Appendix F, Life Cycle Analyses

Attachment F.1 Maunder and Deriso Revised Model

F.1.1 Model Overview

The Delta Smelt life cycle model published by Maunder and Deriso (2011) was updated in 2021 following the approach of Polansky et al. (2021) as far as practical, by modifying and generalizing the originally published model.

An update to the Maunder Deriso life cycle model (henceforth referred to as the MDR) models a single cohort life strategy species that dies after it reproduces (i.e., the final transition is from adults to recruits and very few adults survive to the next time period e.g., an annual species). It is modelled in a Frequentist state-space framework allowing for both process variation and observation error. Transition between stages (i.e., survival and the stock-recruitment relationship) can be a function of density and covariates, in addition to unexplained temporal variation (process error). Covariates can also be used to influence the density dependent relationship or the survey catchability (bias). The model can be fit to any number of surveys representing any of the stages. There is also flexibility in the timing of density dependence, surveys, process error and covariates. The covariates can be estimated as random variables to represent uncertainty in the measurement of the covariates, dealing with missing covariates, or allowing for uncertainty in projections, but this is not illustrated here.

Relative to the 2011 publication, the MDR includes an additional stage (sub-adults), with stages adjusted appropriately, fit to two additional indices of abundance for adults (spring midwater trawl prior to 2001 and spring Kodiak trawl for 2001 and later). Additionally, catchability (survey bias) is now estimated for the spring midwater trawl, and the likelihood function was changed to a log normal. The time period was also extended and now includes cohorts between 1995 and 2015. Potential covariates of survival and recruitment were borrowed from Smith et al. (2021). The surveys were fit at the start of the stage before any other processes occurred. Covariates and process variation were added after density dependence when it was included.

F.1.2 Model Development

F.1.2.1 Methods

In 2021 and 2022, Mark Maunder developed a generalized life cycle model, extending the model described by Maunder and Deriso (2011) [henceforth referred to as the M&D model] and applied the resulting model to Delta smelt, with candidate covariates and several of the model extensions borrowed from Polansky et al. (2021). Important differences between the original M&D model and the application of Polansky et al. nevertheless remain, and include model structure, surveys used, inference method, covariates tested and consideration of density dependence; these differences are summarized in Table F.1-1. The updated model, hereafter referred to as the MDR, is programmed in Template Model Builder (TMB; Kristensen et al. 2016) within R (R Core Team 2017) in a Frequentist, state-space framework allowing for both process variation and observation error. Transition between stages (i.e., survival and the stock-recruitment relationship) can be a function of density and covariates, in addition to unexplained temporal variation (process error). For the purposes of the application described herein – and based on previous analysis showing near equal support for density-dependent and -independent model forms – all transitions were assumed to be density-independent.

The MDR was modified from the original M&D model to include an additional stage (sub-adults; with the other stages adjusted appropriately) and estimate catchability (i.e., survey bias). The MDR is also fit to two additional indices of abundance for adults (spring midwater trawl prior to 2001 and spring Kodiak trawl for 2001 and later), and the likelihood function was changed to a log-normal likelihood (see Appendix A, *Facilities Description*, for additional detail). The period (1995-2015) and the covariates used by Polansky et al. (2021) are different than those used in Maunder and Deriso (2011), and so were also updated in the MDR.

F.1.2.1.1 Workflow for application of MDR to Scenario Evaluation

Building from Mark Maunder's 2021 work, ICF has extended the MDR for evaluation of alternative management scenarios. The underlying population dynamics model, and the statistical model fitting procedures, as coded in C++ were not altered, but ICF significantly expanded upon the R code used to fit, validate, and project the population dynamics model given alternative sets of environmental covariate values and associated model parameter estimates. Primary extensions include streamlined processing of covariate data to allow for rapid iteration between model formulations, an automated process for generating scenarios with modified covariate values based on hypothetical management actions, a series of functions for producing visualizations that aid in model interpretation and validation, and a function-based approach to model projection under multiple scenarios. The general methods for such scenario evaluation are as follow:

1. Select candidate covariates of each life-stage transition.

   An initial, extensive set of covariate data taken from the analysis of Smith et al. (2021) was provided by USFWS and served as the candidate set for model selection.

2. Select a base model.

   The "best" model was defined as the combination of covariates resulting in the lowest Akaike's Information Criterion and was identified through a hybrid approach that used both stochastic and step-wise methods (see below).

3. Fit the model to historic abundance indices and covariate data.

   The model is fit using maximum likelihood with optimization algorithms provided by TMB.

4. Project the model with baseline and alternative covariate values.

    a. Although theoretically possible, the state-space nature of the MDR poses challenges for backward-looking projection. That is to say, it is difficult to "rewind" the model to the beginning of the time-series used in model fitting and project forward from the historical abundances. As a result, model runs were projected forward from 2015, the last year in the data used for fitting.

    b. The predicted effect of various management actions was evaluated by modifying the historical covariates (Old and Middle River [OMR] and Delta Outflow) to reflect alterations in water operations. Modified timeseries of covariates were then used in the model projection phase. A baseline projection was also created by recycling all 1995-2015 covariate data.

5. Calculate annual population growth rates for the projected populations and compare them to baseline projections.

    a. Projected populations trajectories for each scenario were compared with one another and with the baseline (i.e., projection with unmodified historic covariates) to evaluate the relative performance of Delta Smelt under varying levels of entrainment loss during December-April.

    b. Note that the projections should be used only for comparative purposes and should not be interpreted as accurate predictions of future abundances. In developing and evaluating the MDR, Mark Maunder noted that forward projection resulted in highly uncertain abundance estimates because even after the inclusion of covariates and density dependence, a large amount of unexplained temporal variation in survival remains (see the discussion in Appendix A).

F.1.2.1.2 Model Selection

A wide range of environmental and operational covariates have been hypothesized to impact recruitment and/or life-stage specific survival in Delta Smelt. As a statistical model, the MDR is suitable for identifying and evaluating the strength of correlations between each of the modeled vital rates and one or more candidate covariates. In contrast to a mathematical simulation, such as the Delta smelt individual based model (IBMR), the form and strength of any covariate influence cannot be manually specified, and so hypothetical management scenarios can only be compared through projection when a managed covariate is found to significantly influence one or more vital rate. A commonly used approach for selection of an optimal model is to begin with all candidate covariates included and then sequentially remove variables based on some selection criterion. However, this stepwise approach has several important limitations when applied to the MDR model:

1. Inclusion of multiple correlated covariates of a single life-stage transition in the model tends to produce poor fits and obscure the influence of such covariates. Stepwise selection must therefore be initiated from a set a candidate set where covariates of a given transition are not highly correlated (i.e., r> ~0.6-0.7).

2. The importance of a covariate may depend on the inclusion of another covariate in the same, or a separate life-stage transition, and in such cases a stepwise approach to model selection can exclude an important covariate.

3. Retention of a covariate may depend on whether density dependence is included in one or more of the life-stage transitions.

A global model selection approach where all potential combinations of covariates are evaluated would theoretically overcome these limitations, but such an approach is precluded by computational time: given a large pool of potential survival and recruitment covariates, and four separate transitions to which covariates may be applied, the number of potential model parameterizations is extremely large. As an alternative approach, a stochastic model selection procedure was therefore developed that attempts to realize the benefits of global model selection (i.e., identifying potential synergies or dependencies between covariates) within a reasonable amount of computational time. The stochastic approach involved random selection of two covariates per transition from the complete set of candidates (Table F.1-2) and random selection of which, if any, life stages were subject to density dependence (options for density dependence were weighted such that there was equal probability of no density dependence and *any* density dependence).

For each randomly generated model, Akaike's Information Criterion corrected for small sample sizes (AICc) was calculated as an index of overall model performance. Next, 80% confidence intervals were calculated for each covariate in the model, and were evaluated for significance (i.e., overlap of zero). This stochastic model fitting procedure was repeated 400,000 times. After completion of stochastic model building, the results were summarized by calculating, for each candidate covariate, the proportion of times the covariate was significant in a model, given that it was selected (i.e., 80% confidence interval excluding zero), and the average AICc of the models in which a covariate was included. In addition, the model with the lowest overall AICc score was used as a starting point for a final, stepwise model selection approach in order to evaluate whether a better model could be produced by including more or less than two

F.1.3 Model Application

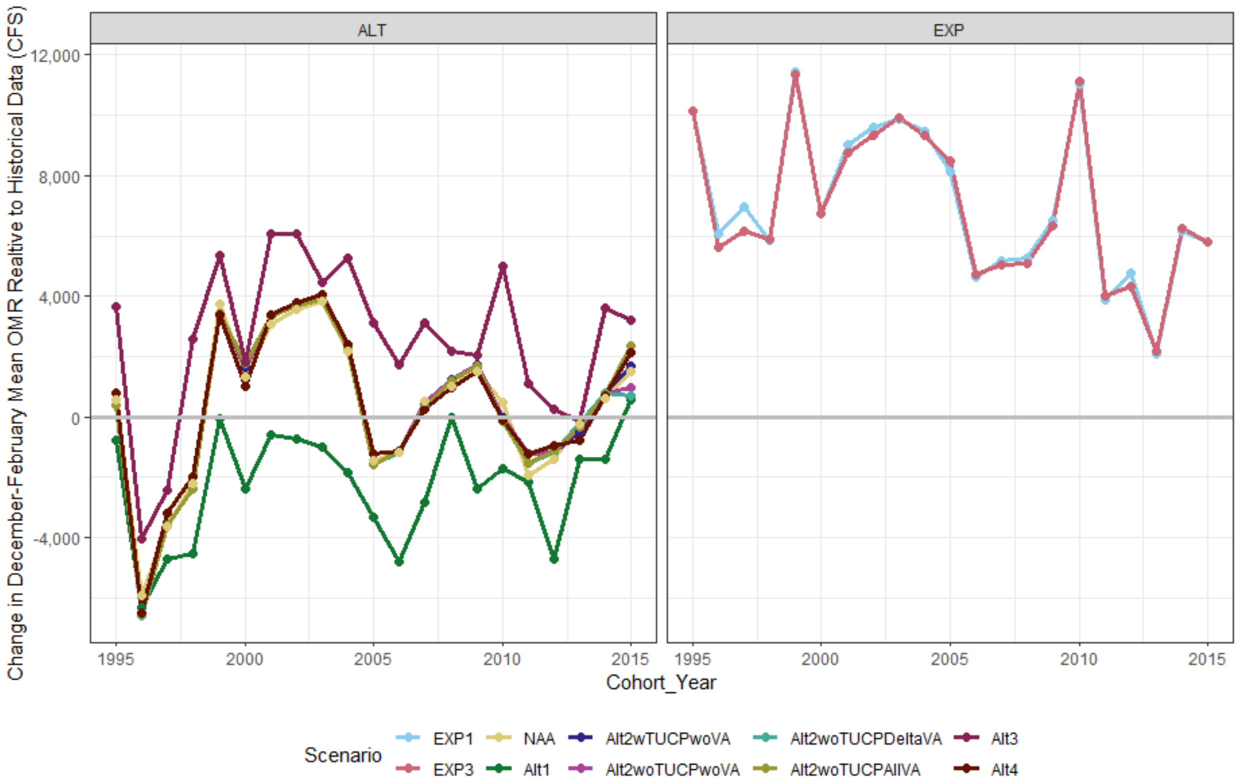

Figure F.1-1. Difference in December-February mean OMR relative to observed data used for model fitting.

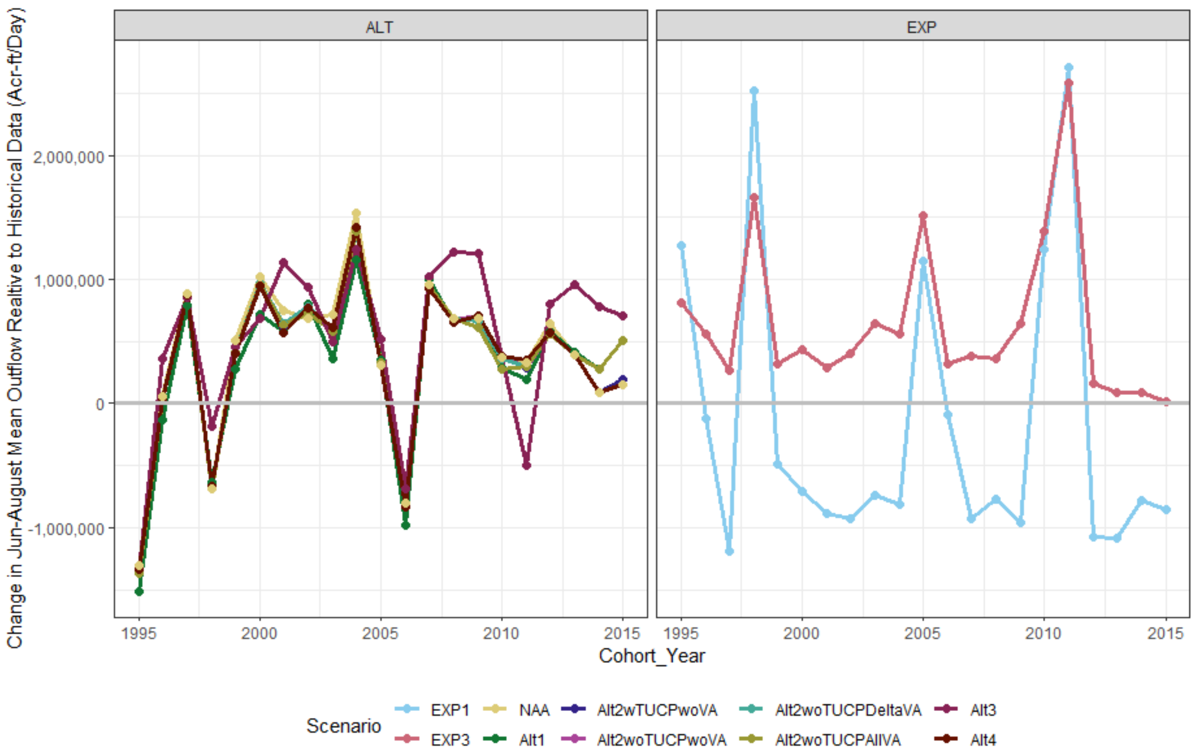

Figure F.1-2. Difference in December-February mean OMR relative to observed data used for model fitting.

F.1.4 Assumptions/Uncertainty

1. Abundance indices are assumed to be normally distributed.
2. Stock-recruitment and survival process error are assumed to be lognormally distributed and density-independent.
3. Delta Smelt are treated as annual species.
4. Covariates are independent: the approach to scenario evaluation modifies values of prescribed covariates, and assumes that it would be possible to achieve such values without influencing other covariates (e.g., outflow could be increased without impacting Sacramento–San Joaquin Delta (Delta) water temperature or turbidity).
5. Projections do not incorporate any uncertainty in covariate estimates and cannot be interpreted as actual predictions of future annual abundance. The utility of projections is the ability to compare the relative performance of multiple alternatives; absolute abundances and population growth rates should therefore be discussed with great caution and with proper caveats.

F.1.4.1 Code and Data Repository

All data and code for fitting models, projecting alternatives and summarizing/visualizing results are located in: USBR_2021LTO/Public Draft Alternatives/Appendix K. Summer and Fall X2/K. Summer and Fall X2_Maunder and Deriso/Data and Code

F.1.5 Results

The overall "best" model identified after application of the hybrid stochastic-stepwise model selection process included South Delta Secchi depth and Beverton-Holt density dependence for the sub-adult survival transition. The lowest AICc model excluding density dependence also included OMR as a significant covariate of sub-adult survival (Table F.1-1). Models where ΔAICc <2 are generally considered to be essentially equal in terms of parsimony, and so based on this analysis the role of density dependence remains equivocal.

Table F.1-1. Summary of "best" models as identified through a hybrid stochastic and stepwise model selection procedure.

	With Density-Dependence	No Density-Dependence
Density Dependent Transition	Sub-adult Survival	N/A
Post-Larval Survival	Temperature_mean_Jun0Aug0 NJACM_BPUV_Jun0Aug0 [a]	Temperature_mean_Jun0Aug0 NJACM_BPUV_Jun0Aug0 [a]
Juvenile Survival	Secchi_mean_Sep0Nov0 Temperature_mean_Sep0Nov0	Secchi_mean_Sep0Nov0 Temperature_mean_Sep0Nov0
Sub-Adult Survival	SouthSecchi_mean_Dec0Feb1	OMR_Dec0Feb1 SouthSecchi_mean_Dec0Feb1
Recruitment	Fall_X2_Lag	N/A
Minimum AICc	215	217

[a] Summer food density or X2 can be substituted for summer outflow with negligible impact on AICc

All covariate data sources, and summarization approaches are as reported in Smith et al. (2021)

Ranked by the frequency with which a covariate was found to be significant (given that it was randomly selected to be included in a model), the five highest ranked variables are all relevant to South Delta entrainment for density independent models. OMR was the covariate most frequently identified to be significant in the absence of density dependence and was retained in nearly all randomly generated models in which it was included. South Delta Secchi depth was also retained in nearly every model where it appeared, regardless of density dependence. PEL high, salvage and PEL low followed with each being retained in more than 75% of the density-independent models. Models that included OMR had substantially lower average AICc values than for any other variable (Figure F.1-3 and Figure F.1-4). Inclusion of density dependence substantially reduced the likelihood the PEL variables would be significant covariates of survival but increased the likelihood of raw salvage being significant.

Results from forward projections should be interpreted cautiously and used only for comparative purposes (see Appendix A for further discussion of uncertainties associated with projecting the MDR).

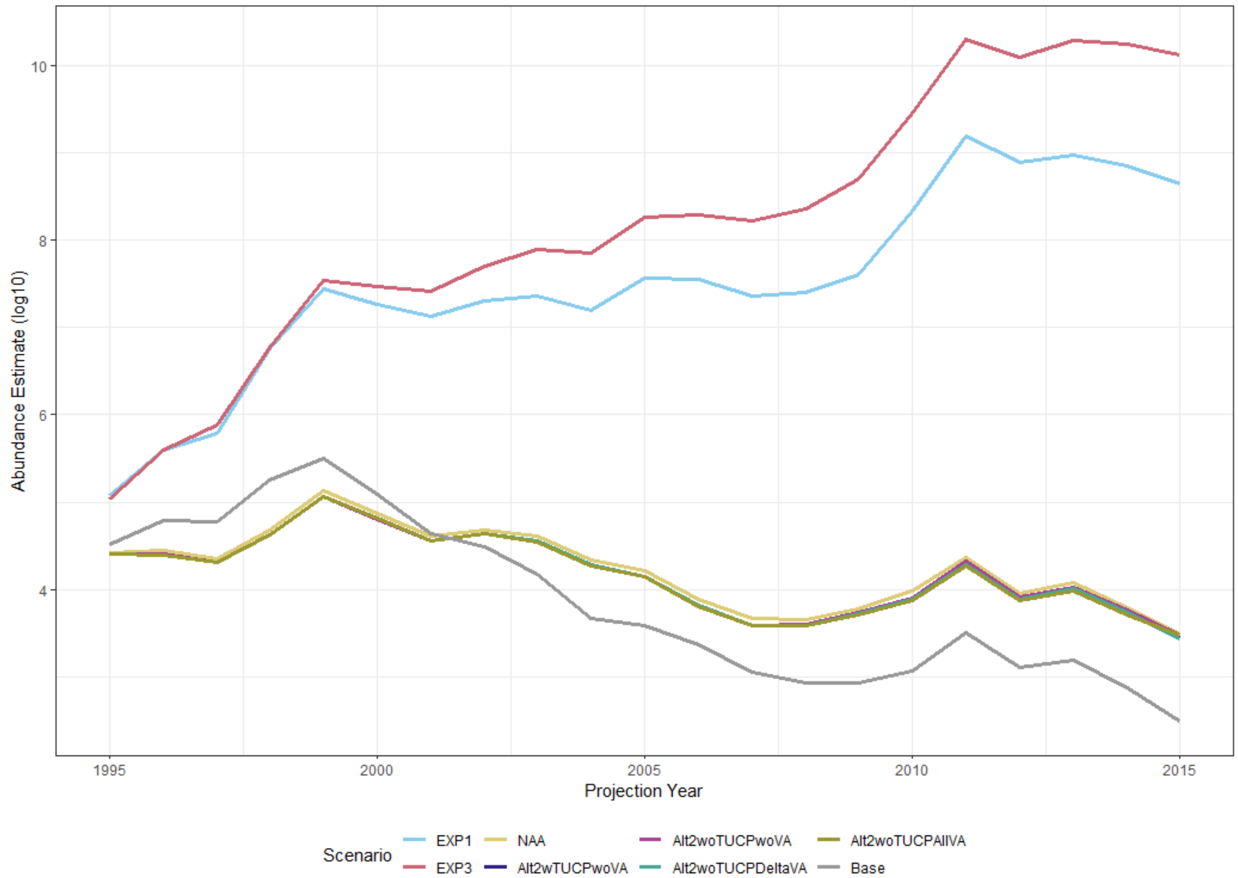

Figure F.1-3. Plot of annual abundance in EXP1, EXP3, No Action Alternative, and Proposed Action components.

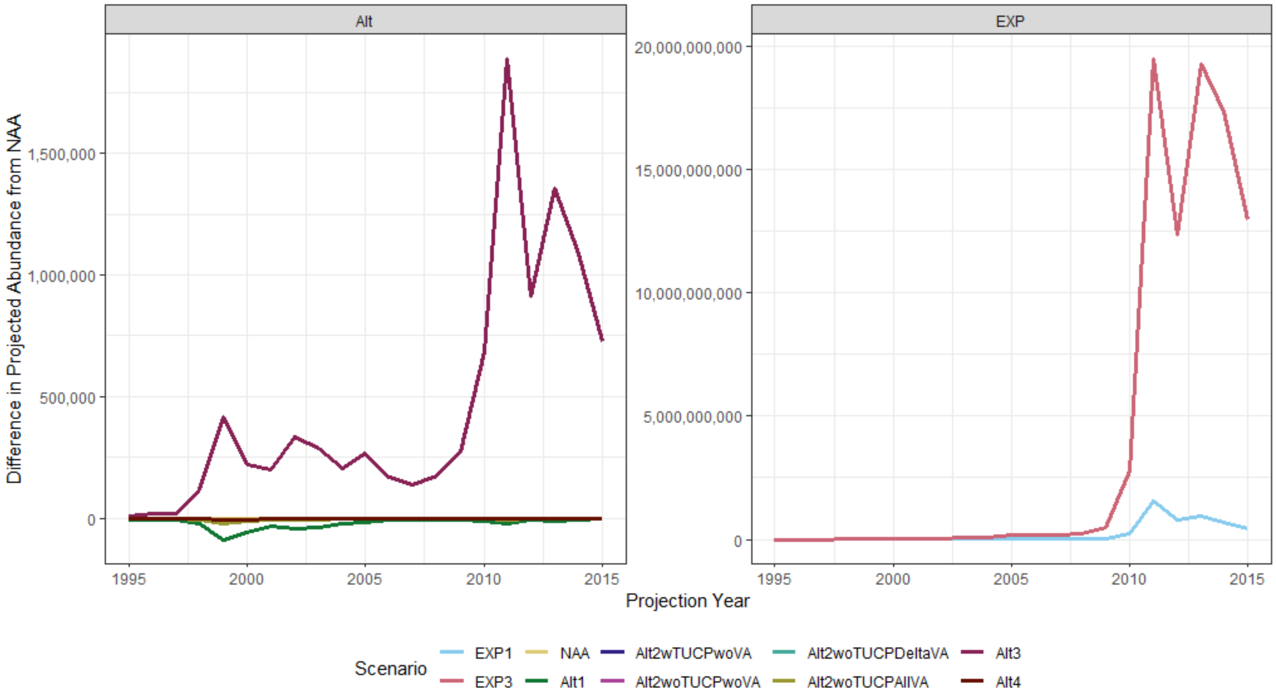

Figure F.1-4. Plot of difference in annual abundance from No Action Alternative.

Table F.1-2. Estimates annual abundance for alternatives (millions of adults). Difference from No Action Alternative in parentheses.

Year	NAA	Alt 1	Alt2wTUCP noVA	PAwoTUCP noVA	PAwoTUCP DeltaVA	PAwoTUCP SystemVA	Alt 3	Alt 4
1995	0.026 (0)	0.022 (-0.004)	0.025 (-0.001)	0.025 (-0.001)	0.025 (-0.001)	0.025 (-0.001)	0.035 (0.009)	0.027 (0.001)
1996	0.028 (0)	0.021 (-0.007)	0.025 (-0.003)	0.025 (-0.003)	0.025 (-0.003)	0.025 (-0.003)	0.048 (0.02)	0.026 (-0.002)
1997	0.023 (0)	0.015 (-0.008)	0.021 (-0.002)	0.021 (-0.002)	0.021 (-0.002)	0.021 (-0.002)	0.045 (0.022)	0.023 (0)
1998	0.048 (0)	0.026 (-0.022)	0.043 (-0.005)	0.043 (-0.005)	0.042 (-0.006)	0.042 (-0.006)	0.167 (0.119)	0.049 (0.001)
1999	0.134 (0)	0.047 (-0.087)	0.114 (-0.02)	0.114 (-0.02)	0.114 (-0.02)	0.114 (-0.02)	0.549 (0.415)	0.13 (-0.004)
2000	0.074 (0)	0.017 (-0.057)	0.064 (-0.01)	0.064 (-0.01)	0.065 (-0.009)	0.065 (-0.009)	0.297 (0.223)	0.068 (-0.006)
2001	0.041 (0)	0.006 (-0.035)	0.036 (-0.005)	0.036 (-0.005)	0.036 (-0.005)	0.036 (-0.005)	0.242 (0.201)	0.038 (-0.003)
2002	0.048 (0)	0.005 (-0.043)	0.043 (-0.005)	0.043 (-0.005)	0.044 (-0.004)	0.043 (-0.005)	0.382 (0.334)	0.046 (-0.002)
2003	0.041 (0)	0.002 (-0.039)	0.036 (-0.005)	0.036 (-0.005)	0.036 (-0.005)	0.035 (-0.006)	0.328 (0.287)	0.039 (-0.002)
2004	0.022 (0)	0.001 (-0.021)	0.019 (-0.003)	0.019 (-0.003)	0.019 (-0.003)	0.019 (-0.003)	0.227 (0.205)	0.021 (-0.001)
2005	0.017 (0)	0 (-0.017)	0.014 (-0.003)	0.014 (-0.003)	0.014 (-0.003)	0.014 (-0.003)	0.283 (0.266)	0.016 (-0.001)
2006	0.008 (0)	0 (-0.008)	0.006 (-0.002)	0.006 (-0.002)	0.007 (-0.001)	0.006 (-0.002)	0.179 (0.171)	0.007 (-0.001)
2007	0.005 (0)	0 (-0.005)	0.004 (-0.001)	0.004 (-0.001)	0.004 (-0.001)	0.004 (-0.001)	0.144 (0.139)	0.004 (-0.001)
2008	0.005 (0)	0 (-0.005)	0.004 (-0.001)	0.004 (-0.001)	0.004 (-0.001)	0.004 (-0.001)	0.178 (0.173)	0.004 (-0.001)
2009	0.006 (0)	0 (-0.006)	0.005 (-0.001)	0.005 (-0.001)	0.005 (-0.001)	0.005 (-0.001)	0.281 (0.275)	0.006 (0)
2010	0.01 (0)	0 (-0.01)	0.008 (-0.002)	0.008 (-0.002)	0.008 (-0.002)	0.007 (-0.003)	0.694 (0.684)	0.008 (-0.002)
2011	0.023 (0)	0 (-0.023)	0.021 (-0.002)	0.021 (-0.002)	0.019 (-0.004)	0.019 (-0.004)	1.913 (1.89)	0.022 (-0.001)
2012	0.009 (0)	0 (-0.009)	0.008 (-0.001)	0.008 (-0.001)	0.008 (-0.001)	0.007 (-0.002)	0.923 (0.914)	0.009 (0)
2013	0.012 (0)	0 (-0.012)	0.011 (-0.001)	0.011 (-0.001)	0.01 (-0.002)	0.01 (-0.002)	1.369 (1.357)	0.011 (-0.001)
2014	0.006 (0)	0 (-0.006)	0.005 (-0.001)	0.006 (0)	0.005 (-0.001)	0.005 (-0.001)	1.096 (1.09)	0.006 (0)
2015	0.003 (0)	0 (-0.003)	0.003 (0)	0.003 (0)	0.003 (0)	0.003 (0)	0.731 (0.728)	0.003 (0)

Year	NAA	Alt 1	Alt2wTUCP noVA	PAwoTUCP noVA	PAwoTUCP DeltaVA	PAwoTUCP SystemVA	Alt 3	Alt 4
All year								

Table F.1-3. Estimates by annual growth rates.

Year	EXP 1	EXP 3	NAA	PAwoTUCPnoVA	PAwoTUCPDeltaVA	PAwoTUCPSystemVA
1995	5.45	4.95	1.22	1.18	1.18	1.18
1996	3.37	3.74	1.06	0.98	0.98	0.98
1997	1.54	1.93	0.82	0.83	0.83	0.83
1998	9.20	7.72	2.09	2.05	2.05	2.05
1999	4.97	5.83	2.82	2.68	2.69	2.69
2000	0.66	0.84	0.55	0.56	0.57	0.57
2001	0.71	0.89	0.56	0.55	0.56	0.56
2002	1.52	1.96	1.17	1.20	1.21	1.19
2003	1.14	1.53	0.84	0.83	0.83	0.82
2004	0.68	0.90	0.54	0.53	0.53	0.53
2005	2.36	2.63	0.76	0.74	0.74	0.75
2006	0.96	1.05	0.46	0.46	0.46	0.46
2007	0.65	0.85	0.61	0.61	0.60	0.60
2008	1.10	1.38	0.98	1.00	1.00	1.00
2009	1.56	2.15	1.33	1.37	1.35	1.34
2010	5.43	5.66	1.57	1.50	1.47	1.45
2011	7.16	7.04	2.42	2.58	2.50	2.50
2012	0.51	0.63	0.39	0.40	0.40	0.40
2013	1.21	1.56	1.30	1.28	1.31	1.29

Year	EXP 1	EXP 3	NAA	PAwoTUCPnoVA	PAwoTUCPDeltaVA	PAwoTUCPSystemVA
2014	0.74	0.90	0.51	0.54	0.54	0.54
2015	0.62	0.75	0.50	0.51	0.50	0.59
All years…						

Table F.1-4. Maunder and Deriso in R estimated population growth rates by water year type.

	EXP 1	EXP 3	NAA	PAwoTUCPnoVA	PAwoTUCPDeltaVA	PAwoTUCPSystemVA
Wet	3.67	3.82	1.32	1.30	1.29	1.29
Above Normal	0.80	1.05	0.63	0.63	0.63	0.63
Below Normal	1.45	1.74	0.80	0.80	0.79	0.79
Dry	1.10	1.42	0.99	0.99	1.00	0.99
Critically Dry	0.68	0.82	0.51	0.53	0.52	0.56

F.1.6 References

Kristensen et al. 2016

Maunder, M. N., and R. B. Deriso. 2011. A state–space multistage life cycle model to evaluate population impacts in the presence of density dependence: illustrated with application to delta smelt (*Hyposmesus transpacificus*). *Canadian Journal of Fisheries and Aquatic Sciences* 68(7):1285–1306.

Polansky et al. 2021

R Core Team, 2017. *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing, Vienna, Austria.

Smith, W. E., L. Polansky, and M. L. Nobriga. 2021. Disentangling risks to an endangered fish: using a state-space life cycle model to separate natural mortality from anthropogenic losses. *Canadian Journal of Fisheries and Aquatic Sciences* 78(8):1008–1029.