (1 fMonth), data)	
M4c<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (1 fishid) + (1 fLHS) + (c.(log(Age)) fMonth), data)	
M4d<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fishid) + (1 fLHS) + (1 fMonth), data)	
M4e<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fLHS) + (1 fMonth), data)	
M4f<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fishid) + (1 fLHS) + (c.(log(Age)) fLHS), data)	
M4g<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (1 fLHS) + (c.(log(Age)) fMonth), data)	
M4h<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (1 fishid) + (c.(log(Age)) fLHS) + (c.(log(Age)) fMonth), data)	
M4i<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fLHS) + (c.(log(Age)) fMonth), data)	
Fixed Effects Models	
M2d0<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fMonth), data)	
M2d1<- lmer (log(Increment) ~ c.(log(Age)) + fCohort + sex + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fMonth), data)	
M2d2<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fMonth), data)	
M2d3<- lmer (log(Increment) ~ c.(log(Age)) + fCohort + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fMonth), data)	
M2d4<- lmer (log(Increment) ~ c.(log(Age)) * fCohort + fLHS + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fMonth), data)	
M2d5<- lmer (log(Increment) ~ c.(log(Age)) + fCohort + fLHS + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fMonth), data)	
M2d6<- lmer (log(Increment) ~ c.(log(Age)) * fLHS + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fMonth), data)	
M2d7<- lmer (log(Increment) ~ c.(log(Age)) + fLHS + c.(log(agecap)) + (c.(log(Age)) fishid) + (c.(log(Age)) fMonth), data)	

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

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California Department of Fish and Wildlife Contract E1183004-1-3

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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.

2612 In addition, otolith growth metrics were explored to better understand the effect of fish health
2613 on reproductive output (fecundity) for female Delta Smelt collected during the Spring Kodiak
2614 Trawl Survey. In this report we focus on otolith based metrics (growth and life history
2615 phenotype and salinity history via otolith microchemistry) to assess the effect of habitat
2616 attributes on short-term recent growth rates and fall growth rates of Delta Smelt.

2617

2618 **INTRODUCTION**

2619

2620 Fish are robust indicators of the ecological conditions in aquatic habitats. As such, fish
2621 growth is an important endpoint for assessing the effect of environmental stressors on ecological
2622 processes and functions. Growth in fish is indeterminate; where fish will continue to grow in
2623 perpetuity given suitable habitat and feeding conditions, thus growth can be a reliable indicator
2624 of habitat quality. To this end, fish otoliths (“ear-bones”) have been commonly used to
2625 determine fish age (daily, annual) and age specific growth. Otoliths are comprised of calcium
2626 carbonate and proteins, sequentially layered daily onto a primordial core formed prior to birth.
2627 The layering of calcium and protein, when examined under light microscopy can be used to
2628 quantify daily age, and the width of daily increments can be used as a proxy for daily growth, as
2629 the secretion of calcium and protein is tied to the fish’s metabolism. However, validation of
2630 direct proportional otolith growth and fish growth is required to make full use of this technique.
2631 In previous studies, we have validated proportion otolith growth and fish growth for laboratory
2632 cultured Delta Smelt (Hobbs et al. 2007). Thus, the growth history of Delta Smelt can be
2633 reconstructed from the increment widths recorded since birth.

2634 The chemical composition of the otolith can reveal provenance. Elements with similar
2635 chemical properties to calcium are deposited within the otolith (e.g. Sr, Mg, Ba) in relative
2636 proportion to the concentrations in the environment. Otoliths are biologically inert, such that,
2637 once formed the chemical composition of the otolith is “locked” in place. This is particularly
2638 valuable for determining the movement patterns of mobile fishes that undergo movements across
2639 the landscape in association with reproduction. In our previous research we have used strontium
2640 isotope ratios to reconstruct the salinity history of smelt utilizing the Low-Salinity Zone, as the
2641 strontium isotope ratios of freshwater mix conservatively and predictively with saltwater, such
2642 that narrow salinity zones can be identified with strontium isotope ratios in otoliths (Hobbs et al.

2643 2010). Thus, otoliths can be used to determine daily growth rates and the salinity habitat where
2644 this growth occurred, making otoliths a valuable tool for assessing the effects of environmental
2645 variability on habitat quality and fish production.

2646

2647 *Conceptual Model*

2648 The IEP-MAST life-cycle model of Delta Smelt was applied to develop predictions for Fall
2649 Low-Salinity effects on habitat attributes and the response of Delta Smelt. Using published
2650 research, knowledge gained from the recent Delta Smelt synthesis effort (IEP-MAST 2015), and
2651 expert opinion we made directional predictions for how each variable would respond to high
2652 outflow conditions in the fall of 2011 relative to 2012-2014. Predictions were made for Summer
2653 (July – August), and Fall (September – December) and Winter (January – March). These
2654 seasonal groupings correspond to general periods when Delta Smelt juveniles, subadults and
2655 maturing adult are present in the Low-Salinity Zone. These groupings, correspond to the
2656 Summer Towntnet Survey (TNS) Fall Midwater Trawl (FMWT) and Spring Kodiak Trawl (SKT
2657 (**Honey et al. 2004**). The full list of variables, and predictions for each season, are given in Table
2658 1.

2659 Elevated fall freshwater outflow was predicted to effect the distribution of the Delta Smelt and
2660 move the population downstream, closer to the ocean and away from water projects in the South
2661 Delta. Higher than normal fall outflow was predicted to move X2 into Suisun Bay and increase
2662 the area of the Low-Salinity, reduce water clarity and water temperatures. High fall flows were
2663 also predicted to improve feeding conditions for Delta Smelt and reduce toxicity. These effects
2664 on habitat attributes in the Low-Salinity Zone would predict that Delta Smelt abundance and
2665 survival from summer to fall would improve growth and support a more diverse population, with
2666 higher fecundity.

2667 The IEP-MAST drought synthesis project work team has evaluated the current monitoring
2668 data and other special studies data to evaluate the impact of the recent drought on habitat
2669 attributes in the Low-Salinity Zone and the response of Delta Smelt utilizing the MAST
2670 conceptual model for Delta Smelt (**IEP-MAST 2015**).

2671 While this effort was designed to address the impact so drought, many of the same results
2672 could be examined for the Fall Low Salinity Habitat Study. We examined anomaly values from
2673 standardized long-term trends (2004-2014) comparing 2011 to 2012-2014 and have summarized
2674 the finding in Table 1. Attributed with a solid black arrow depict the direction of the trend,
2675 greyed arrows represent attributes not assessed. Water year 2011 was the second wettest period
2676 since the beginning of the century. Freshwater outflows were extremely high and the resulting
2677 location of X2, a geographic marker of Low-Salinity Zone was located in further downstream in
2678 Suisun Bay in summer and fall, and the total area of Low-Salinity habitat was greater. Air
2679 temperature, Mississippi Silverside abundance (larval predators of Delta Smelt) and Ammonia
2680 concentrations (Sac Regional WWTP) were lower while water clarity (Secchi depth)
2681 Largemouth Bass abundance and food abundances were greater. Delta Smelt were more
2682 abundant in 2011, and had a broader spatial distribution resulting in faster growth rates (based on
2683 an index of growth), greater life history diversity and higher reproductive output.

2684 In this report we address research questions pertaining to the effect of fall habitat conditions
2685 in 2011 on Delta Smelt growth rates in comparison to drier years of 2012-2015. Specifically we
2686 quantified “Fall Growth” using the marginal increment widths of otoliths of Delta Smelt
2687 collected during the Fall Midwater Trawl and the habitat attributes at the regional level and
2688 reconstructed salinity history from otolith strontium isotope ratios to assess habitat attribute
2689 effects on Delta Smelt growth. For fish collected during the Spring Kodiak Trawl, we quantified
2690 the increment widths of daily increments formed during the Fall. However, fish collected in the
2691 winter were beginning the formation of the annual winter band, and thus daily increment
2692 periodicity is no longer reliable for back-calculating daily increments to a calendar date.
2693 Therefore, we calculated the mean age at calendar dates for the fall months (Sept 1, Oct 1 and
2694 Nov 1) of the Delta Smelt yearclass from the fish collected during the Fall Midwater Trawl.
2695 Mean ages at calendar dates were then used to back-calculate a fall otolith increment growth
2696 (Sept, Oct, and Nov) for Delta Smelt collected in the Spring Kodiak Trawl. Growth rates were
2697 assessed among years and salinity history for the corresponding otolith growth using the otolith
2698 strontium isotope ratios. Lastly, we examine the relationship between growth rates, life history
2699 phenotypes and fecundity of Delta Smelt from 2011-2014.

2700

2701 **METHODS**

2702 In the current report, delta smelt received from the FMWT and SKT fish survey were
2703 removed from liquid nitrogen by staff at the Aquatic Health Program at UC Davis. Fork lengths
2704 (FL) and body weights (BW) were measured while frozen to determine condition factor (CF).
2705 Samples were allowed to thaw briefly to allow the skin to appear natural, then pictures were
2706 taken, with a ruler and ID tag, for future image analysis. Otoliths were removed for age, growth,
2707 and isotopic microchemistry determinations. The gonads and liver were carefully separated from
2708 the GI tract. The GI tract was preserved in 95% ethanol at room temperature and sent to Randy
2709 Baxter (Co-PI) at DFW for gut content analysis. Liver and gonads were weighed to determine
2710 hepatosomatic (HSI) and gonadosomatic (GSI) indices, respectively. When livers and/or gonad
2711 weights were greater than 0.005 g the samples were split into two portions. Un-split liver and
2712 gonads were placed in 10% buffered formalin. If the liver or gonad were split then the first
2713 portion was placed in 10% buffered formalin at room temperature for histopathology. Gonads of
2714 females were histologically scored for development and a subset of the ripest females (late stage
2715 4) was selected to quantify fecundity.

2716

2717 *Otoliths*

2718 Sagittal otoliths were dissected from the head during necropsy and stored dry in tissue culture
2719 trays. Before mounting, the otoliths were “cleared” by soaking in 95% ethanol for 24 hours.
2720 Otoliths were mounted onto glass slides with Crystal Bond® thermoplastic resin in the sagittal
2721 plane, ground to the core on both sides with wet-dry sandpaper and polished with a polishing
2722 cloth and 0.3-micron polishing alumina. Otoliths were digitized with a 12 Megapixel digital
2723 camera (AM Scope: www.amscope.com) at a magnification of 20X with an Olympus CH30
2724 compound microscope. Otolith increments were enumerated and the distance from the core to
2725 each daily ring was measured using Image-J NIH software . Three age readers separately
2726 quantified otolith increments; the mean, median, average percent error and the coefficient of
2727 variation of each individual fish were assessed. If the age reading by the three readers for an
2728 individual fish was greater than 10% average percent error, the sample was selected for
2729 processing of the second otolith for age analysis. When age agreement among multiple readers
2730 could not be resolved, ageing was conducted by the principle investigator. If age agreement
2731 could not be reduced to less than 10% APE the sample was removed from the study.

2732 Otolith accretion for the fall months Sept-Dec were back-calculated from the otolith by
2733 counting back from the edge of the otolith on daily increments and extracting the length of
2734 otolith accreted for each month. Accretion rates were calculated by dividing by the number of
2735 increments in each month.

2736

2737 *Microchemistry*

2738 Otoliths were mounted on petrographic slides (20 per slide) for otolith microchemistry.
2739 Otolith strontium isotope ratios were quantified using methods previously developed (Hobbs et
2740 al 2007; 2010). Briefly, the strontium isotope profile from the core to the edge along a similar
2741 path used for aging was scanned using a laser beam of 55-microns moving at a speed of 10-
2742 microns per second. Laser profiles began at 100-micron in the core to ensure the analysis
2743 encompass the entire natal chemistry. The otolith strontium isotope $^{87}\text{Sr}:$ ^{86}Sr profile was aligned
2744 with the daily increments to determine the age and size at life history transition stages. The
2745 strontium isotope ratios were resolved using methods developed for delta smelt (Hobbs et al.
2746 2005). The data were resolved to the micron distance from the core using the scan speed and
2747 verified by post laser ablation digital imaging to make sure the laser line-scan length matched the
2748 data resolved length.

2749

2750 *Habitat Attributes and Environmental Drivers*

2751

2752 Delta Smelt habitat attributes were identified using several approaches. Salinity zones were
2753 identified (<1psu, 1-6psu and >6psu) using the surface salinity at each station where Delta Smelt
2754 were collected during the Fall Midwater Trawl Survey. In addition stations within the Cache
2755 Slough and Sacramento Deepwater Ship Channel were further identified amongst the <1psu
2756 stations. The salinity zone habitat the fish utilized during the fall was determined using the
2757 strontium isotope ratios of the last 200 μm of otolith before capture. Our previous work has
2758 established a relationship between strontium isotope ratios and salinity (**Hobbs et al 2010**).

2759

2760 **RESULTS**

2761 *Marginal Otolith Accretion and Salinity Habitats*

2762 We measured otolith accretion rates (daily increment widths (μm)) and strontium isotope ratios
2763 profiles for 325 Delta Smelt collected during the Fall Midwater Trawl from 2011-2014 (Table 2).
2764 A majority of the samples came from 2011 (N = 233) while few fish were collected in 2012 (N =
2765 42), 2013(N = 17) and 2014 (N = 33) (Table 2). Accretion rates did appear to be faster in 2011
2766 for the September, October and November surveys (Figure 1). However, there was a significant
2767 ontogenetic effect with trends across months with marginal otolith accretion slowing from
2768 September through December and with fish size as approximated by otolith length (Figure 2).

2769 To account for the ontogenetic effect we modelled the marginal accretion of otolith using a
2770 generalized linear model with a Gaussian distribution and log link function to account for the
2771 otolith size effect and compare models with year as a factor and three metrics for salinity regions
2772 including the CDFW region grouping, the Fall-Low Salinity habitat zones (Cache Slough-
2773 Sacramento Deepwater Ship Channel, <1psu, 1-6psu and >6psu) at capture, and the fall salinity
2774 history from otolith strontium isotope ratios. Modeling was conducted is a stepwise removal
2775 procedure and in all models otoliths size and year were retained, and comparisons were made
2776 amongst the three models for fall habitat using AIC's. Each model provided a robust fit to data,
2777 no heterogeneity in variance was observed and data were residual plots showed no inherent
2778 spatial or temporal correlation. The model including the fall salinity habitat derived from the
2779 otolith strontium isotope ratios provided the lowest AIC of 2793.4, while the model with CDFW
2780 regions provided the second lowest AIC of 2812.5 and the Fall Low-Salinity Habitat salinity
2781 region the highest AIC of 2817.3 (Table 3). Marginal otolith accretion appeared to be lower for
2782 individuals having spent the fall in salinity habitats greater than 2.5psu (Figure 3).

2783 *Fall growth rates estimates from otolith increments of Delta Smelt collected from the Fall*
2784 *Midwater Trawl*

2785 Otolith accretion rates in September 2011 were approximately 1.5 times faster than
2786 September accretion rates for the 2012-2014 years (ANOVA, MS=30.6, df=3, $p<0.0001$, while
2787 October accretion rates were approximately 20% faster in 2011 (ANOVA, MS= 4.518, df=3,
2788 $p<0.0001$ (Figure 4). There were no differences in accretion rates in November, and in
2789 December accretion rates for 2011 were only faster than 2012, while 2013 and 2014 accretion
2790 rates were faster than 2011 (ANOVA, MS= 2.159, $p<0.0001$. Ontogenetic effects were not
2791 accounted for in these models.

2792 Mean September otolith accretion rates differed among the regions of the estuary. In 2011
2793 accretion was slower for fish collected in Suisun Bay and the Sacramento Deepwater Ship
2794 Channel (SDWSC), while in 2012 accretion was fastest in Suisun Bay and Montezuma Slough
2795 (Figure 5) Overall, fish collected in Montezuma Slough appeared to have the highest otolith
2796 accretion rates while the SDWSC had the lowest for the month of September. However, these
2797 are general patterns in means and no statistical tests were used since sample sizes were too low
2798 in most cases (Figure 5).

2799 *Fall growth rates estimates from otolith increments of Delta Smelt collected from the Spring*
2800 *Kodiak Trawl*

2801 We back-calculated the otolith accretion that occurred during the fall for 664 fish collected
2802 during the Spring Kodiak Trawl (2012 = 195, 2013 = 198, 2014 = 156 and 2015 = 115). Since
2803 fish collected during this survey are undergoing the formation of an annual age band, daily
2804 otolith increment resolution was not possible and thus precise increment formation at calendar
2805 date was not possible. We used the mean age-at-calendar date for the Delta Smelt collected
2806 during the Fall Midwater Trawl Survey for each yearclass to select the age increments formed
2807 during the fall for SKT fish. Since marginal otolith accretion was significant for September and
2808 October, we used only these months to estimate fall growth for SKT fish. Strontium isotope
2809 ratios deposited in the otolith during the fall was determined using the mean otolith length-at-age
2810 for the Fall period. Salinity zones were then estimated using the described ranges of strontium
2811 isotope ratios for defines salinity zones.

2812 Greater than 90% of all Delta Smelt collected in the SKT survey from 2012-2015 reared in
2813 habitats with salinity less 2.5psu (Table 4). The proportion of fish rearing in freshwater during
2814 the fall and subsequently having spent the entire life in freshwater varied among the study years,
2815 with 2013 having the greatest proportion, while the critically dry 2015 contributed the fewest
2816 freshwater resident fish. The 2012 survey, which was the 2011 yearclass that experienced the
2817 higher than normal fall outflow condition had a larger proportion of fish rearing in salinity
2818 habitats from 1.6 to 2.5 psu (Table 4).

2819 To account for the ontogenetic effect we modelled fall otolith accretion using a generalized
2820 linear model with a Gaussian distribution and log link function to account for the otolith size
2821 effect and test for a significant slope effect for year (survey years of SKT) and for salinity zones

2822 as a categorical variable. Examination of diagnostic plots suggested no violation of the
2823 homogeneity of variance, independence and normality assumption. The ontogenetic effect
2824 (otolith length at Sept. 1), larger-older fish having slower growth than younger-small fish was
2825 highly significant $p < 0.0001$, thus accounting for the ontogeny when comparing between years
2826 was important (Figure 6). Inter-annual growth trends were similar to both back-calculated Fall
2827 growth using FMWT fish and for marginal otolith increment accretion of FMWT fish. The 2011
2828 yearclass (SKT 2012 survey) had higher accretion rates than 2012-2014 yearclasses, with a
2829 highly significant negative slope through time (Figure 6). Fish rearing in the 0.5-1.0, 1.1-1.5 and
2830 2.1-2.5 had faster otolith accretion rates relative to fish rearing in freshwater (Table 5).

2831 *Growth, Life History Phenotype and Fecundity*

2832 To determine the effect of fall otolith growth and life history phenotype on fecundity, we
2833 examined the fecundity of 97 late stage 4 female Delta Smelt collected during the Spring Kodiak
2834 Trawl Survey from 2012-2014 (2012 N = 36, 2013 N = 21 and 2014 N = 40) and fall otolith
2835 accretion rate as a proxy for growth and the life history phenotype (freshwater resident or
2836 migratory type). Linear regression of fecundity with fork-length, fall growth and life history
2837 phenotype as a factor was analyzed using the lm function in R. The model provided a good fit to
2838 the fecundity data, with an adjusted R² of 0.61, and was highly statistically significant (Table 6).
2839 Examination of diagnostic plots suggested no violation of the homogeneity of variance,
2840 independence and normality assumption. Fish fork-length and fall growth had a significant
2841 positive effect on fecundity and freshwater resident fish had slightly higher fecundity than
2842 migratory fish (Figure 7).

2843 DISCUSSION

2844 Delta Smelt responded to the high freshwater outflow conditions in the Fall of 2011 with
2845 faster growth rates and higher fecundity. However, we were not able directly assess the
2846 cumulative effect of different environmental drivers on growth and fecundity, as with field data,
2847 high freshwater flows can have many interactive effects on habitat attributes simultaneously and
2848 thus associating effects to any one driver is not possible. Growth rates can be influenced by a
2849 variety of habitat attributes including temperature, salinity and prey availability. In general,
2850 temperatures were cooler and salinity was lower in the fall of 2011 relative to 2012-2014. We

2851 did not directly assess prey availability in this report, however diet data was collected for Delta
2852 Smelt collected during the 2012 and 2013 Spring Kodiak Trawl Surveys (2012 = 2011 yearclass
2853 and 2013 = 2012 yearclass). Although we did not make direct comparison of otolith growth and
2854 stomach fullness, mean stomach fullness did appear to be greater in winter 2012 compared to
2855 2013, thus food availability was likely higher during the wet year of 2011-2012 (*S.Slater*
2856 *unpublished data*). The increased outflow conditions in the fall of 2011 appeared to provide
2857 better overall habitat conditions for Delta Smelt rearing in freshwater and the Low-Salinity Zone,
2858 which resulted in greater abundance in the fall and winter, a wider spatial distribution, increased
2859 feeding conditions and faster growing fish.

2860 Marginal increment accretion showed similar inter-annual trends to fall growth accretion and
2861 was driven by other habitat attributes including the salinity history of individuals derived from
2862 the otolith strontium isotope ratios. Fish having reared in habitats with salinity greater than 2.5
2863 psu exhibited reduced growth rates. Exposure to higher salinity can incur a greater energetic cost
2864 from increased osmoregulation than lower salinity habitats and reduce growth rates. However,
2865 Kammerer et al. (2015) showed that growth was not affected by elevated salinities as high as 10
2866 psu in short term lab rearing studies. Diet data for fish rearing in different salinity zones in the
2867 fall and winter months exhibited similar stomach fullness indices, but diet composition did vary,
2868 and thus prey quality across the salinity zones may be an additional important driver of Delta
2869 Smelt growth (*S.Slater unpublished data*). Nutritional indices did not appear to be significantly
2870 different among low and high salinity habitats in this study, but there was some tendency for
2871 RNA/DNA ratios and TAG concentrations to be slightly higher in freshwater (*S. Teh et al*
2872 *unpublished data*). Contaminant exposure may be an additional stressor reducing growth rates in
2873 higher salinity habitats, however there is limited information on contaminant exposures collected
2874 at appropriate spatial and temporal scales to correspond with otolith growth rates. Hammock et
2875 al. (2015) found evidence of nutritional stress in Delta Smelt collected in Suisun Bay, but
2876 histological evidence of contaminant effects was greater in the Cache-Liberty region of the North
2877 Delta, thus it is less likely reduced growth in high salinity habitats was driven by contaminant
2878 stress.

2879 Adaptive management of the Low-Salinity Zone habitat for Delta Smelt, as prescribed by the
2880 biological opinion issued for continued operation of the state and federal pumping facilities, call

2881 for increased freshwater flows in the fall to increase growth and subsequent fecundity of Delta
2882 Smelt. While, it appeared that Delta Smelt growth and fecundity was elevated during a naturally
2883 high freshwater outflow in the fall of 2011, such a response may not be directly inferred if
2884 freshwater flows were artificially increased during a dry year. Environmental conditions
2885 throughout the year influence the growth and production of eggs in Delta Smelt, thus if fish are
2886 experiencing poor habitat conditions during a dry spring and summer, it is uncertain whether
2887 increased flows in fall are going to produce similar results as measured in 2011. Moreover,
2888 warm and dry springs have been associated with poor recruitment to the juvenile stage, thus few
2889 fish may benefit from an artificially induced fall flow, and given the financial and political cost
2890 of such an action, the result may not be quantifiable if new few are around to benefit. We
2891 recommend such an action be utilized when high spring flows support recruitment of juveniles,
2892 but summer and fall conditions are anticipated to be poor without a management action.

2893 Using the Delta Smelt life cycle model produced by the IEP-MAST predicted growth and
2894 fecundity would be higher in the fall and winter of 2011. Using otolith increment accretion rates
2895 of marginal otolith increments deposited during the Fall Midwater Trawl Survey and back-
2896 calculated fall increment accretion for fish collected during the Spring Kodiak Trawl, we showed
2897 that growth was elevated in the fall of 2011 compared to 2012-2014. Moreover, increased fall
2898 growth was associated with increased fecundity. Based on these data we recommend careful
2899 management of freshwater outflows not only during the critical fall months, but through-out the
2900 year to support growth and reproduction of Delta Smelt. The 2011-2012 years provide the best
2901 example of why we suggest environmental conditions need to be maintained year round. The
2902 conditions in 2011 resulted in high production of offspring in the spring of 2012, with the 20-mm
2903 survey index reaching abundance levels similar years prior the pelagic organism decline.
2904 However, by mid-June abundance declined rapidly, as we entered the first year of a significant
2905 drought period, thus any benefits the Delta Smelt may gain from increased fall flows could be
2906 easily wiped out by poor conditions the following spring. Management of Delta Smelt requires a
2907 life-cycle approach, linking the habitat attributes and environmental drivers form life-stage to
2908 life-stage much like the model put forth by the IEP-MAST synthesis report.

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2912 Table 1. Fall habitat and Delta Smelt response predictions in response to elevated outflow.

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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	↑

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2917 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

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2936 Table 3. GLM model results for marginal otolith accretion.

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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

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2950 Table 4. The proportion of total catch rearing in different salinity habitats during the fall based
2951 on otolith strontium isotope ratios.

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	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
2953 2015	12%	24%	33%	15%	13%	3%	1%	0%	0%	112

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2969 Table 5. GLM model results for Fall otolith accretion for Delta Smelt collected during the Spring
2970 Kodiak Trawl Survey 2012-2015 (2011-2014 Yearclasses).

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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

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2984 Table 6. Linear regression model results for fecundity with fish fork-length, Fall otolith
2985 accretion rate and the life history phenotype (0 = freshwater resident, 1 = migratory)

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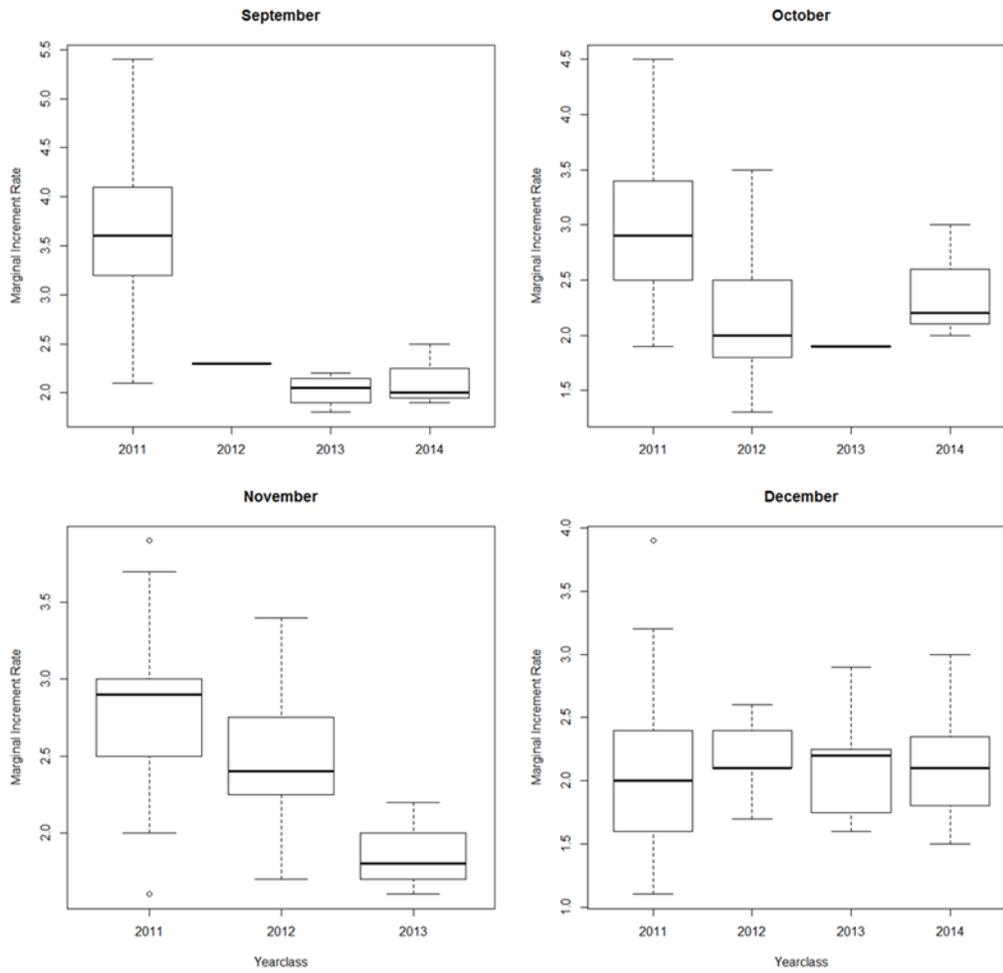
Coefficients:	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-3212.36	384.014	-8.365	< 0.0001 ***
fork_length	64.451	5.794	11.124	< 0.0001 ***
Fall.g.d	176.582	46.91	3.764	0.000294 ***
migration[T.1]	-174.893	75.492	-2.317	0.02274 *

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

2987 F-statistic: 50.75 on 3 and 92 DF, p-value: < 2.2e-16



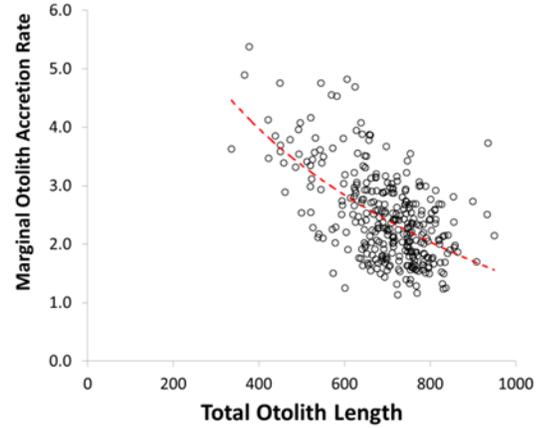
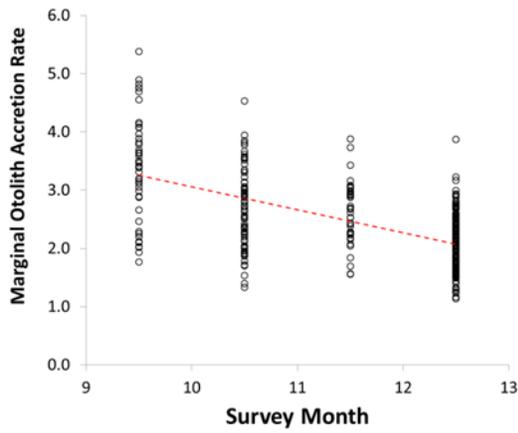
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2989 Figure 1. Otolith marginal increment accretion rate ($\mu\text{m}/\text{day}$) for Delta Smelt collected in the
 2990 Fall Midwater Trawl from September to December in 2011-2014.

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2996 Figure 2. Marginal otolith increment accretion rate ($\mu\text{m}/\text{day}$) for Delta Smelt collected in the
 2997 Fall Midwater Trawl Survey by Survey Month (left) reflecting the decreasing growth over time
 2998 (and age) and by the total otolith length (right) depicting the ontogenetic influence of fish size.

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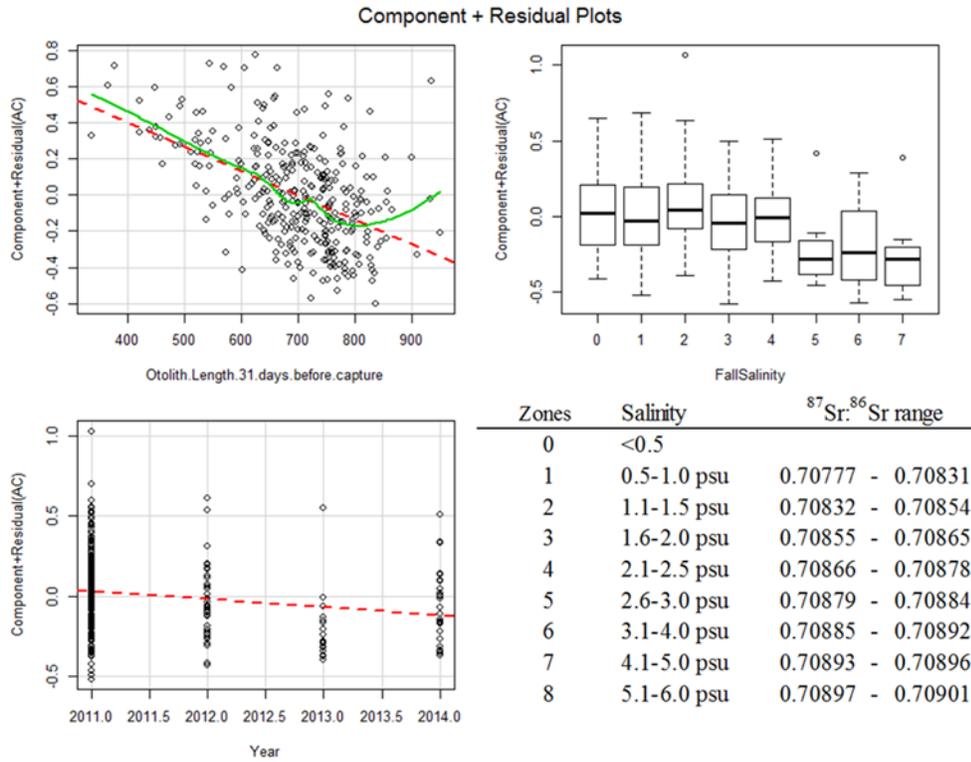
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3007 Figure 3. GLM results for marginal otolith accretion accounting for the otolith size ontogenetic
 3008 effect, and fall salinity habitat derived from otolith strontium isotope ratios and the year effect.

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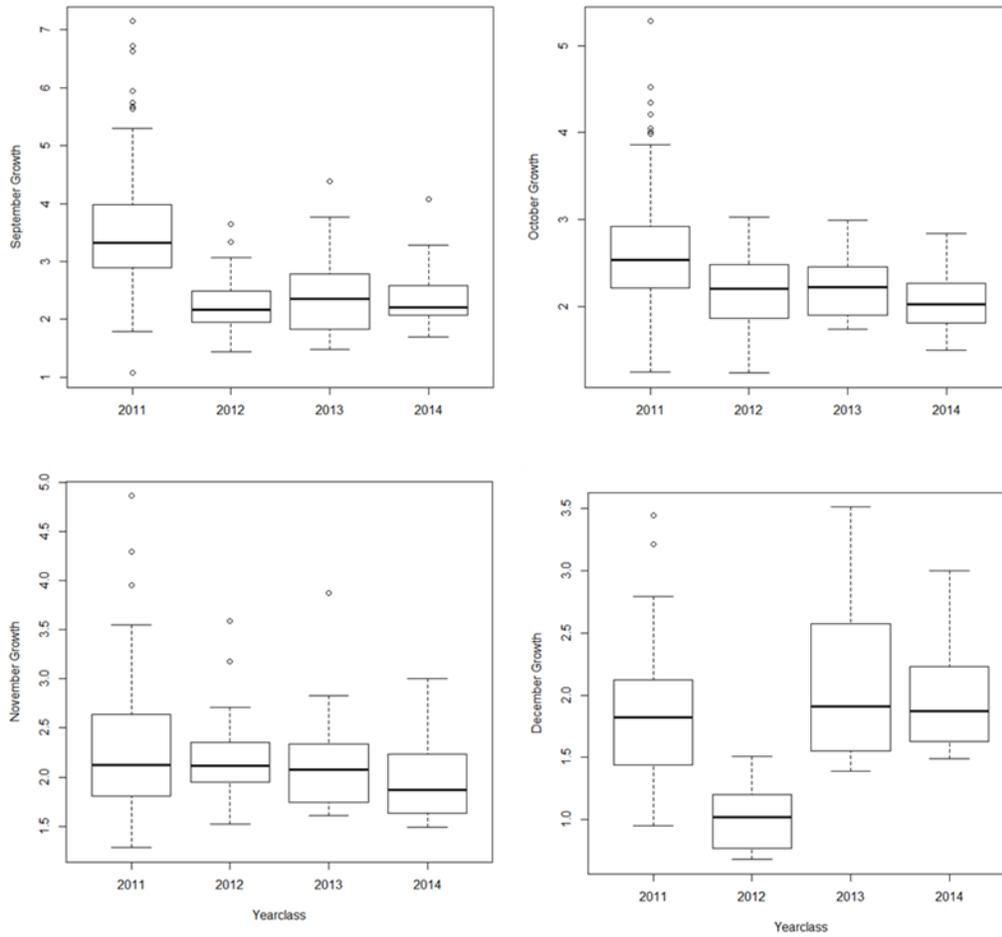
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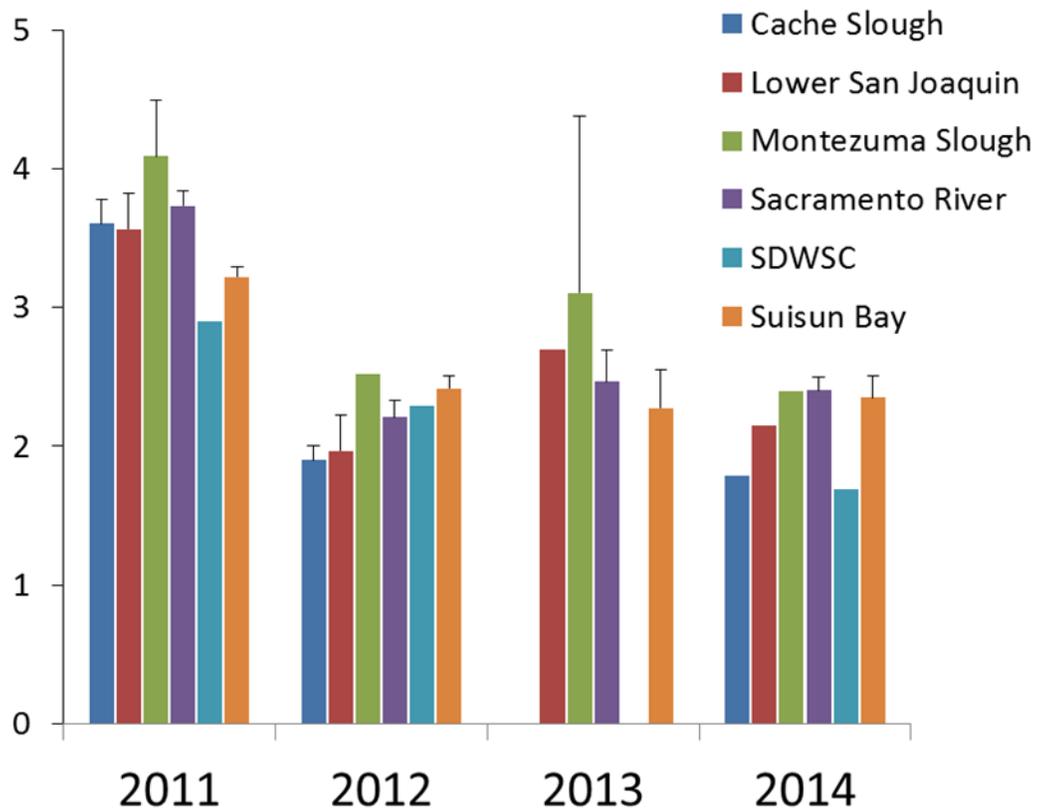
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3017 Figure 4. Boxplots of otolith accretion rate ($\mu\text{m}/\text{day}$) accreted during the months of Sept-Dec.
 3018 Data are from fish collected during the Fall Midwater Trawl 2011-2014.

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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	0	1	2	6	0	8
2014	1	1	1	27	1	2

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3022 Figure 5. Bar plot of mean otolith accretion rate ($\mu\text{m}/\text{day}$) for the month of September. Data are
 3023 from the Fall Midwater Trawl 2011-2014. Error bars depict $\pm 1\text{SE}$. Bars without error bars had
 3024 only single individuals capture and analyzed for growth. Table under figure is the sample size
 3025 for each bar. No statistical test were attempted with this data.

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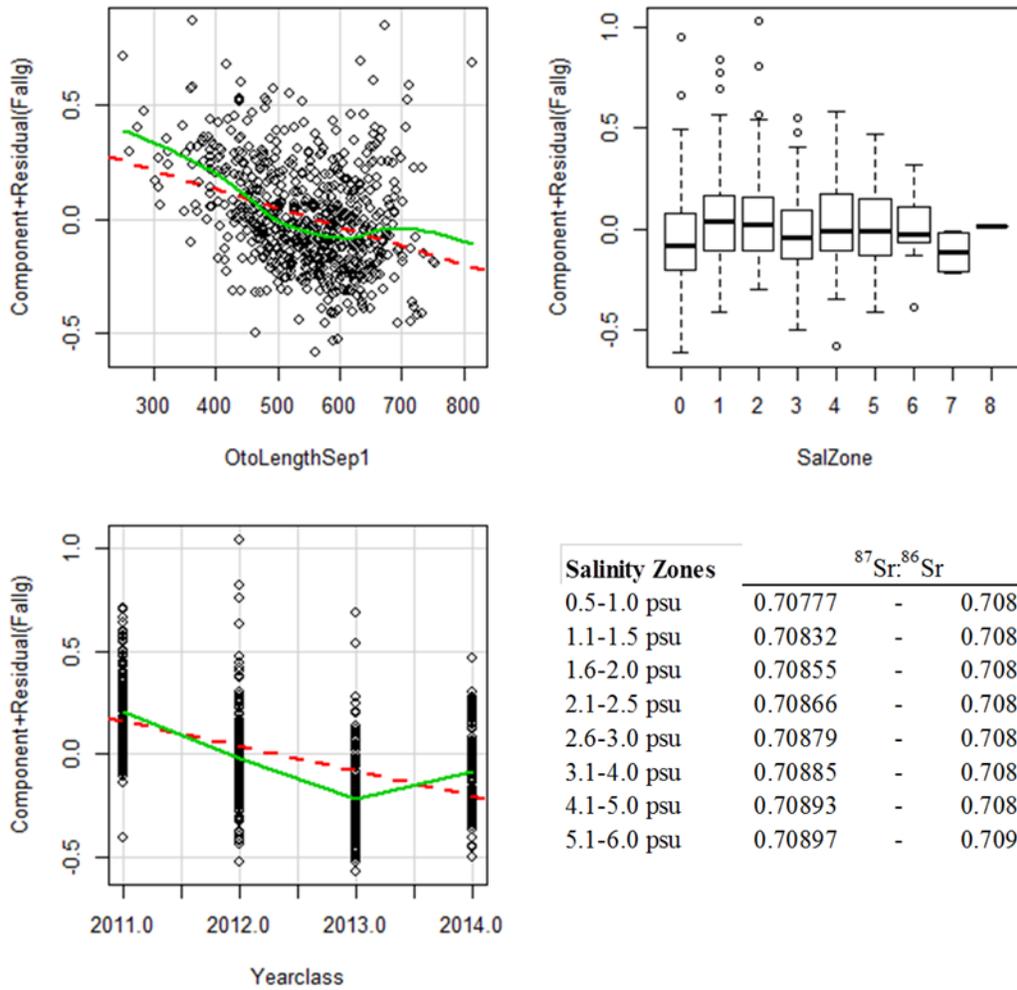
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Component + Residual Plots

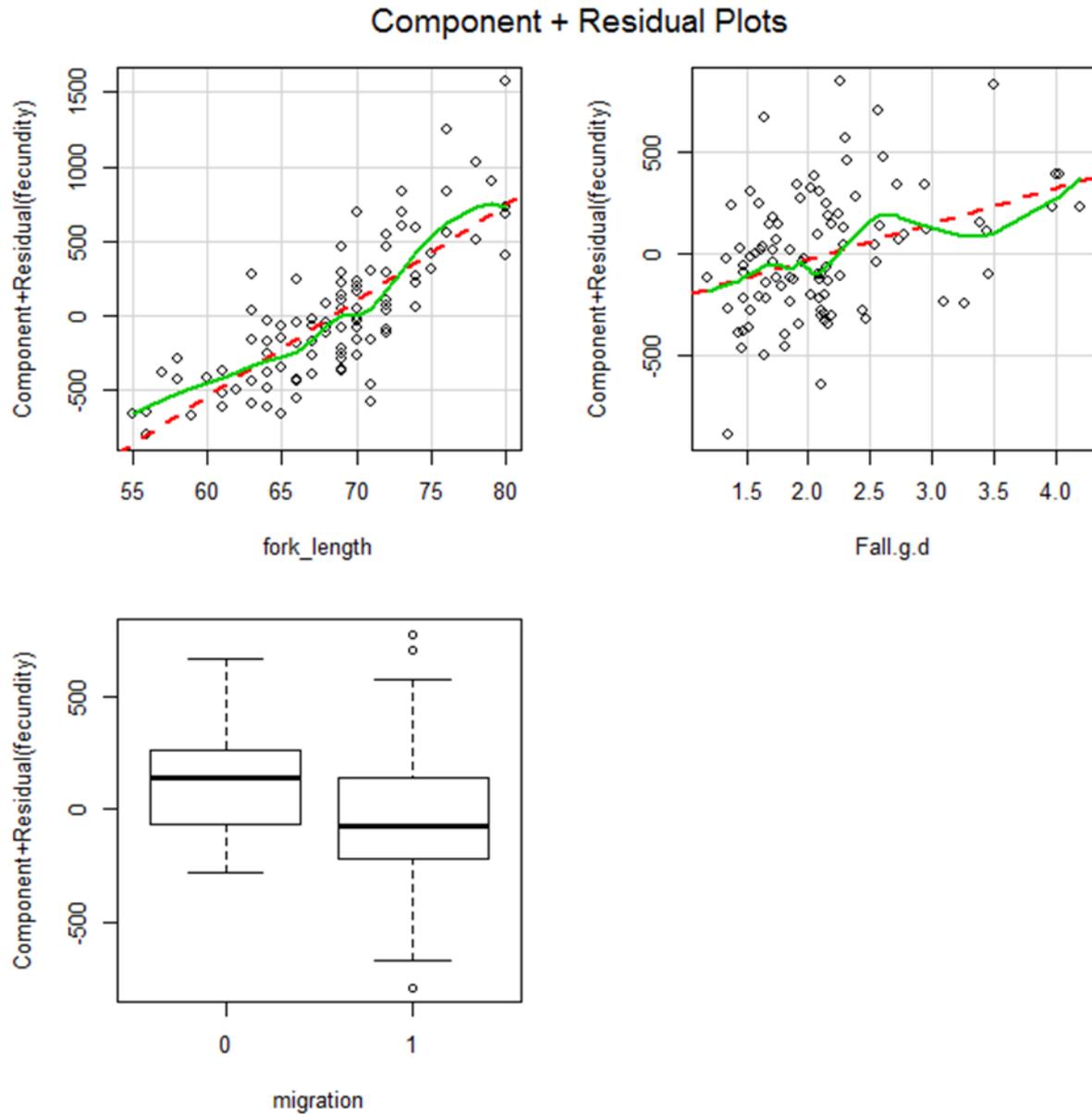


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3032 Figure 6. GLM results for Fall otolith accretion accounting for the otolith size ontogenetic
 3033 effect, and fall salinity habitat derived from otolith strontium isotope ratios and the year effect.

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3037 Figure 7. Linear regression model results for Fecundity with fork-length (mm), fall otolith
 3038 accretion (Fall.g.d) and life history phenotype (0 = freshwater resident, 1 = migratory) as
 3039 predictor variables.

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