Memorandum: Preliminary results of delta smelt SDM action evaluation with the Maunder and Deriso Model in R

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Methods:

All analyses were based upon the C++ and R code provided by Mark Maunder which collectively constitute what we hereafter refer to as the MDR (Maunder and Deriso model in R). The underlying population dynamics model, and the statistical model fitting procedures, as coded in C++ were not modified for the analyses described here. Rather, we 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.

A series of models were developed for evaluation of six initial actions (three formulations of X2/Outflow, Sediment supplementation/Turbidity, Tidal wetland restoration and OMR management). The full list of LCME covariates served as the initial universe of variables from which to select, with one exception. Polansky et al. (2021) evaluate a lagged effect of fall (Sep0Nov0) X2 on recruitment — this potential effect is relevant to X2 actions — so the X2_Lag covariate was added to the full LCME covariates list.

A high-level goal of selecting the appropriate covariates for each model was to match the models fit using the LCME (Figure 1.) as closely as possible. There were several further constraints that influenced the ultimate covariate sets selected. The structure of the LCME separates each year class into sub-cohorts and also distinguishes between natural and entrainment mortality. The MDR has neither of these features, and so the time periods over which covariates were averaged required some amount of modification. Subject to this constraint, the initial variable set for each action's model was based on the lists given in Figure 1. From there, avoidance of multicollinearity was a primary consideration for covariate selection. When covariates for both natural and entrainment mortality were included for a single transition in the LCME it was necessary to remove a variable because the two covariates were highly correlated. Similarly, inclusion of some covariates, notably ACM_BPUV for subadult survival, proved problematic in model fitting, resulting in poorly estimated process errors for one or more transitions; when this occurred, the offending covariate was excluded. After addressing these issues, we gave special consideration to the Fall_X2_Lag. Because it was not included in any of the LCME models, we only included lagged X2 in the "Full" models if its inclusion reduced AICc. For each Full model we fit one version with no density dependence, and a second where the best combination of Beverton-Holt density dependence on each stage transition was optimized by comparison of AICc.

We next created two additional model versions for each action by sequentially removing covariates with 80% confidence intervals that overlapped zero. This variable removal was subject to the constraint that at least one covariate was retained for each transition, and so in some cases a variable with limited effect was nevertheless retained. The full list of models and their covariates is shown in Table 1.

Each of the four resulting models for each action was then projected into the future as follows: For density-independent model fits, projection was initiated from the 2015 adult abundance estimated during the fitting stage and projected 21 years into the future. Covariate values for the 21 projection years were populated either by simply repeating the covariates used for fitting (i.e. baseline projection) or by updating the covariates as modified by the actions. For models that included density dependence, an additional 30 years of projection were included during which all covariates were fixed at their mean values. This allowed the simulated populations to reach equilibrium rather than initiate from the low abundances observed at the end of the historic timeseries. For each model and action level the population growth rate was calculated by dividing the estimated number of adults in a year by the estimated number of adults in the prior year. The annual lambda values from each action level were then divided by the baseline projection values, giving the change in population growth relative to baseline conditions. Finally, the median population growth rate was calculated across all projection years.

Results and Discussion

Relative population growth rates for each model, action, and action level are given in Table 2. At a synoptic level, the patterns are essentially in agreement across all models and formulations. The LCME and density-independent MDR models are especially well aligned with a few exceptions that can be easily explained by the dynamics of the MDR. At the most aggressive action levels (i.e., most highly modified covariates) the MDR projects near-exponential growth at the end of the projection period. Figure 2 shows an example of these dynamics compared with a model including density dependence. Cases in which these dynamics were observed are noted in Table 2. While in these cases the actual values of the relative change in population growth rate should be ignored, they are nevertheless in qualitative agreement with the LCME as being the actions/action levels with the greatest positive impact on population growth. The results for models including density dependence should be considered provisional as we are awaiting an opportunity to discuss some finer details of the projection process with Mark Maunder, but a few obvious patterns in these results seem appropriate to discuss. First, across the board, the inclusion of density dependence tends to attenuate the apparent impact of management actions. This makes intuitive sense, as the relative contribution of covariates to each transition should be reduced when density is used to explain some portion of the dynamics. Notwithstanding notable differences in magnitude, the patterns still match those produced by the LCME and density-independent MDR models with higher action levels producing greater positive impacts on population growth rate.

	Lifestage	late recruitment	PL2	Juv	SA1	SA2	A1		
	Months to average for recruitment and natural mortality covariates	AprMay	JunAug	SepNov	DecJan	Feb	Mar		
	Model	Covariate							Status
1	LCME best, Summer X2/outflow	Temperature_mean_Apr0May0	Outflow_Jun0Aug0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		**ready**
2	X2	Temperature_mean_Apr0May0	X2_Jun0Aug0	X2_Sep0Nov0	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		Very low evidence for a positive effect of X2 on Juv natural mortality
	X2_2	Temperature_mean_Apr0May0	X2_Jun0Aug0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		**ready**
	X2_3	Temperature_mean_Apr0May0	Outflow_Jun0Aug0	Outflow_Sep0Nov0	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		**ready**
	X2_4	Temperature_mean_Apr0May0	NJACM_BPUV_Jun0Aug0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		**ready**
3	Silversides	ISS	Outflow_Jun0Aug0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		Very low evidence for a negative effect of ISS on recruitment
	Silversides_2	ISS+Temp	Outflow_Jun0Aug0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		
4	Food/Wetlands	NJ_BPUV_Mar0May0	NJACM_BPUV_Jun0Aug0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		**ready**
	Food/Wetlands_2	NJ_BPUV_Mar0May0	NJACM_BPUV_Jun0Aug0	ACM_BPUV_Sep0Nov0	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		Very low evidence for a negative effect of Food on Juv natural mortality
	Food/Wetlands_3	NJ_BPUV_Mar0May0	NJACM_BPUV_Jun0Aug0	Secchi_mean_Sep0Nov0, ACM_B	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		
5	Turbidity	Secchi_mean_Apr0May0	Secchi_mean_Jun0Aug0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0	ACM_BPUV_Feb1Feb1	ACM_BPUV_Mar1Mar1		**ready**

Figure 1. Summary of models fit and projected using the LCME. Yellow highlighted models were not reported on.

Table1. Summary of all MDR models fit.

Model	**Full/Reduced**	**Density Depend.**	**Covariates**			
			Recruitment	Post-Larval Survival	Juvenile Survival	Subadult Survival
X2	Full	None	Temperature_mean_Mar0May0	X2_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	X2_Sep0Nov0	ACM_BPUV_Dec0Feb1, SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
X2_2	Full	None	Temperature_mean_Mar0May0	X2_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
X2 (Outflow)	Full	None	Temperature_mean_Mar0May0	Outflow_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	Outflow_Sep0Nov0	SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
Food/ Wetlands	Full	None	NJ_BPUV_Mar0May0	NJACM_BPUV_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1

Model	**Full/Reduced**	**Density Depend.**	**Covariates**			
			Recruitment	Post-Larval Survival	Juvenile Survival	Subadult Survival
Turbidity	Full	None	Fall_X2_Lag, Secchi_mean_Mar0May0	Secchi_mean_Jun0Aug0	Secchi_mean_Sep0Nov0	OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1, SBAge1Plus_Dec0Dec0
OMR	Full	None	Temperature_mean_Mar0May0, Fall_X2_Lag	OMR_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
X2	Full	BH: Subadult, Recruitment	Temperature_mean_Mar0May0, Fall_X2_Lag	X2_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	X2_Sep0Nov0	ACM_BPUV_Dec0Feb1, SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
X2_2	Full	BH: Juvenile, Subadult, Recruitment	Temperature_mean_Mar0May0, Fall_X2_Lag	X2_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
X2 (Outflow)	Full	BH: Subadult, Recruitment	Temperature_mean_Mar0May0, Fall_X2_Lag	Outflow_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	Outflow_Sep0Nov0	ACM_BPUV_Dec0Feb1, SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
Food/ Wetlands	Full	BH: Juvenile, Subadult, Recruitment	NJ_BPUV_Mar0May0, Fall_X2_Lag	NJACM_BPUV_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	Secchi_mean_Sep0Nov0	ACM_BPUV_Dec0Feb1, SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
Turbidity	Full	BH: Juvenile, Subadult, Recruitment	Fall_X2_Lag, Secchi_mean_Mar0May0	Secchi_mean_Jun0Aug0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
OMR	Full	BH: Juvenile, Subadult, Recruitment	Temperature_mean_Mar0May0, Fall_X2_Lag	OMR_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
X2	Reduced	None	Fall_X2_Lag	X2_Jun0Aug0	X2_Sep0Nov0	SouthSecchi_mean_Dec0Feb1, OMR_Dec0Feb1
X2_2	Reduced	None	Fall_X2_Lag	X2_Jun0Aug0	Secchi_mean_Sep0Nov0	SouthSecchi_mean_Dec0Feb1, OMR_Dec0Feb1

Model	**Full/Reduced**	**Density Depend.**	**Covariates**			
			Recruitment	Post-Larval Survival	Juvenile Survival	Subadult Survival
X2 (Outflow)	Reduced	None	Fall_X2_Lag	Outflow_Jun0Aug0	Outflow_Sep0Nov0	OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
Food/ Wetlands	Reduced	None	Fall_X2_Lag	NJACM_BPUV_Jun0Aug0	Secchi_mean_Sep0Nov0	SBAge1Plus_Dec0Dec0, OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
Turbidity	Reduced	None	Fall_X2_Lag	Secchi_mean_Jun0Aug0	Secchi_mean_Sep0Nov0	OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
OMR	Reduced	None	Fall_X2_Lag	OMR_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	Secchi_mean_Sep0Nov0	OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
X2	Reduced	BH: Subadult, Recruitment	Fall_X2_Lag	X2_Jun0Aug0	X2_Sep0Nov0	SouthSecchi_mean_Dec0Feb1, OMR_Dec0Feb1
X2_2	Reduced	BH: Juvenile, Subadult, Recruitment	Fall_X2_Lag	X2_Jun0Aug0	Secchi_mean_Sep0Nov0	SouthSecchi_mean_Dec0Feb1, OMR_Dec0Feb1
X2 (Outflow)	Reduced	BH: Subadult, Recruitment	Fall_X2_Lag	Outflow_Jun0Aug0	Outflow_Sep0Nov0	OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
Food/ Wetlands	Reduced	BH: Juvenile, Subadult, Recruitment	Fall_X2_Lag	NJACM_BPUV_Jun0Aug0	Secchi_mean_Sep0Nov0	OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
Turbidity	Reduced	BH: Juvenile, Subadult, Recruitment	Fall_X2_Lag	Secchi_mean_Jun0Aug0	Secchi_mean_Sep0Nov0	OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1
OMR	Reduced	BH: Juvenile, Subadult, Recruitment	Fall_X2_Lag	OMR_Jun0Aug0, SouthSecchi_mean_Apr0Jun0	Secchi_mean_Sep0Nov0	OMR_Dec0Feb1, SouthSecchi_mean_Dec0Feb1

Note: Red text indicates covariates with 80% CIs overlapping zero

Table 2. Summary of estimated population growth rates relative to baseline conditions

Scenario	Population growth rate relative to baseline conditions			
	MDR No DD, Full	**MDR No DD, Reduced**	**MDR DD, Full**	**MDR DD, Reduced**
OMR_Port1a	1.287	1.296	1.109	1.09
OMR_Port1b	1.314	1.323	1.117	1.096
SediSupp	2.079	2.079	1.248	1.232
TidWet EcoRes low	1.079	1.084	1.118	1.157
TidWet EcoRes high	1.185	1.204	1.133	1.16
TidWet MoreRes low	1.171	1.187	1.131	1.159
TidWet MoreRes high	1.618	1.704	1.164	1.153
X2 sum low	1.564	1.649	1.322	1.382
X2 sum 1	1.298	1.338	1.258	1.33
X2 sum 2	1.125	1.141	1.194	1.277
X2 sum 3	0.975	0.975	1.118	1.222
X2 sum high	0.865	0.855	1.034	1.135
X2 sum low*	1.527	1.613	1.129	1.129
X2 sum 1*	1.28	1.322	1.122	1.122
X2 sum 2*	1.118	1.135	1.117	1.117
X2 sum 3*	0.976	0.975	1.106	1.106
X2 sum high*	0.87	0.859	1.095	1.095
Outflow sum low	2.02	2.239	1.263	1.376
Outflow sum 1	1.277	1.321	1.154	1.261
Outflow sum 2	1.056	1.065	1.105	1.22
Outflow sum 3	0.931	0.925	1.064	1.172
Outflow sum high	0.871	0.859	1.044	1.132

*A second parameterization of the X2 model with Secchi_mean_Sep0Nov0 instead of fall X2

Several of the models without density dependence achieve adult abundances far greater than during the historical period and so these values need to be interpreted cautiously and in the context of the density dependent results.

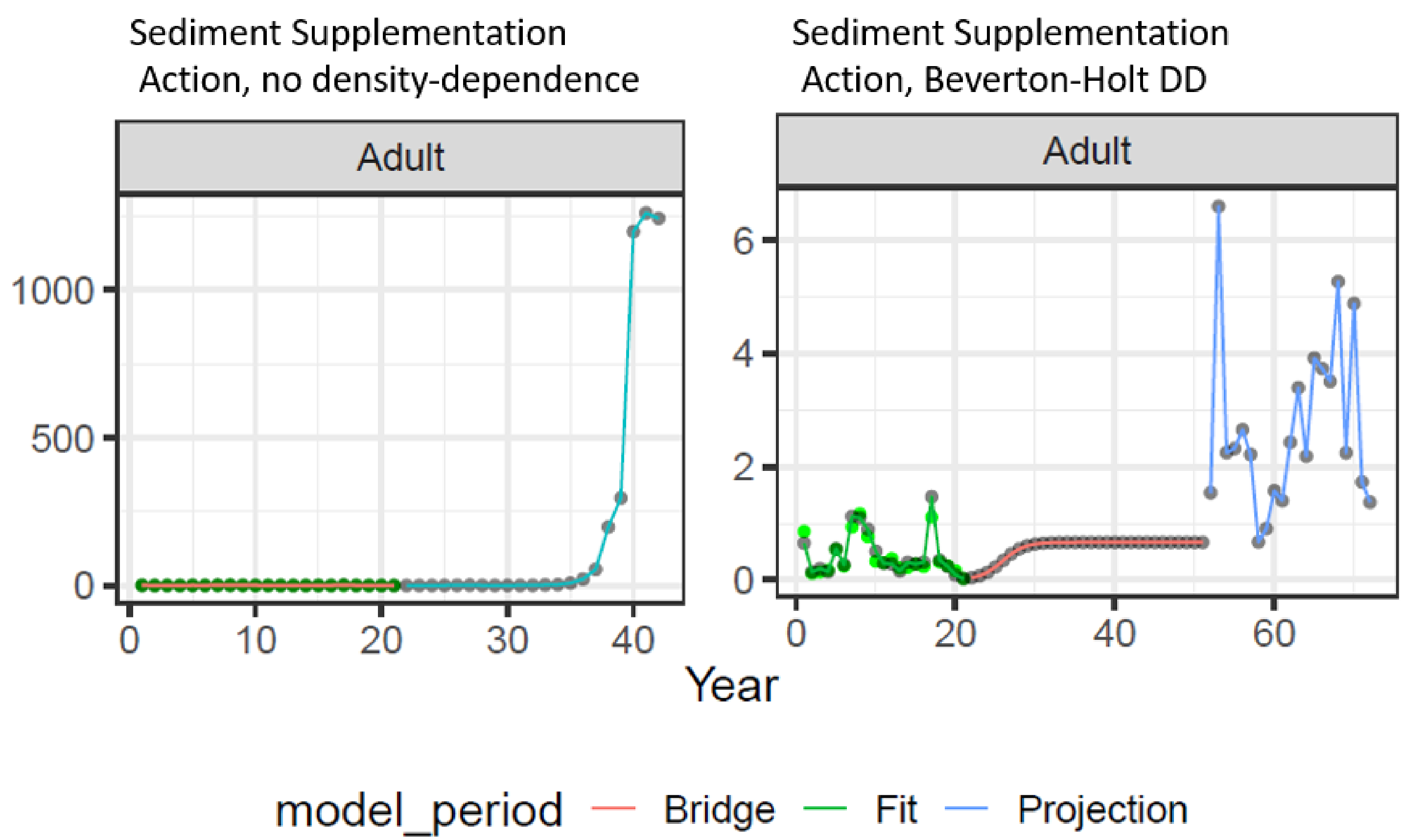

Figure 2: Example of problematic dynamics in density-independent model projection