APPENDIX A
A Simplified Example of the Implementation of the Limiting Factor Approach with Comparison to Other Forms of Estimation

Given the novelty of the multivariate technique presented in this paper, we provide a simple, synthetic example to demonstrate its implementation.

Suppose we have seven years of data and three candidate explanatory environmental variables, as shown in Table A1.

TABLE A1 | Synthetic data on abundance and covariates.

Year	N_y	ACR_y	X_1	X_2	X_3
0	12.0				
1	35.3	2.942	40	60	20
2	257.5	7.295	60	160	20
3	192.1	0.746	220	10	30
4	13.4	0.070	5	10	40
5	73.5	5.485	50	90	65
6	161.8	2.201	65	30	80
7	533.1	3.295	85	45	40

The Abundance Change Ratio (ACR) is then log transformed and linearly transformed to provide a range from 0, for one third lower than the lowest value, to 1, for one third higher than the highest value as shown in Table A2.

Coefficients α, β can now be estimated for candidate covariates to minimize the residual sum of squares between predicted and actual ACR Index (Equation 8). The resulting R^2 is 0.986 and the estimated coefficients are shown in Table A3.

Data for the above example were deliberately selected to demonstrate the application of limiting factors. Calculating the estimated X* (equation 6) helps demonstrate how limiting factors manifest, as shown in Table A4. The X_i* values are multiplied together to provide the predicted ACR Index for each year.

TABLE A2 | Transformation of the dependent variable.

Year	N_y	ACR_y	Log (ACR_y)	ACR Index
0	12.0			
1	35.3	2.942	0.468	0.776
2	257.5	7.295	0.863	0.946
3	192.1	0.746	-0.127	0.519
4	13.4	0.070	-1.157	0.076
5	73.5	5.485	0.739	0.893
6	161.8	2.201	0.343	0.722
7	533.1	3.295	0.518	0.797
Min		0.070		
Max		7.295		
Min * 0.667		0.047	-1.332	
Max * 1.333		9.724	0.988	
Range			2.320	

ACR Index values are calculated as: $[\log(ACR_y) - \log(0.667*ACR_{min})] / [\log(1.333*ACR_{max}) - \log(0.667*ACR_{min})]$

TABLE A3 | Estimated coefficients for the example.

	X_1	X_2	X_3
α	0.092	0.420	0.452
β	0.017	0.009	0.032

TABLE A4 | Estimated value for X*.

Year	ACR Index	X_1*	X_2*	X_3*	Pred. ACR Index
1	0.776	0.753	0.986	1.000	0.743
2	0.946	1.000	1.000	1.000	1.000
3	0.519	1.000	0.514	1.000	0.514
4	0.076	0.175	0.514	1.000	0.090
5	0.893	0.919	1.000	1.000	0.919
6	0.722	1.000	0.703	1.000	0.703
57	0.797	1.000	0.844	1.000	0.844

Thus, X_1 constrains delta smelt performance (has values less than 1) in years 1, 4, and 5, and X_2 in years 1, 3, 4, 6, and 7. No factor was found to be limiting in year 2 – the year with the maximum ACR in the example. X_3 is shown to be extraneous – never having an influence on the population. By returning to the original data (Table A1), this approach identifies (provides some insight into) when factor conditions are limiting. X_1 was limiting in years 1, 4, and 5 when its values were 40, 5, and 50, indicating that species performance is limiting at least for values of 50 and below but not at values of 60 or above. Similarly, X_2 is limiting at least for values of 60 and below. X_3 is not limiting for values above 20. Thresholds for limiting factors can be estimated using Equation 10. For X_1, X_2, and X_3 the thresholds in the example are 54.9, 61.5, and 17.2, respectively.

To compare methods, we used the same data and estimated coefficients using ordinary least squares for a simple additive model, where abundance in one year was a function of X_1, X_2, X_3, and abundance in the prior year N_{y-1}. This type of model, being additive, would not be expected to capture the interactive nature of factors influencing abundance (Equation 1). Consequently, the R^2 was 0.29 and no coefficients had *p* values less than 0.55. Converting the model to a multiplicative model, by taking the logs of the same explanatory factors, captures the interactive nature of the factors. The R^2 now increases to 0.82 with the minimum *p* value for any coefficient being 0.13. However, that formulation misses the phenomena of limiting factors when and where certain factors do not influence abundance in certain years.

By applying the thresholds estimated previously, 54.9, 61.5, and 17.2 for X_1, X_2 and X_3, respectively, so that the value or each data point (from Table A1) is the actual value or the threshold value (whichever is lower), no additional weighting is applied to values that are not constraining. Applying OLS to this formulation now increases the R^2 to 0.97, X_3 is identified as being extraneous, and the *p* values for $\log(N_{y-1})$, $\log(X_1)$, and $\log(X_2)$ respectively, are: 0.003, 0.215, and 0.006. This example suggests that simple additive models are not suited to detecting limiting factors from historical data and that multiplicative models provide a more realistic representation, especially if thresholds can be identified and incorporated.

APPENDIX B
Model Verification and Validation

To verify that the multivariate estimation procedure -- Equation [6] -- can identify influential covariates from among non-influential covariates, we generated a simulated data set of 50 covariates in which just four influenced the abundance index and 46 were randomly generated and had no influence. Each covariate had thirty uniformly distributed observations and normally distributed disturbance terms, the standard deviation of which could be adjusted. The disturbance terms were included as a percentage adjustment to the original observation. A generated disturbance value of -0.1, for example, would result in the observation being adjusted to 90% of its original value. The purpose of this verification process was to see if the approach could identify the four correct covariates and not include extraneous covariates. We manipulated the disturbance term to simulate observation error by introducing variance into the observations but calculating the abundance index from the covariates before the disturbance term was added. We then increased the disturbance term to see at what point the approach fails.

This verification procedure provided insight in establishing model criteria to improve the likelihood of identifying influential environmental covariates. We observed that the approach tends to overfit the data. Unconstrained, when there are more covariates than observations, the approach can obtain a good fit to the data by setting α to a value close to 1. This allowed a factor to be influential in just one year, but with a small influence. We found that by sequentially removing those covariates with the highest α values, the correct relevant factors could be effectively identified. When there was no observation error and using different starting values, the approach always identified the four correct influential covariates. However, once observation error was introduced, the approach began to introduce extraneous variables. If the average absolute percentage error was less than 10%, the approach typically led to the identification of the correct covariates by sequentially excluding the covariates with the highest α values and the covariates that appeared in the trial solution set only once. In real world settings it is possible that a limiting factor may influence the population only once in 30 years (the number of observations in our simulation), but because of the risk of overfitting and including non-relevant covariates, we decided that it was pragmatic to exclude covariates that appeared in the trial solution set only once. Above an average absolute percentage error of 10%, the approach was found to drop influential covariates, and above 15%, the number of extraneous variables rapidly increased.

We conducted a second verification procedure that compared modeling results using ordinary least squares regression analysis (OLS) with the results from the limiting factor model in the current study. While it is not multiplicative (see Equation [1]), an additive model should provide a linear approximation of the influence of the factors limiting abundance. We regressed the nine covariates from the preferred model against the log of the abundance change ratio and obtained an R^2 of 0.75 (see Table B1 for data and Figure B1 for graphical presentations of the relationships between the covariates and the log of the abundance change ratio). We then applied the thresholds estimated from the limiting factor model to the OLS covariate data so that, in the case of covariates positively correlated with abundance, no covariate values exceeded the threshold and for covariates negatively correlated with abundance, no covariate values were less than the threshold. That adjustment caused no additional weight to be given to covariates when covariate values were expected to be not limiting – consistent with the law of the minimum. Running the regression with applied thresholds produced an R^2 of 0.89 (Table B2), close to the R^2 provided by the limiting factor model (see Table 4). This comparison supports the limiting-factors modeling approach; both methods explained changes in abundance and the explanatory power increased when thresholds were applied. The comparative analysis presented here highlights some of the advantages and disadvantages of each approach. The limiting-factor model had the advantages of being able to consider many covariates simultaneously, many more than the number of observations, and it provides estimates of thresholds that could not be readily derived through regression analysis. The advantages of OLS are that the data are easier to prepare and the significance of the covariates are readily available.

TABLE B1 | Data for covariates from the preferred model used to conduct regression analysis.

Year	Log ACR	Magnitude of FF	SS Food April	% Adq Food: Jul-Aug	Central Temp: Apr	Central Temp: Jul	Last Flush	% Adq EC: Nov-Dec	Power Plants	Predation Index: Sep Oct
1991	0.28	4.33	457	99%	15.24	21.20	0%	82%	838	6.46
1992	-0.65	4.54	104	92%	17.71	22.58	0%	62%	1287	10.48
1993	0.84	4.82	3,287	83%	16.44	22.02	23%	51%	403	10.36
1994	-1.02	4.36	361	75%	17.43	20.92	0%	20%	808	8.31
1995	0.95	5.11	7,582	91%	15.65	21.60	57%	43%	272	13.07
1996	-0.85	4.50	1,389	49%	16.33	22.72	94%	97%	434	12.10
1997	0.38	5.19	1,651	70%	17.21	22.35	0%	96%	705	16.78
1998	0.14	4.42	3,492	72%	16.94	23.33	6%	75%	313	5.24
1999	0.31	4.72	3,873	47%	12.42	22.50	0%	91%	0	10.09
2000	-0.06	4.87	732	53%	17.30	20.32	0%	21%	0	5.07
2001	-0.10	4.57	169	68%	15.49	20.92	0%	56%	2107	11.81
2002	-0.64	4.74	172	62%	16.03	21.94	0%	17%	773	7.56
2003	0.18	4.75	1,065	79%	15.75	23.55	67%	47%	376	11.43
2004	-0.45	4.69	386	58%	16.34	21.23	0%	33%	540	32.72
2005	-0.45	4.65	1,094	23%	16.20	22.92	97%	63%	207	12.24
2006	0.20	5.26	3,424	35%	15.10	23.89	25%	36%	130	19.60
2007	-0.17	4.49	75	78%	16.31	21.73	0%	28%	10	23.23
2008	-0.09	4.48	217	35%	15.98	22.69	0%	100%	73	17.49
2009	-0.13	4.55	429	52%	15.72	22.02	0%	47%	93	20.43
2010	0.23	4.67	436	56%	14.37	21.31	0%	19%	0	25.59
2011	1.07	4.86	3,000	98%	14.10	22.29	1%	96%	0	7.75
2012	-0.91	4.44	137	58%	14.49	22.27	0%	7%	8	17.46
2013	-0.37	4.72	575	6%	17.87	21.34	0%	86%	22	14.64
2014	-0.30	4.21	1,518	51%	16.67	22.05	0%	22%	30	11.34
Thesholds		4.99	457.53	88%	16.67	23.38	49%	0.28	1.26	15.80

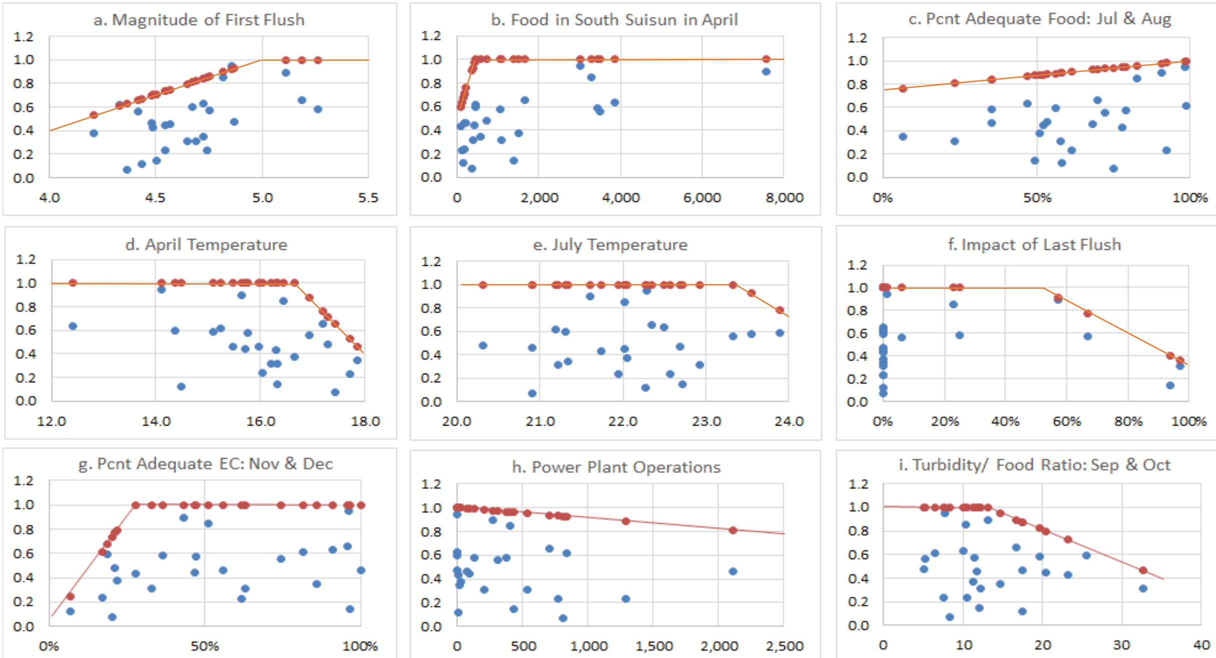

FIGURE B1 | Graphical presentations of the relationships between the covariates (horizonal axis) from the preferred model and the log of the abundance change ratio (vertical axis). Units on the horizontal axes are: a) log of average 30-day flow following first flush, b) µgC/m^3, c) percentages, d) degrees Celsius, e) degrees Celsius, f) percentages, g) percentages, h) megawatt hours produced, and i) is a ratio. Red dots and lines indicate the response functions estimated from the limiting factor analysis.

FIGURE B2 | Comparison of alternative estimation techniques used to contribute to verifying the plausibility of the limiting-factor approach.

TABLE B2 | Regression results when covariates from the preferred model are used to predict changes in abundance.

Covariates	Without thresholds	With thresholds applied
R^2	0.747	0.892
	P-value	*P*-value
Flows		
[2] Magnitude of first flush	0.055	0.001
[6] Percentage of larvae impacted by last flush	0.419	0.001
Food Availability/Turbidity Conditions		
[19] Biomass of copepods in South Suisun in April	0.125	0.047
[20] Percentage of population in adequate prey density in July-August	0.035	0.035
[15] Turbidity/food risk in September-October	0.930	0.018
Water Temperature		
[22] Average temperature in central regions in April	0.294	0.001
[22] Average temperature in central regions in July	0.453	0.153
Salinity		
[29] Percentage of population in adequate salinity ranges in November and December	0.058	0.018
Entrainment		
[12] Powerplant operations	0.185	0.077

We conducted three validation analyses. First, we conducted a cross-validation analysis, wherein we consecutively left out one observation, re-estimated the parameters and estimated the missing ACR Index, repeating this process for each of the 24 annual observations, we then calculated the regression correlation (R^2) between the ACR Index estimated in the cross-validation analysis against the actual ACR Index. The resulting R^2 was 0.70 (Figure B3).

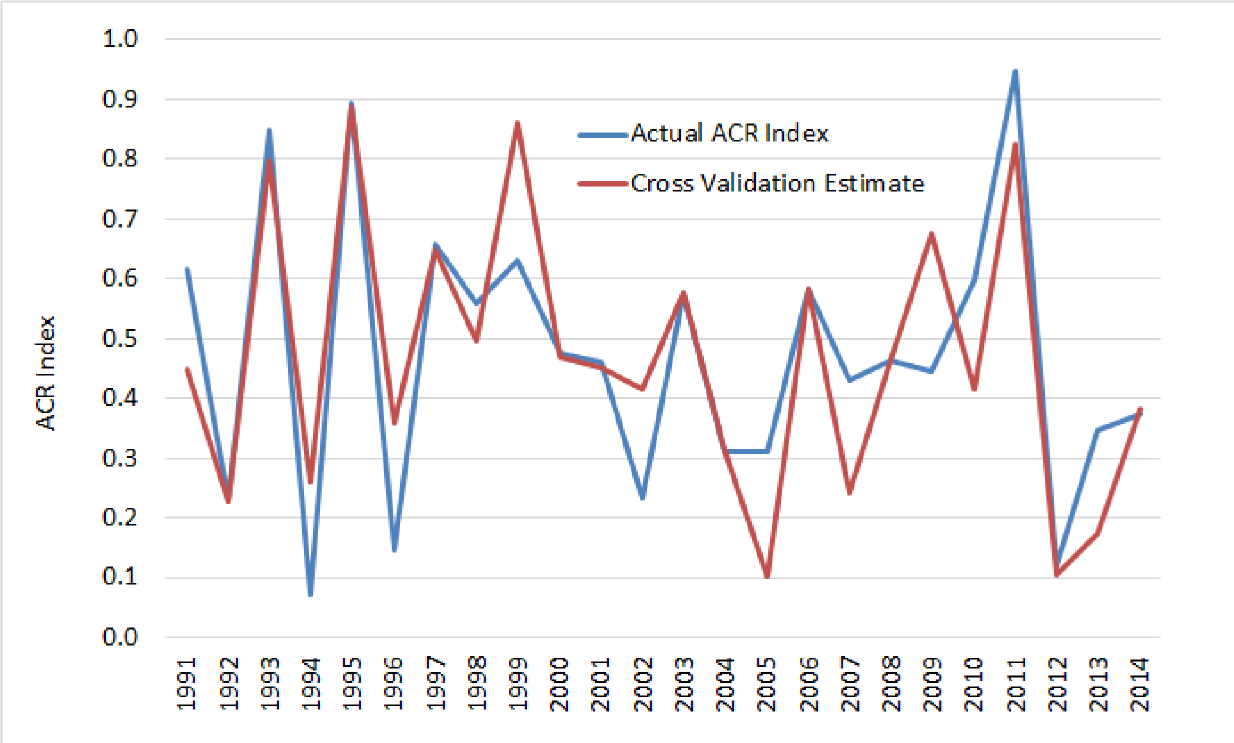

FIGURE B3 | Results of the cross-validation analysis.

Second, we applied the preferred model to estimate the ACR for 15 years that had not been used to develop the model -- 1973, 1978, 1981-1990, 2015-2017 -- to assess the predictive ability of the model. Applying the covariate coefficients from the preferred model to the validation data set consistently overestimated performance of delta smelt. Adding a scalar and a dummy variable for the years following the introduction of the Asian calm (*Potamocorbula amurensis*) in 1986 provided an R^2 of 0.67 (Figure B4). On review of the data, it appeared that entrainment of juvenile delta smelt at the export pumps in the south Delta was a potential limiting factor in some years. That covariate was identified in the covariate selection process but was eliminated because it was projected to influence abundance in only one year in the model-development data set. It may have appeared more frequently but protective measures that were initiated in 2007 may have prevented influences of that factor on abundances after that date. If juvenile entrainment at the export pumps was added to the preferred model, the coefficients were re-estimated and then applied to the validation data set, the R^2 increased to 0.77.

It is likely that the relationship between environmental factors and abundance of delta smelt changes over time. Re-estimating coefficients for covariates from the preferred model using the validation data set, with juvenile entrainment added, , identified only five influential covariates and increased R^2 to 0.88. The five covariates were magnitude of first flush, percentage of larvae impacted by last flush, biomass of copepods in South Suisun in April, juvenile salvage, and power plant operations. The results of the second validation test led us to conclude that juvenile entrainment was likely a limiting factor prior to 2008, but only infrequently

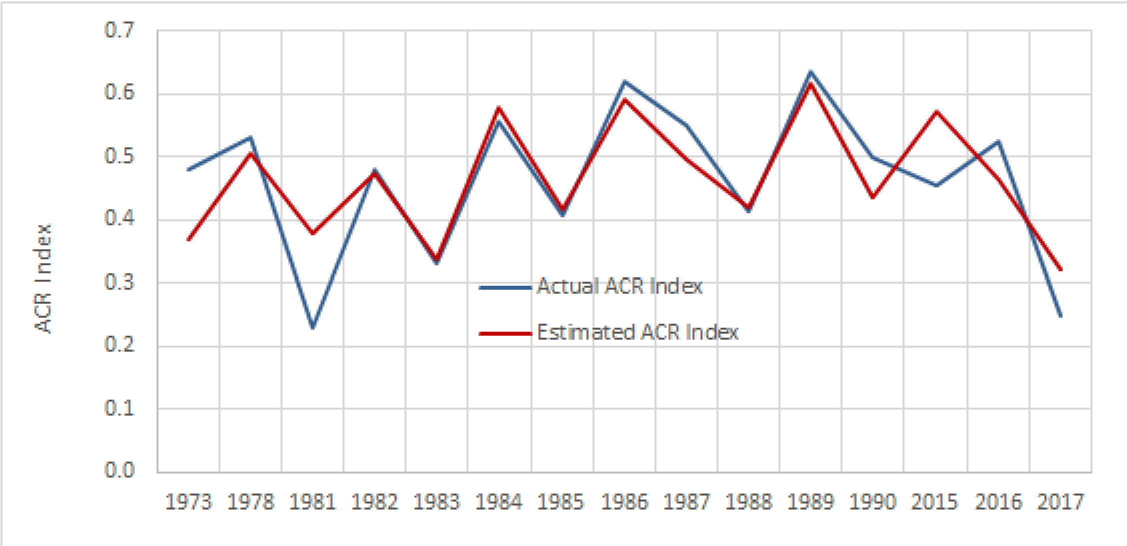

FIGURE B4 | Result of fitting the preferred model to 15 years not in the original data set.

While we sought to identify covariates that could explain year-over-year change in delta smelt abundance for sub-adults in the autumn, other surveys can be used to provide an indication of changes in annual abundance. Polansky (2019) developed abundance indexes derived from a midwater trawl (January to March) from 1991 to 2001 and from the Spring Kodiak Trawl (January to May) from 2002 to 2017. Utilizing those data sets allowed us to calculate an abundance change ratio for adult delta smelt for the period from 1992 to 2014, excluding 2002 (the year in which a calculation of a change ratio would not be appropriate given a change in gear type). The generation of that variable provides the opportunity for a third validation test – the application of the covariates from the preferred model to a different dependent variable – the ACR Index for adults. In this case, the validation test focuses on the sensitivity of selected covariates to noise in the dependent variable, since year-over-year changes in abundance are being measured, but in this case two different life stages – for subadults in autumn and adults in winter. The correlation (r) between these two metrics is 0.78. When the covariate coefficients were applied to the winter abundance-change ratio, the resulting R^2 was 0.62 (Figure B5) when the same covariate coefficients were used. When the coefficients were re-estimated the R^2 increased to 0.85.

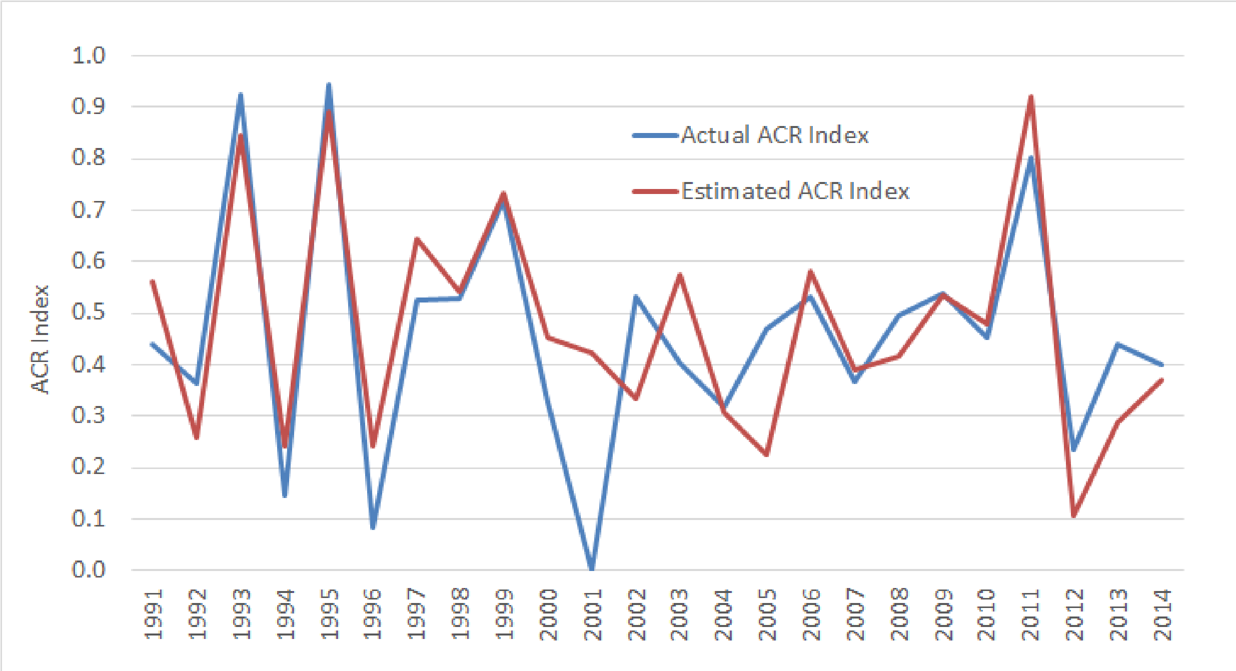

FIGURE B5 | Result of applying the preferred model developed for subadults abundance indices to adult abundance indices, without re-estimating coefficients.

APPENDIX C
Synthetic Review of Influential Environmental Covariates

As part of the validation process in this study, we considered the results obtained herein against other quantitative studies, looking to confirm or question our findings. This discussion has relevance for resource managers looking to interpret and apply our results in conservation planning in the Delta.

A large first flush and consequent large flows across floodplains were associated with excellent performance of delta smelt. Strong and early storm events directly, and through increased snowpack in the upstream mountains, generate flows into the Delta and across floodplains, bringing nutrients and turbidity to the Delta in the winter, modifying the salinity field, and enhancing lower trophic levels of the food web (Sommer et al. 2004). Larger storms produce more extensive flows across floodplains. Delayed snowmelt in the mountains from early storm events can enhance flows well into summer. The inclusion of the magnitude of first flush as an influential factor has a strong conceptual basis (see IEP MAST 2015).

The phenomenon of delta smelt demonstrating particularly good performance in some, but not all, wet years has been acknowledged for some time. Heretofore it was generally considered to influence adult delta smelt performance, as well as their zooplankton prey (USFWS 1996, Moyle 2002, USFWS 2008). We found this explanation unlikely and instead explored the impact on larval fish, specifically the percentage of larval fish that may be transported to unfavorable conditions by large and late storm events. Many wet years do not have a large, late storm event following the appearance of larval delta smelt in the estuary, so that covariate is expected to constrain delta smelt abundance only infrequently – modeling results indicate four years in 24 – but when the covariate does manifest, the impact can be large. In two of the three years, delta smelt abundance was projected to be reduced by 60%.

For a fish that displays many of the characteristics of an r-selected species, recruitment success would be expected to be a major factor influencing the abundance of delta smelt. Two deterministic environmental factors that enhance recruitments rates include an extended duration of the spawning season (incorporated in this study as cool water temperatures in April) and sufficient food for weak swimming larvae (incorporated through strong first flushes that fuel the food web). A deterministic contribution of cooler April water temperatures is consistent with a finding from Polansky et al. (2021) that cooler March-May temperatures were associated with increased recruitment.

The availability of prey for delta smelt during its mid-year rearing period is critical to delta smelt performance (Maunder and Deriso 2011, Hamilton and Murphy 2018). Prey density in summer (July and August) emerged from this analysis as a limiting factor in 20 of 24 years. In years with excellent performance by delta smelt, prey in the summer and fall is plentiful and delta smelt are infrequently found in areas with inadequate prey. In years with poor performance, delta smelt were recorded in areas with lower prey densities more frequently and in clearer-water (circumstances with reduced turbidity).

An interaction between turbidity and prey availability in early fall is apparent, with the turbidity/food ratio in September and October estimated to influence abundance in 7 of 24 years. Presumably, as food becomes limiting and the water clearer, delta smelt hunt longer in clearer water, making them more vulnerable to predation. Prey density and turbidity therefore may be companion phenomena affecting delta smelt performance. In contrast to Polansky et al. (2021), we did not find that prey availability in the late fall and winter influences delta smelt performance. That factor could improve bodyweight, therefore egg production and winter survival. Possibly the importance of winter food was masked by the covariate relating to the magnitude of first flush.

Higher summer water temperatures have been found to be associated with reduced survival in delta smelt (Mac Nally et al. 2010, Maunder and Deriso 2011, Hobbs 2016). Food shortages in summer may be exacerbated by higher temperatures, as the fish's bioenergetic demands increase, hence the summer temperature factor may be manifested through the summer prey-availability factor. Consistent with these findings, high summer water temperatures in the Confluence, Lower Rivers, and Suisun Marsh subregions were associated with reduced performance of delta smelt.

Operations of two power plants along the south shore of the Delta resulted in measured losses of millions of delta smelt to entrainment and impingement in certain years (Matica and Sommer 2005). These power plants now rarely operate, and their cooling systems have been modified to substantially reduce entrainment and impingement impacts on fish. Our results suggest that historic power plant operations in May and June, when sub-juvenile delta smelt frequently occupy areas around the Confluence, were associated with lower abundance indices. However, the addition of the covariate did not increase the adjusted R^2 of the preferred model, suggesting that the additional explanatory power from including this covariate is negligible.

Several environmental factors identified as important by previous investigators were not identified here as deterministic in the multivariate analysis. Delta outflow, quantified here as the location of the 2 parts per thousand isohaline (X2) in the upper estuary, has a major influence on salinity in the upper estuary. It is regulated during the autumn of certain years to enhance the areal extent of low-salinity conditions. Polansky et al. (2021) found no influence of outflow *per se* on delta smelt abundance indices during any life stage, but did find an association between the location of the low-salinity zone in the fall and subsequent recruitment. Salinity has been demonstrated to influence occupancy (LaTour 2016, Bever et al. 2016, Peterson & Barajas 2018, Simonis & Merz 2019). However, our study indicates salinity in the summer and early fall does not influence performance, but salinity is influential in November and December. Delta smelt apparently utilize a suite of conserved molecular mechanisms to adjust their osmoregulatory physiology in response to salinity changes, providing them an ability to tolerate a broad range of salinities, at least up to 12 ppt (Komoroske et al. 2014, Komoroske et al. 2016, Hammock et al. 2017, Davis et al. 2019). Consistent with these studies and our results, Kammerer et al. (2016) found no apparent decrease in delta smelt length, weight, or survival with increasing salinity. We can only speculate as the mechanism underlying the effects of November and December salinity on delta smelt. Salinity varies widely across the upper estuary in November and December. The Suisun Marsh region is frequented by delta smelt and prone to salinity levels that are inadequate for delta smelt (Hamilton and Murphy 2020). The Confluence and Lower Rivers subregions typically do not experience salinity levels that are inadequate for delta smelt at this time of the year. Suisun Marsh is one of the popular spawning areas for delta smelt (Merz et al. 2011, Murphy and Hamilton 2013). When salinity reaches levels that become inadequate for delta smelt, Suisun Marsh is less attractive to pre-spawning adults. The percentage of the delta smelt population in Suisun Marsh in January and February following years when salinity in November and December was adequate (less than 11,500 μS/cm) averaged 68% (in years from 1991 to 2014). When salinity conditions in Suisun Marsh were inadequate in November and December, that average dropped by nearly half (to 38%), suggesting that November and December salinity levels have an influence on subsequent delta smelt occupancy in Suisun Marsh.

Predation on delta smelt and competition by the non-native invasive silversides (*Menidia audens*), identified by Hamilton and Murphy (2018) and Polansky et al. (2021) as affecting delta smelt abundance indices, was not identified here as a deterministic factor. Despite the lack of identification of silversides here as a limiting factor, recent work by Grossman (2016), Schreier et al. (2016), and Mahardja et al. (2016) suggest that silversides predation on delta smelt can be moderate to intensive, with impacts varying subregionally and with turbidity.

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APPENDIX D
Review and Specification of Environmental Factors Potentially Limiting the Abundance and Recovery of Delta Smelt

The purpose of our investigation was to elicit the critical environmental stressors constraining the size of the delta smelt population. In this supplemental section we provide detailed information on the methods and rationales for specification of the candidate environmental covariates. We looked to reliable studies and published observations on delta smelt, its habitats, and known and suspected ecosystem attributes that affect smelt survival and reproduction to inform covariate selection and specification.

We drew on an updated conceptual model of delta smelt (IEP MAST 2015). That conceptual model noted the influence of environmental drivers (air temperature, hydrology, flows, turbidity, contaminant loading, nutrients, water diversions) on habitat attributes for delta smelt (food, predation, temperature, entrainment, toxicity, transport, size and location of the low salinity zone, and harmful algal blooms). Drawing on these environmental factors, for each habitat attribute, we reviewed the literature to identify means for quantifying appropriate covariates consistent with previous studies and/or ecological theory. We then searched publicly available data sources (see section titled “Data Sources” prior to the References) seeking time-series data, and as data permitted, specified covariates (Table D1). The specification of each candidate covariate represents an implicit hypothesis -- that the covariate has a detectable effect on the abundance of delta smelt and is among a set of covariates that could provide the best explanation for annual changes in abundance. With a discrete number of environmental factors affecting habitat conditions for delta smelt, correlations among some covariates can be high. All of the candidate covariates have a plausible ecological basis. The intent here is to elicit from among those, a set of covariates that provide the best explanation for changes in abundance.

Hydrology, flows, and transport

Freshwater flows into, across, and out of the Delta likely affect many other physical, chemical, and biotic factors, thereby influencing recruitment and survival of delta smelt (Kimmerer 2002a, 2004). Flows directly or indirectly influence the location of fishes, migratory cues, habitat availability, feeding success, nutrient delivery, contaminant concentrations, and the relative success of native and non-native fishes (Healey 2007, Lund et al. 2008), interactions with predators (Kimmerer 2002b, Dege and Brown 2004, Kimmerer and Bennett 2005), and may set an upper limit to delta smelt stock recruitment (Moyle and Herbold 1989).

We considered 6 covariates related to hydrology, flows and transport. The first major storm of the water year (October to September) brings increased flows into the Delta. This event is colloquially referred to as the “first flush.” We defined the first flush as an event wherein Delta inflows increase by 12,600 cfs over a 7-day period and Delta inflows stay above 24,500 cfs for 7 days. The first flush brings increased turbidity and food into the Delta. The earlier in the water year that the first flush occurs, the more time pre-spawning adults reside in potentially better feeding conditions and the more time they have to arrive at spawning areas prior to optimal spawning conditions. We specified [1] “start of first flush” as the number of days the first flush occurred before April 1. The larger the first flush, the greater the turbidity, and presumptively nutrient and food supply, flowing into the Delta, which may accommodate the food web for much of the year. To represent the magnitude of the first flush, we specified [2] “the size of the first

TABLE D1 | Candidate covariates included in the analysis of factors influencing population growth rate (the ratio of the abundance-index value in one year relative to the abundance-index value in the prior year).

Factor		Covariate Metric {and expected sign}	Number of periods/yr	Source Data
Hydrology, Flows & Transport				
[1]	Start of first flush	Number of days from start of first flush to April 1 {+}	1	Dayflow
[2]	Magnitude of first flush	Log of average delta inflow (cfs) during the 30 days following the start of first flush {+}	1	
[3]	First flush index	Start of first flush multiplied by size of first flush {+}	1	
[4]	Floodplain quantity	Outflow from Yolo bypass December-June (maf) {+}	1	
[5]	Floodplain duration	Number of days flows in Yolo bypass exceed 5000 cfs {+}	1	
[6]	Impact of last flush	The percentage of fish that hatched prior to the peak of the last flush – an inflow event of more than 60,000 cfs {-}	1	Dayflow 20mm
Entrainment				
[7]	Exports	Average export rate during a 2-month period January to October (cfs) {-}	4	Dayflow
[8]	Adult salvage	Salvage of adult delta smelt December-March/ previous FWMT Index {-}	1	Salvage
[9]	Juvenile salvage	Salvage of juvenile delta smelt April-June/ previous FMWT Index {-}	1	
[10]	OMR in March	Combined average daily flow in March in Old and Middle rivers (cfs) {+}	1	Dayflow
[11]	OMR in April	Combined average daily flow in April in Old and Middle rivers (cfs) {+}	1	
[12]	Power plant operations	Combined power plant production at Antioch and Contra Costs power plants May-June (mWh) {-}	1	
Predation				
[13]	Silverside abundance	Average catch of silversides in the Confluence (number per seine) {-}	1	Beach seine
[14]	Fall predators	– the sum of centrarchids and striped bass CPUE (excl age-0 striped bass) in September and October weighted by the subregional distribution of delta. Average catch of striped bass (no. per trawl)	1	FMWT
[15]	Predation Risk Index	Weighted average of turbidity/prey availability in July-August and September-October	2	
Toxicity				
[16]	Contaminants	Not considered	0	
[17]	Harmful algal blooms	Not considered	0	
Food				
[18]	Prey density	Weighted average biomass of copepods (μg C/m^3) {+}	6	Zoo-plankton

[19]		Average biomass of copepods in South Suisun Bay in April	3	
[20]		Percentage of delta smelt population in adequate prey density ranges {+}	6	
Temperature				
[21]	Ambient temperature	Maximum 15-day average air temperature at Davis, CA during a year (ºC) {-}	1	UCD
[22]	Surface water temperature	Average water temperature in – Suisun Marsh, Confluence, Lower Rivers (ºC) April to July {-}	4	Trawl data
[23]		Weighted average of water temperature July-August (ºC) {-}	1	
[24]		Percentage of population in suitable water temperature during July & August {+}	1	
[25]	Spawning duration	Estimated duration of the spawning window (days) {+}	1	20mm
[26]	End of spawning	Julian day that average daily water temperature at Rio Vista exceed 20˚C	1	CDEC
Salinity and the Low Salinity Zone (LSZ)				
[27]	Size and location of the LSZ	Avg X2 location - location of the 2 ppt isohaline (km) {-}	5	Dayflow
[28]	Electrical conductivity	Weighted average of salinity conditions (µS/cm) {-}	2	Trawl data
[29]		Percentage of delta smelt population in adequate salinity ranges {+}	4	
Turbidity				
[30]	Secchi depth	Weighted average of turbidity conditions (cm) {-}	5	Trawl data
[31]		Percentage of delta smelt population in adequate turbidity ranges {+}	5	
Total			64	

flush" as the log of average Delta inflow during the 30 days following initiation of the first flush.

The previous two factors may have a synergistic impact; for example, large, early flows may possibly be more productive than large late flows. To represent that phenomenon, we specified [3] a "first-flush index" by multiplying the previous two factors together.

Feeding the delta with water and nutrients is Yolo Bypass, a wide floodplain approximately 65,000 acres in area and 38 miles long. It is designed to divert flood water around the City of Sacramento. It begins to operate when Sacramento River flows begin to reach flood stage (33.5 feet at Fremont Weir, which occurs at a river flow of approximately 55,000 cfs). The Yolo Bypass is considered a rich source of nutrients and food for the Delta. To represent its use, we specified two covariates: [4] "floodplain quantity" – the volume of water flowing through the Bypass from December through June, and [4] "floodplain duration" – the number of days flows in Yolo Bypass exceeds 5,000 cfs in January through April.

Population growth rates for delta smelt tend to be greater in wet years, but this is not true for all wet years. For example, 1983 and 1996 were two wet years in which the performance of delta smelt was poor. Previous investigators have suggested that the poor performance of delta smelt in wet years was due to high flows adversely influencing the distribution of adults and their prey (USFWS

1996, Moyle 2002, USFWS 2008). Rather, we hypothesize that large inflows late in the spring transport newly hatched delta smelt that have poor swimming ability, through the Delta and into the western waters of the estuary that are likely excessively saline, therefore unfavorable for delta smelt (USFWS 2008 p.148, IEP MAST 2015). We specified covariate [6] the "impact of the last flush" as the percentage of fish that hatched prior to the peak of the last flush – an inflow event with a peak of more than 60,000 cfs. This percentage was calculated by first deriving a cumulative distribution of larval hatch by Julian day using length data of larval fish less than 15mm in the 20mm survey and back-casting a hatch date assuming a growth rate of 0.35mm/day following hatching at 5 mm with a 5-day post-hatch phase of no-growth (Bennett 2005). For years prior to the 20mm survey (i.e., 1991-1994) hatching was assumed to occur linearly, ending 14 days after the end of spawning. End of spawning was estimated to occur when water temperatures at Chipps Island exceed 17°C, a figure derived based on correlations with 20mm data.

Entrainment

The Central Valley Project and State Water Project have large pumping plants at the south end of the Delta. Each project has fish collection facilities upstream of the pumps that record the number of delta smelt salvaged likely reflecting a small proportion of delta smelt losses. Total take (entrainment) includes losses of delta smelt prior to salvage, fish that die at the pumps, and fish that are salvaged, but subsequently die. Large numbers of delta smelt have been estimated to be lost at these water-export projects (Brown et al. 1996, Kimmerer 2008, Miller 2010, Kimmerer 2011). Adults are typically taken at the pumps from December through April, and juveniles from April through June, with considerable year-to-year variation (Hymanson and Brown 2006). Only juveniles greater than 20mm are recorded; delta smelt of less than 20mm are likely frequent in the eastern estuary in March and April but are not recorded. Several previous analyses did not find significant relationships between salvage and subsequent delta smelt abundance (USFWS 1996, Mac Nally et al. 2010, Thomson et al. 2010, Maunder and Dersio 2011, Miller et al. 2012, Hamilton and Murphy 2018), while other studies have found some evidence of such a relationship (Rose et al. 2013, Polansky et al. 2020). Because the lack of a relationship in some of the previous studies may be due to an incorrect specification of entrainment losses, we developed 5 specifications for entrainment at water export facilities: [7] "exports" – the average export rate, in cfs, during each 2-month period from January to October, [8] "adult salvage" – the salvage of adult delta smelt from December through March divided by the previous FWMT Index, the denominator being used to correct for population size (USFWS 2008); [9] "juvenile salvage" – the salvage of juvenile delta smelt from April through June divided by the previous FMWT Index. While these latter two covariates only measure salvage, the implicit assumption is that salvage is proportional to entrainment, and if so, capture the impact of entrainment. Two additional covariates represent entrainment: [10] "OMR in March" and [11] "OMR in April" – the combined average daily flow in Old and Middle rivers in cfs in March and April respectively. These latter two covariates are intended to capture the flow of water towards the water-export pumps during the period when larval smelt (less than 20mm in length) are likely present in the Delta.

Two power plants are located near the confluence of the Sacramento and San Joaquin rivers, referred to as the Contra Costa and Pittsburg power plants. The facilities are located in the low-salinity rearing habitats of delta smelt. Historically, the power plants used unscreened diversions for once-through cooling; their operations presented concerns because of both the temperature and toxicity of discharged water (USFWS 2008). Current data on entrainment are few, but tens of millions of delta smelt were estimated to have been entrained at power plant diversions in

1978 and 1979 (Matica and Sommer 2005). The two plants combined, at maximum capacity, could circulate 3,240 cfs or 10,500 acre feet of water per day (Matica and Sommer 2005). As with the water project facilities, we hypothesized the greatest risk was to young fish and consequently specified [12] "Power plant operations" reflecting combined power-plant production at Antioch and Contra Costa power plants during May and June (mWh).

Predation

Although delta smelt have coexisted with non-native, piscivorous fishes for many decades, the number of species and abundance of some species have increased dramatically in recent years (Brown and Moyle 2005, Calamusso et al. 2005, Mueller et al. 2005). We developed covariates to reflect abundance of the two major predator groups that feed on delta smelt.

Inland silversides (*Menidia beryllina*), which feed on the eggs and larvae of young delta smelt, have increased in numbers in recent years to the extent that they may be causing population-level impacts (McComas and Drenner 1982, Bennett 1995, Bennett and Moyle 1996, Bennett 2005, Mahardja et al. 2016, Hamilton and Murphy 2018). We therefore specified [13] "silversides abundance" as average catch of silversides (number per seine) in the Confluence from beach seine data collected by USFWS. Beach seines are not conducted uniformly throughout the data so, rather than weighting silversides abundance by the distribution of delta smelt (as we had done for other covariates) we selected the silversides catch in the Confluence to reflect predation pressure from silversides throughout the range of delta smelt.

Juvenile delta smelt are subject to predation by a number of fish species (Schaefer 1970, Rulifson and McKenna 1987, Dill and Cordone 1997, CDFG 1999, Brown 2003, Nobriga & Feyrer 2007). We therefore specified [14] "fall predators" – the sum of centrarchids and striped bass CPUE (excl age-0 striped bass) in September and October weighted by the subregional distribution of delta. The species comprising the list of fall predators included black crappie (*Pomoxis nigromaculatus*), white crappie (*Pomoxis annularis*), bluegill (*Lepomis macrochirus*), green sunfish (*Lepomis cyanellus*), warmouth (*Lepomis gulosus*), redear sunfish, (*Lepomis macrolophus*), spotted bass (*Micropterus punctulatus*), and striped bass age-1 and older (*Morone saxatilis*).

Toxicity

Contaminants have acute and chronic impacts on aquatic organisms. Contaminants enter the Delta from urban and agricultural runoff, municipal wastewater effluent, atmospheric deposition, recreational and commercial boating activities, naval operations, and as legacy effluent from historical mining operations and impair Delta waters (SWRCB 2010). The means by which the contaminants are transported from application sites to surface waters is relevant but complex, depending in part on proximity to water ways, storm intensity and storm duration (Daum and Hoenicke 1998, Kuivila 1993, Kratzer et al. 2002, Teh et al. 2005, Guo et al. 2007). Once in the estuary, contaminants are transported by complex sediment re-suspension and distribution processes (Daum and Hoenicke 1998). Numerous sampling programs have detected contaminants at toxicologically relevant concentrations, often in combination, in Delta water and sediment samples (Thomson et al. 2000, Oros et al. 2006, Orlando et al. 2013, Smalling et al. 2013). However, in the San Francisco Estuary, the ecological effects of contaminants remain unquantified and for pelagic fish are difficult to investigate with standard methods based on acute toxicity (Brooks et al. 2012). There is also increasing evidence that the interactive effects of contaminants can compound to show adverse effects at concentrations at which no effects were observed for individual contaminants (e.g., Baas et al. 2009, Silva et al. 2002, Walter et al. 2002). The large number of likely contaminants (including metals, nitrogen-rich effluents, pesticides, and cyanobacterial blooms), the influence of their complex interactions on aquatic organisms, and the lack of time-series data on those contaminants made it infeasible to specify relevant covariates for toxicity in our study.

Food

Feeding success influences long-term trends in abundance of several pelagic fishes in the Delta (Baxter et al. 2008). Feeding success for delta smelt is a function of the size of individuals, their location within the estuary, and the type and density of prey (Hobbs et al. 2006, Kimmerer et al. 1994, Kimmerer and Orsi 1996, Lott 1998, Nobriga 1998, Nobriga 2002, Moyle 2002). Co-occurrence patterns of delta smelt and their prey affect subsequent fish abundance (Stevens et al. 1990, Miller 2000, Resources Agency 2007). Dramatic reduction in the densities of prey for delta smelt (Lott and Nobriga 1998) is a likely contributor to its decline in abundance (Kimmerer et al. 1994, Kimmerer and Orsi 1996, Nobriga 2002, USFWS 1996, Moyle 2002).

Delta smelt eat copepods (zooplankton) almost exclusively, especially during early life stages (Nobriga 1998). Copepods consumed by delta smelt include *Eurytemora affinis*, *Sinocalanus doerrii, Pseudodiaptomus forbesi*, *Arcartiella sinensis* and *Limnoithona tetraspina* (Nobriga 2002, IEP MAST 2015). Larval delta smelt are primarily dependent on *Eurytemora, Pseudodiaptomus,* and several cyclopid species (Nobriga 2002); delta smelt at all sizes appear to prefer *Eurytemora* to more-recently-arrived non-native copepod species (Lott and Nobriga 1998).

We quantified prey biomass, and density of preferred prey species, both across the general distribution of the delta smelt and weighted by seasonal proximity of prey to delta smelt. We also included covariates for prey availability conditions in Suisun Marsh, North Suisun, and South Suisun, separately, in April under the hypothesis that larval delta smelt will have increased feeding success, therefore grow more quickly, and have better survival rates when prey is plentiful. *Acartia* spp. were excluded as they primarily occur in higher-salinity waters and have not been identified in gut content analyses in delta smelt (IEP MAST 2015).

We specified three sets of food covariates: [19] average biomass of copepods, using the data is Table D2, in each subregion weighted by the distribution of delta smelt, for each two-month period throughout the year, and [20] the percentage of delta smelt population in subregions with adequate prey density (Hamilton and Murphy 2020) during each two-month period throughout the year.

TABLE D2 | Prey items and assumed biomass for delta smelt.

Prey Items for adult delta smelt	Biomass (µgC/M^3)
Acartiella sinensis	3
Diaptomidae	3
Eurytemora affinis	2.5
Pseudodiaptomus forbesi	3
Pseudodiaptomus marinus	5
Sinocalanus doerrii	4
Tortanus spp.	5.4
other calanoid copepod adults	3
Additional prey items for juvenile delta smelt	
copepodids	1
Acanthocyclops vernalis	3
Limnoithona spp. (0.3g),	0.3
Oithona davisae	0.2
Oithona similis	0.5
Oithona spp.	1

Temperature

Water temperature affects the bioenergetic demands for fish and so it is plausible that temperature could influence the performance of delta smelt during any season; however, two periods of the year appear to have particular relevance. The lethal temperature for delta smelt is close to 25°C (Swanson et al. 2000); they have an aversion to warm water, with water above 22.1 being unsuitable (Hamilton and Murphy 2020), suggesting that performance of delta smelt could be impacted at temperatures close to the unsuitable level. Specifying water temperatures can be problematic. Some continuous recorders for water temperature exist in the Delta, but are not present in every subregion. Water temperatures are typically recorded during fish surveys, but these might miss extreme seasonal conditions, depending on when surveys are conducted. Given the different metrics, we specified four covariates for water temperatures. Water temperatures in the Delta are primarily affected by air temperature, which has been recorded continuously for longer periods than water temperature. The closest weather station with long-term air temperature data is at Davis, California. We specified [22] "Ambient temperature," the 15-day average air temperature at Davis, during a year to reflect the temperature extremes. During the summer, Delta smelt are most frequently found in Suisun Marsh, Confluence, and Lower Rivers subregions. We calculated [23] the "average water temperature" across these three regions from fish survey data for each month from April to July. However, that may not capture conditions the fish experience. We therefore specified [24] the "weighted average of water temperature" during July and August, with weights being the percentage of delta smelt in each subregion. But this might be misleading because some fish might be in subregions with suitable water temperature and some in subregions with unsuitable water temperature. We specified [25] the percentage of delta smelt in suitable water temperature conditions during July and August, that is, temperatures less than 20.8^{o}C (Hamilton and Murphy 2020).

Native fishes in the Delta tend to spawn earlier in the year in cooler water than most non-native fishes (Meng and Matern 2001, Feyrer 2004, Grimaldo et al. 2004, Sommer et al. 2004). Water temperatures during spawning and hatching affect recruitment rates. Increased duration of optimal temperatures during spawning enhances recruitment: the number of multiple spawning events increases, a higher proportion of eggs hatch, first feeding occurs earlier, and larval length at hatch is greater (Bennett 2005, Damon et al. 2016). To capture the effect of water temperature on spawning and hatching we used [23] the "average water temperature" across Confluence and Lower Rivers subregions from fish survey data for each April. We also calculated two additional covariates: [26] "spawning duration" and [27] the "end of spawning." The former is the estimated duration of the spawning window, derived by calculating the cumulative distribution, by date, of fish hatching, where hatch date was calculated from the length of larval fish less than 15mm in the 20mm survey, assuming a growth rate of 0.35mm following hatching at 5 mm with a 5-day post-hatch phase of no-growth (Bennett 2005). Spawning was assumed to occur 2 weeks before hatching (Bennett 2005). To eliminate outliers, we assumed the spawning period to start at the 5th percentile and end at the 95th percentile. For years prior to 1995 (before the 20mm survey) we identified a correlation between start and end dates and water temperature at Chipps Island, using it to infer spawning duration for the years 1991-1994. The covariate "end of spawning" was the Julian day at which the daily average water temperature at Rio Vista exceeded 20 degrees (following Rose et al. 2013).

Salinity and the low-salinity zone

The location of X2, which serves as a water management standard in Delta water resource planning, is the distance from the Golden Gate to the point where daily average salinity is 2 parts per thousand at 1 meter above the estuary bottom. It is correlated with multiple Delta attributes, including inflow to the Delta (Kimmerer 2004). Numerous positive and negative linkages between X2 and delta smelt abundance have been postulated (Estuarine Ecological Team 1997) or demonstrated (Herbold 1994, Stevens and Miller 1983, Jassby et al. 1995, Moyle et al. 1992, Moyle 2002, Kimmerer 2002b). X2 location has a strong relationship with the extent of the low-salinity zone (Kimmerer et al. 2013). We specified 5 covariates: [28] the "average X2 location" for each two-month period from January to October.

Salinity is measured as electrical conductivity in the Delta fish surveys. Since the location of X2 does not necessarily indicate the salinity conditions that delta smelt experience, we specified covariates for salinity that were similar to those developed for temperature: [29] the weighted average of salinity conditions experienced by delta smelt for the months when salinity is of most concern (July-August, September-October) and [30] the percentage of fish in suitable salinity conditions in prior November-December, January-February, July-August, September-October using suitability thresholds reported by Hamilton and Murphy (2020).

Turbidity

Turbidity may increase feeding success and reduce predation rates on delta smelt (Abrahams and Kattenfeld 1997, Baskerville-Bridges et al. 2004, Nobriga et al. 2005, Feyrer et al. 2007). Paralleling temperature and salinity, we specified two turbidity covariates: [31] the weighted average of turbidity conditions experienced by delta smelt for 5 groupings of months from January through October when delta smelt are actively feeding (Jul-Aug, Sep-Oct) and [32] the percentage of fish in suitable turbidity conditions in prior November-December, January-February, April-June, July-August, September-October using suitability thresholds reported by Hamilton and Murphy (2020).

DATA SOURCES

20MM - CDFW 20MM Survey
ftp://ftp.dfg.ca.gov/Delta%20Smelt/20-mm.mdb

BMWT - CDFW Bay Midwater Trawl,
ftp://ftp.wildlife.ca.gov/BayStudy

CDEC - CDEC http://cdec.water.ca.gov/cgi-progs
Rio Vista (D24A)

Beach Seine - USFWS Beach Seine Survey
http://www.fws.gov/lodi/jfmp

Dayflow - CDWR Dayflow.
https://water.ca.gov/Programs/Environmental-Services/Compliance-Monitoring-And-Assessment/Dayflow-Data

FMWT - CDFW Fall Mid-water Trawl (FMWT) Survey
ftp://ftp.dfg.ca.gov/YoungFishesProject/FMWT%20Data/

Salvage - CDWR Salvage data
ftp://ftp.dfg.ca.gov/salvage

SKT - CDFW Spring Kodiak Trawl
https://wildlife.ca.gov/Conservation/Delta/Spring-Kodiak-Trawl

STN - CDFW Summer Tow Net
https://wildlife.ca.gov/Conservation/Delta/Townet-Survey

Trawl data reflects multiple sources: FMWT, 20MM, STN, SKT, BMT

Zooplankton - CDFW Zooplankton Survey by request from DFW at
http://www.water.ca.gov/bdma/meta/zooplankton.cfm

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