Evaluation of Sacramento River winter Chinook salmon control rules: updated Management Strategy Evaluation analysis

The Ad Hoc Sacramento River Winter Chinook Workgroup

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1 Introduction

The Ad Hoc Sacramento River Winter Chinook Workgroup (Workgroup) was formed by the Pacific Fishery Management Council (PFMC) to develop and evaluate alternative fishery management strategies for Sacramento River winter Chinook salmon (SRWC). Over the course of nearly two years, the Workgroup has developed an abundance forecasting approach for SRWC, proposed a set of nine alternative impact rate control rules, and presented a preliminary evaluation of those control rules informed by management strategy evaluation (MSE) simulations. At the April 2017 PFMC meeting, the Workgroup presented a preliminary MSE analysis to the Council and relevant advisory bodies (O'Farrell, 2017b), receiving recommendations on further work. In the intervening time, additional MSE simulations and analysis have been performed addressing the recommendations received in April. This report describes both the relevant results presented in April 2017 and new results developed since then.

The control rules evaluated here (Figure 1) include constant age-3 impact rate (i_3) strategies representing no fishing (control rule 1), an average historical impact rate (control rule 2; O'Farrell and Satterthwaite, 2015), and an average contemporary impact rate (control rule 3; O'Farrell et al., 2012). Control rules 4–9 specify reductions in i_3 from a maximum level of 0.20 as abundance declines. Control rule 8 is the current control rule, where abundance is specified by the 3-year geometric mean of escapement. Control rules 1–7 and 9 have abundance specified as the forecast age-3 escapement in the absence of fisheries (E_3^0; O'Farrell et al., 2016). Because components of the E_3^0 forecast are uncertain, and that uncertainty is preserved through the forecast model, the resulting E_3^0 forecast is itself a continuous distribution. The median of the E_3^0 forecast distribution was used as the input variable to the control rules for MSE simulations presented in O'Farrell (2017b). In this report we present new results from simulations in which the mode of the E_3^0 forecast distribution is used as the control rule input variable. Distributions of E_3^0 display positive skewness (O'Farrell et al., 2016) and therefore the median exceeds the mode. Differences in conservation benefits and fishery costs were then evaluated for simulations based on the median and mode of the forecast distribution.

The results of four simulation scenarios were presented at the April 2017 PFMC meeting. These scenarios included the Base scenario, the Autocorrelation scenario (temporal autocorrelation in the juvenile survival rate), the Variable productivity scenario (temporal variability in the maximum egg-to-fry survival rate based on river temperature), and the Perfect knowledge scenario (assumes that forecasts of E_3^0 are known without error). In response to recommendations provided in April, we performed new simulations that were elaborations on the Variable productivity scenario. The original Variable productivity scenario assumed that the temperature covariate to the maximum egg-to-fry survival rate was the product of "normal" years that were punctuated by severe droughts. Severe droughts occurred, on average, every 28 years, and elevated river temperatures resulting from that drought lasted for a duration of two years. Alternative Variable productivity scenarios included (1) droughts of longer duration, (2) more frequent droughts, and (3) a climate change scenario where river temperatures were warmer in both drought and non-drought years. Control rules were evaluated under these new variable productivity scenarios with regard to extinct risk and the allowable age-3 impact rate.

The MSE model, and parameter values used in the model, are described in O'Farrell (2017a) and previously in Winship et al. (2012, 2013). The MSE simulations described in this report follow those same methods. Methods used to simulate new variants of the variable productivity scenario are described in the next section.

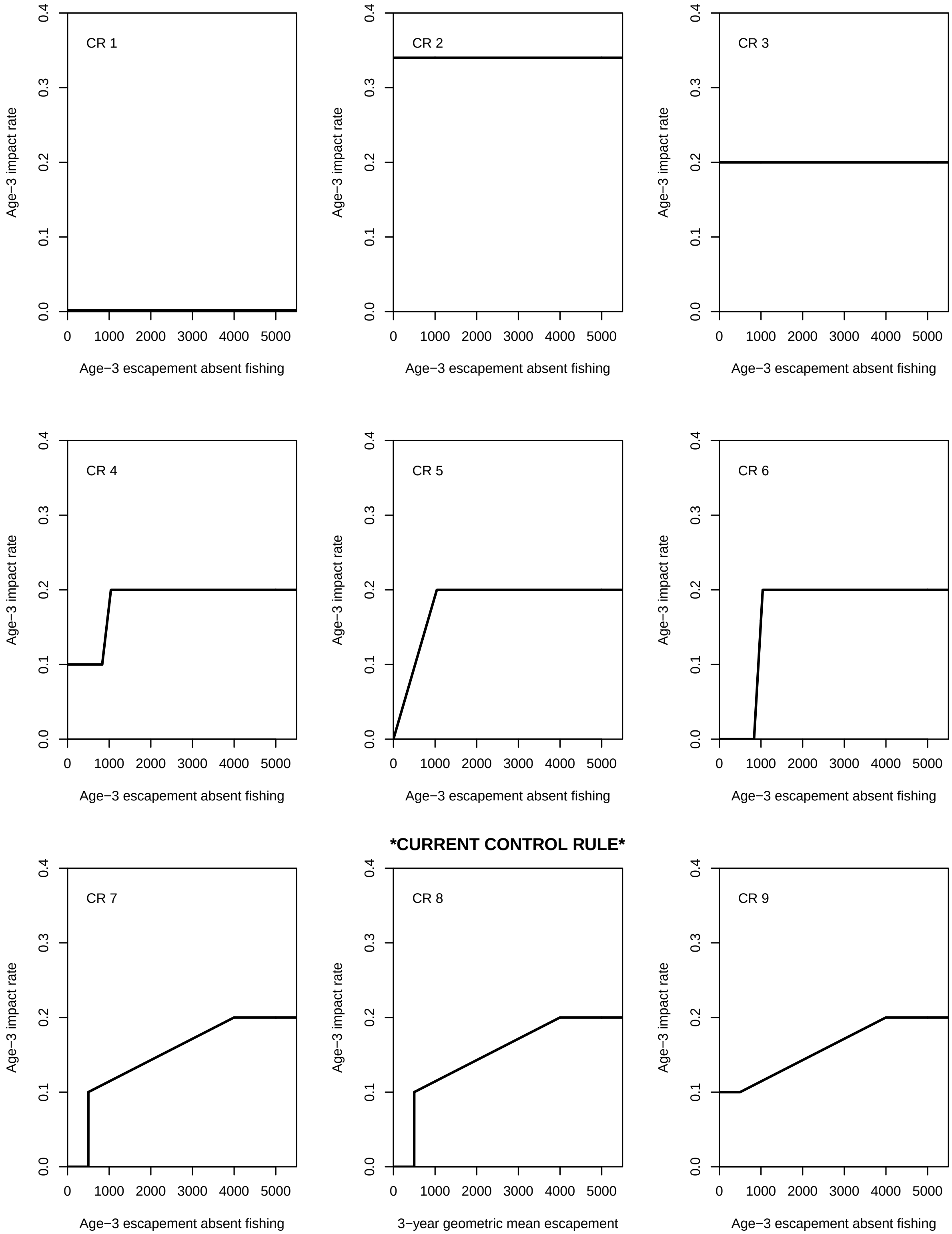

Figure 1. Control rules evaluated through management strategy evaluation. Control rule 8 represents the status quo control rule, which specifies the allowable age-3 impact rate as a function of the three-year geometric mean of spawners. All other control rules specify the allowable impact rate as a function of the predicted age-3 escapement in the absence of fisheries.

Performance of control rules with regard to the SRWC population was evaluated based on the number of spawners and extinction risk criteria developed for Central Valley salmonids (Lindley et al., 2007). Costs to fisheries were evaluated based on the frequency and magnitude of reductions in the allowable impact rate from the maximum level of 0.20 for all abundance-based control rules. In addition to these performance measures presented in the O'Farrell (2017b) report, we also evaluated differences among control rules in the minimum number of spawners observed over simulations, and the simulated response in the number of spawners conditional on spawner abundance falling below a threshold level.

2 Methods

Portions of this section are reproduced from O'Farrell (2017a), which provides a comprehensive description of the MSE model.

2.1 Management strategy evaluation

The MSE operating model is structured by age, sex, and origin (natural and hatchery) and has a time step of one year. Abundance of fish in the ocean is indexed on March 1, and spawning adults are assumed to leave the ocean for the river on the last day of February.

Progeny of natural-area spawners experience density-dependent mortality in the transition from egg to fry in the river. The relationship between egg production and fry abundance is described by a Beverton-Holt model that includes a temperature covariate on the productivity parameter (O'Farrell, 2017a). Survival from the fry stage at Red Bluff Diversion Dam (RBDD) to the end of the first year in the ocean is assumed to be density independent. For adult ages 3–4 in the ocean, fishing mortality and natural mortality rates are applied to the March 1 abundance. To determine allowable fishing mortality rates in a simulation year, a forecast of E_3^0 is made from simulated fry data, incorporating observation error, using the *Base* forecast model (O'Farrell et al., 2016). The median or mode of the E_3^0 forecast distribution is then applied to control rules (with the exception of control rule 8) to determine the allowable age-3 impact rate for that year and simulation. The fishing mortality rate realized by the population is a function of the allowable rate, implementation error, and demographic stochasticity. Following the effects of fishing and natural mortality in the ocean, age and sex-specific maturation rates are applied, which determine the fraction of the cohorts that return to the river.

Hatchery-origin fish are tracked separately from natural-origin fish in the simulations, though they experience the same adult natural mortality rates, fishing mortality rates, and maturation rates as natural-origin fish. Survival from the egg to pre-smolt stage and juvenile survival rates differ for hatchery-origin fish.

The MSE results presented in this report are the result of 20,000 simulations of 100 years in duration, performed for each control rule and simulation scenario.

2.2 Simulation scenarios

Base case simulations assume the maximum egg-to-fry survival rate is constant. This is implemented by setting the temperature covariate for the maximum egg-to-fry survival rate parameter in the Beverton-Holt model to the mean level observed from 1998–2015 (69 degree days above 12°C; O'Farrell et al., 2016; O'Farrell, 2017a). For the juvenile survival rate, no autocorrelation was assumed ($\rho = 0$).

The following alternative scenarios were also considered. For each of these scenarios, only a single modification from the Base case was made.

The Autocorrelation scenario includes temporal autocorrelation in the juvenile survival rate. An autocorrelation coefficient of $\rho = 0.5$ was assumed.

The Variable productivity scenario allows the maximum egg-to-fry survival rate to vary from year to year based on river temperature conditions. Simulations were performed for four variants of the Variable productivity scenario. For each variant, the same general procedure was followed. Time series of the temperature covariate to the maximum egg-to-fry survival rate were generated for "normal" years which were punctuated by severe drought years that resulted in higher river temperatures and thus lower maximum egg-to-fry survival rates.

For the first simulation variant, referred to as “Contemporary”, normal years are represented by random draws from the observed number of degree days above 12°C for the set of years 1998–2013 and 2016. The values for these years range from 0 to 163 degree days above 12°C. None of these years qualify as a “significant event” (drought) by DWR (2015). The temperature covariate in significant drought years is specified by making random draws from the observed number of degree days above 12°C for years 2014–2015. The values for these two years are 339 and 304 degree days above 12°C. Significant drought events were assumed to be two years in duration, and the time between the initiation of drought events was assumed to follow a Poisson process. The waiting time between drought events in each simulation was defined by a random draw from a Poisson distribution with $\lambda = 28$ years, the mean duration of time between the initial years of significant drought events (DWR, 2015). To define the first drought event during the 100 year time series, a draw is made from a uniform distribution defined over the time interval (1, 28). Following this initial drought event, the timing of subsequent drought events is determined by the Poisson process.

The second simulation variant for the Variable productivity scenario is referred to as “Longer droughts”. The procedure for this variant is equivalent to the Contemporary variant with the exception that droughts are four years in duration rather than two years.

The third simulation variant for the Variable productivity scenario is referred to as “Frequent droughts”. The procedure for this variant is equivalent to the Contemporary variant with the exception that the mean waiting time between initiation of drought events is $\lambda = 14$ years.

The fourth simulation variant is referred to as “Climate change”. The procedure for this variant is equivalent to the Contemporary case with the exception that normal and drought years are represented by random draws from model-based values of the number of degree days above 12°C derived from downscaled climate projections. Ensemble climate projections were created based on the Intergovernmental Panel on Climate Change’s (IPCC) fourth assessment report (IPCC, 2007). The ensemble used was a central tendency ensemble with regard to projected changes in precipi-

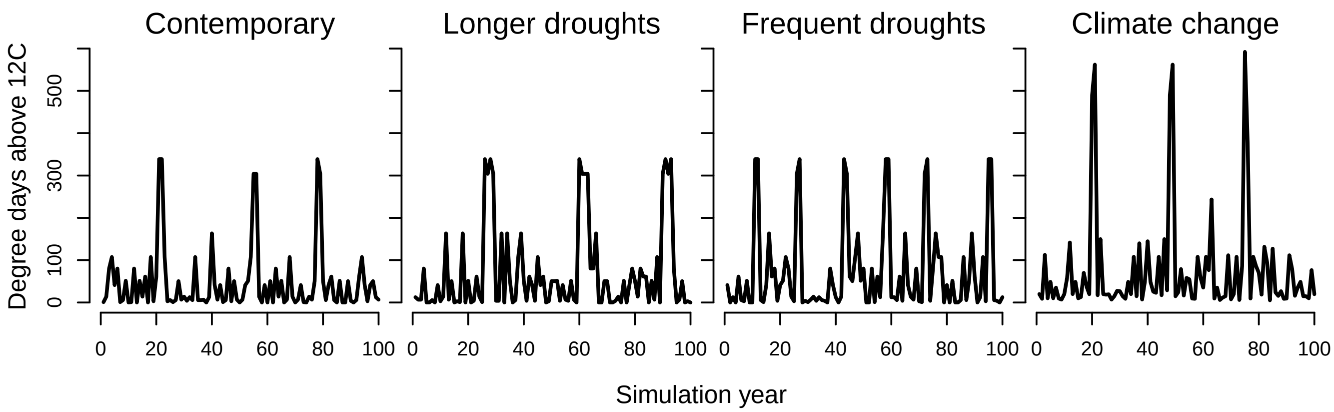

Figure 2. A single random example of the time series of the river temperature covariate to the maximum egg-to-fry survival rate parameter for the four variants of the Variable productivity scenario.

tation and air temperature downscaled to a spatial resolution of 12 km. This ensemble projection provided inputs to a hydrological model (HEC5Q) used to simulate daily Sacramento River water temperatures over years 1921-2003 (see ICF International, 2016, Appendix 5C). Simulated degree day data used for the MSE simulations described in this report were provided by Sara John (*Personal communication*, May 9, 2017). Under the climate change variant, the temperature covariate values for normal years range from 5 to 251 degree days above 12°C. The temperature covariate values for drought years ranged from 377 to 643 degree days above 12°C.

Figure 2 provides single random time series examples of the river temperature covariate for each of the four Variable productivity simulation variants.

Finally, the Perfect knowledge scenario assumes that forecasts of E_3^0 are made without error.

2.3 Performance measures

The following performance measures were used to evaluate the conservation benefits and fishery costs of the alternative control rules.

1. The mean and 95 percent interval of spawner abundance in the final year of the 20,000 simulations ($t = 100$).

2. The proportion of simulations that resulted in a moderate or high risk of extinction for the population size criterion (Lindley et al., 2007). A moderate risk of extinction for this criterion results when the three-year sum of escapement (S) is less than or equal to 2,500, but greater than 250. A high risk of extinction for this criterion results when S is less than or equal to 250 fish.

3. The proportion of simulations that resulted in a moderate or high risk of extinction for the catastrophe criterion (Lindley et al., 2007). The catastrophe criterion ascribes extinction risk on the basis of generational changes in population size. A moderate risk of extinction occurs if there is at least one decline in population size between 50 and 90 percent over the last seven non-overlapping generations. A high risk of extinction occurs if there is at least one decline in population size greater than or equal to 90 percent over the last seven non-overlapping generations. See Winship et al. (2012) for details regarding how this criterion is defined.

4. The proportion of instances across all simulations in years $30 \leq t \leq 99$ where the control rule specified age-3 impact rate was greater than or equal to 0.20. We also calculate the proportion of instances in years $30 \leq t \leq 99$ that fell into allowable impact rates bins to evaluate the degree of the constraint to fisheries when the impact rate is reduced below the maximum level of 0.20.

5. The mean and 95 percent interval of the realized age-3 impact rate in years $30 \leq t \leq 99$. The proportion of instances in years $30 \leq t \leq 99$, falling into impact rates bins was also calculated.

6. The minimum number of spawners for each control rule across all simulations in years $31 \leq t \leq 100$.

7. The conditional response to a spawner abundance less than or equal to a threshold level of 100 fish. The geometric mean of spawners was computed over the three years following an escapement at or below the threshold.

3 Results

Under the Base scenario, the mean number of spawners in the absence of fishing (control rule 1) was approximately 11,000 fish, while under control rules 3–9, mean spawners ranged from approximately 6,500 to 7,000 fish (Figure 3, Table A-1). Including temporal autocorrelation in the juvenile survival rates did not have a large effect on mean spawner levels relative to the Base case, though variability in the distribution of spawner abundance increased. Variable productivity scenario (contemporary variant) simulations resulted in modestly increased mean abundance relative to the Base case. This result is due to the details of how productivity varies over time in the model. For non-drought years, the productivity is higher than the Base case; the Base case assumes a constant temperature covariate of 69 degree days above 12°C, while the mean temperature covariate in non-drought years is 35 degree days above 12°C (lower values of the temperature covariate beget higher productivity–see Figure 1 in O'Farrell, 2017a). When E_3^0 is known exactly, the mean and variability in the number of spawners was similar to the Base scenario.

With regard to extinction risk for the population size criterion, the large majority of simulations resulted in a low risk of extinction (Figure 3, Table A-2). There was a much higher incidence of moderate or high risk of extinction for control rule 2 (which is representative of historical impact rates) relative to all other control rules. Under the Autocorrelation scenario, the proportion of simulations with moderate or high risk of extinction was substantially higher than the Base case. This result likely comes from runs of low or high escapement driven by temporal autocorrelation in the juvenile survival rate. There is some contrast in extinction risk among the abundance-based control rules (4–9) for the Autocorrelation scenario, with control rule 4 having the highest risk and control rule 8 having the lowest risk. For the Variable productivity and Perfect knowledge scenarios the proportion of simulations resulting in moderate or high risks of extinction were very similar to the Base case and there was little contrast among the abundance-based control rules.

For the catastrophe criterion, there was very little difference in extinction risk between the nine control rules under each of the scenarios. (Figure 3, Table A-3). However, there was a slightly increased incidence of moderate or high risk of extinction for the Autocorrelation and Variable productivity scenarios relative to the Base and Perfect knowledge scenarios.

The proportion of simulations where the control rule specified impact rate was at least 0.20 varied substantially between control rules across all four scenarios (Figure 3, Table A-4). For control rules 4–6, impact rates were specified at the maximum level of 20 percent for a high proportion of the simulations. In contrast, impact rates were scaled back much more frequently for control rules 7–9. The degree to which impact rates were reduced was quite variable among the abundance-based control rules, reflecting their respective shapes. For example, when the allowable impact rate for control rule 6 is reduced below 0.20, it is most frequently reduced to zero. Whereas for control rule 9, when the allowable impact rate is reduced below 0.20, it is most frequently reduced to a level between 0.10 and 0.20 (Table A-4). Overall, impact rates were reduced below 0.20 most frequently under the Autocorrelation and Perfect knowledge scenarios.

Mean realized impact rates were generally similar across control rules 3–9 regardless of whether demographic stochasticity was accounted for. While control rules 7–9 have impact rates scaled back much more frequently than control rules 4–6, this led to moderate differences in realized impact rates (Figure 3, Table A-5). Of note, the lower bound of the 95 percent intervals of the i_3 distribution extends to lower values for the Autocorrelation and Perfect knowledge scenarios relative to the Base scenario.

Results presented in Figure 3 and Tables A-1 through A-5 are a product of simulations where control rules were informed by the median of the E_3^0 forecast distribution. However, results of the abundance forecast analysis presented at the November 2016 PFMC meeting suggested similar forecast performance when the median or mode of the forecast distribution was compared to postseason estimates. Figure 4 displays the distribution of spawner abundance and allowable age-3 impact rates when the median and mode of the forecast distribution are used as control rule inputs, and compares these distributions to distributions where the “true” E_3^0 is the control rule input. With regard to the distribution of spawner abundance, there are nearly imperceptible visual differences between the shape of the distributions. In contrast, allowable impact rates are lower when the

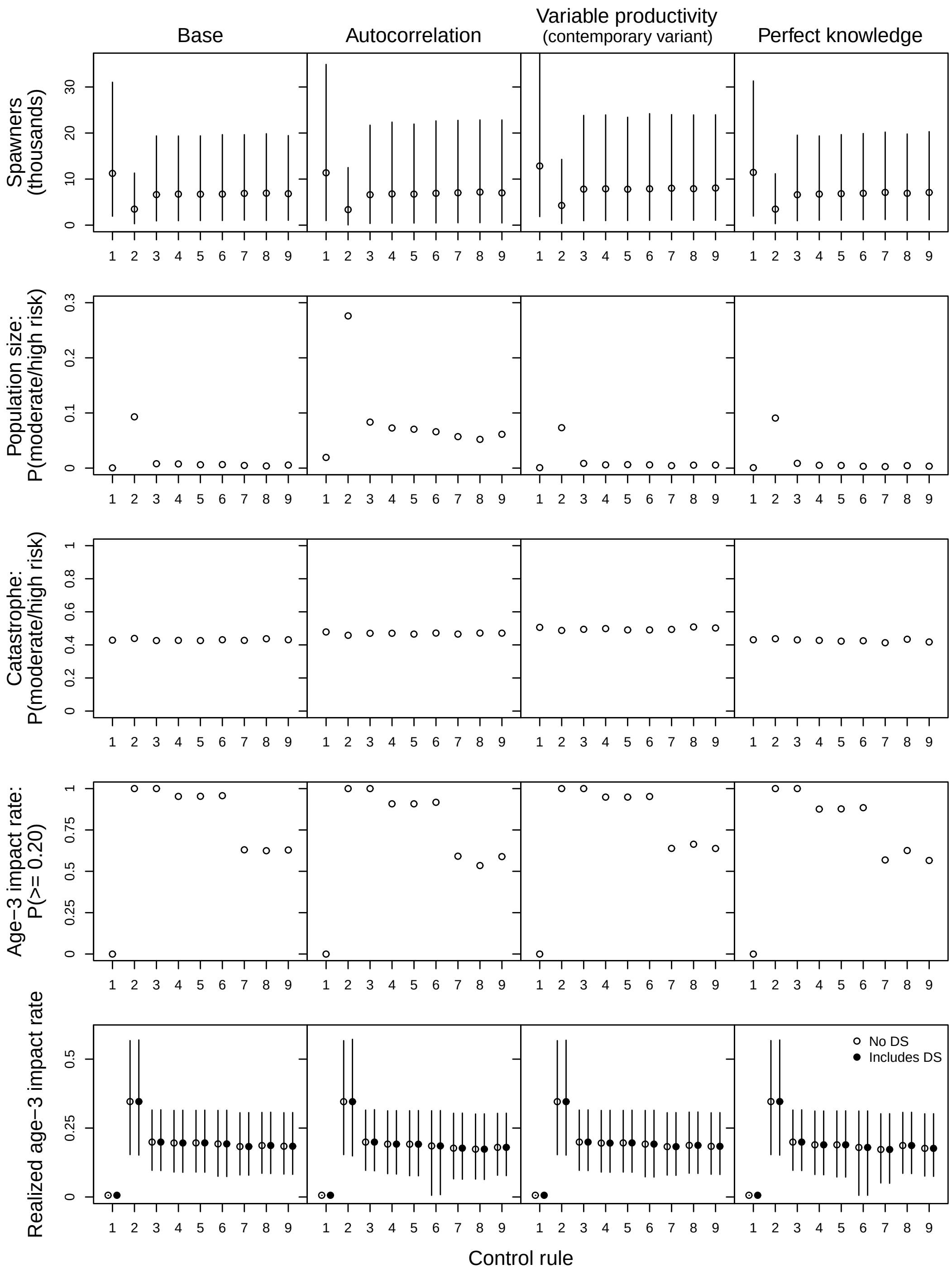

Figure 3. Performance measures evaluated for each of the nine control rules and four scenarios. For "Spawners" and "Realized age-3 impact rate" the circles represent mean values and vertical lines denote the 95 percent intervals of the distribution. Circles for the other performance measures denote point estimates. The "Age-3 impact rate" performance measure denotes the allowable impact rate specified by the control rule. The "Realized age-3 impact rate" is the rate experienced by the population after accounting for implementation error (open circles) and demographic stochasticity (DS, filled circles).

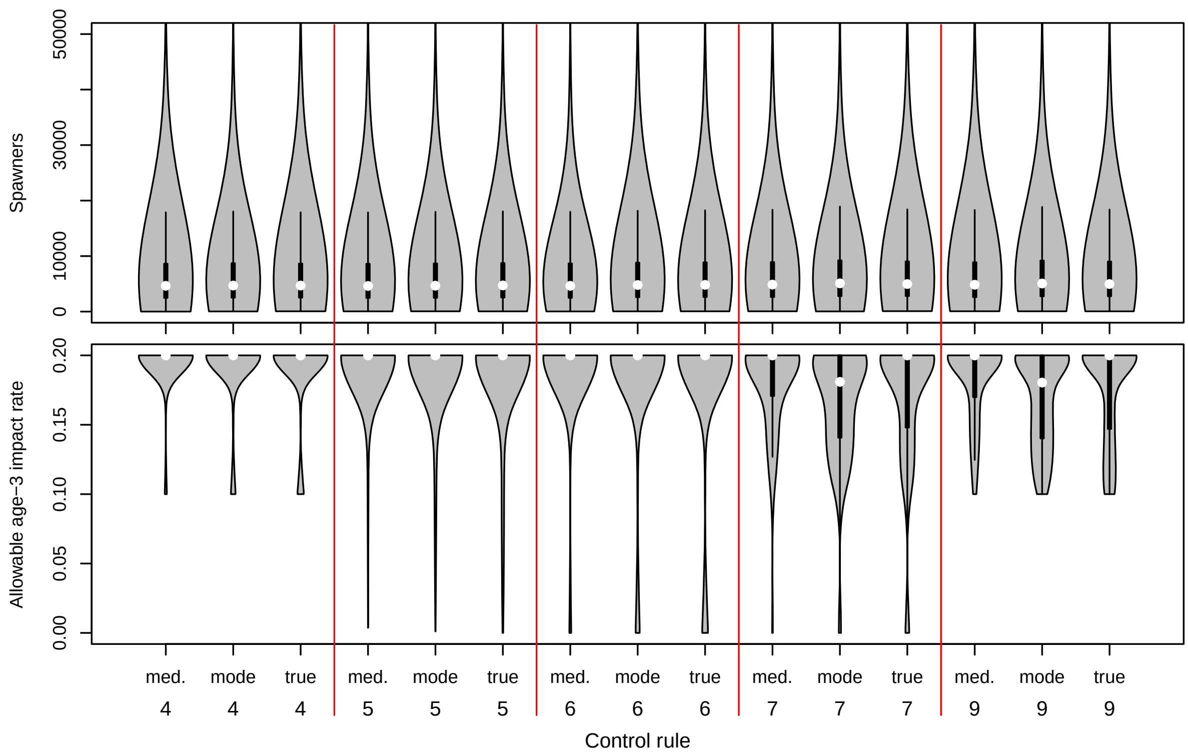

Figure 4. Distributions of the number of spawners and the allowable impact rates for control rules 4–7 and 9 when the input variable for these control rule were the median (med.) and mode of the E_3^0 forecast distribution, and the true value of E_3^0. White circles denote the medians of the distributions, thick bars represent the interquartile range, and thin bars are 1.5 times the interquartile range.

mode of the E_3^0 distribution is used as the control rule input instead of the median. The median of the allowable impact rate distribution is always 0.20 for the cases when the median and known E_3^0 values are control rule inputs, while for control rules 7 and 9, the median of the allowable impact rate distribution is lower than 0.20 when the mode of the E_3^0 distribution is the control rule input variable. These results suggest that use of the mode of the E_3^0 forecast distribution would result in more fishery constraints for control rules 7 and 9 relative to the case when the median of the forecast distribution were used and the case where E_3^0 was known without error. Results were similar for control rules 4–6, with the exception that the case where E_3^0 is known with out error results in similar or greater fishery constraints than the case where the mode of the forecast distribution was used to as the input variable to the control rules.

The effect of longer droughts, more frequent droughts, and more intense droughts was to increase extinction risk based on the population size criterion (Figure 5). The largest increase in extinction risk resulted from the Longer droughts and Climate change variants. There was some contrast between the abundance-based control rules, where control rules 7–9, and in some cases control rule 6, resulted in lower incidence of moderate or high risk of extinction relative to control rules 4 and 5. Fisheries were more constrained for the Longer droughts, Frequent droughts, and Climate change variants relative to the Contemporary case. There was a substantial difference in the frequency and magnitude of allowable impact rate reductions between control rules 4–6 and 7–9 for each variant, though the magnitude differed across variants.

The distribution of the minimum number of spawners over the 20,000 simulations differed little among control rules 3–9 (Figure 6). Unsurprisingly, the highest levels of the minimum number of spawners occurred under control rule 1 (no fishing) while the lowest levels occurred under control rule 2 (historical fishing). Under the Base, Autocorrelation, and Variable productivity scenarios, there were only small visible differences in minimum spawners across control rules 3–9. There were more notable differences between these control rules when abundance was known without error. Overall, the lowest number of minimum spawners occurred for the Autocorrelation scenario.

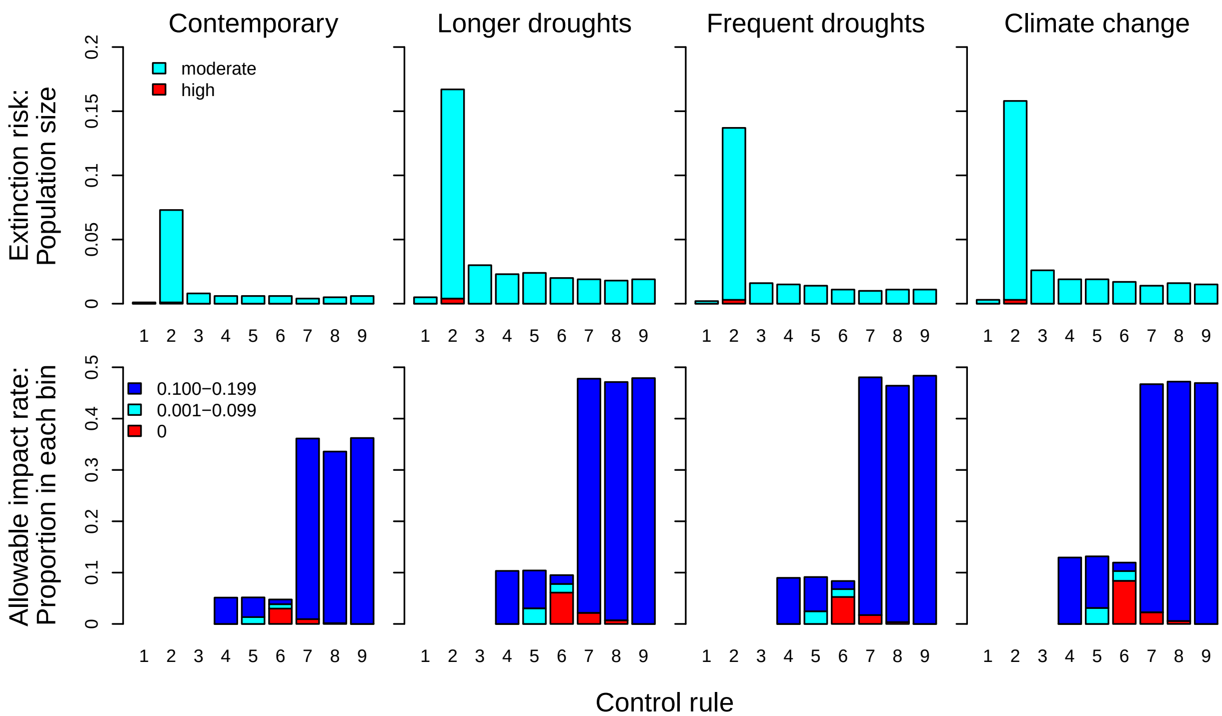

Figure 5. Proportion of simulations resulting in a moderate or high risk of extinction for the population size criterion (top panel) and allowable age-3 impact rates (bottom panel) for the four variants of the Variable productivity scenario.

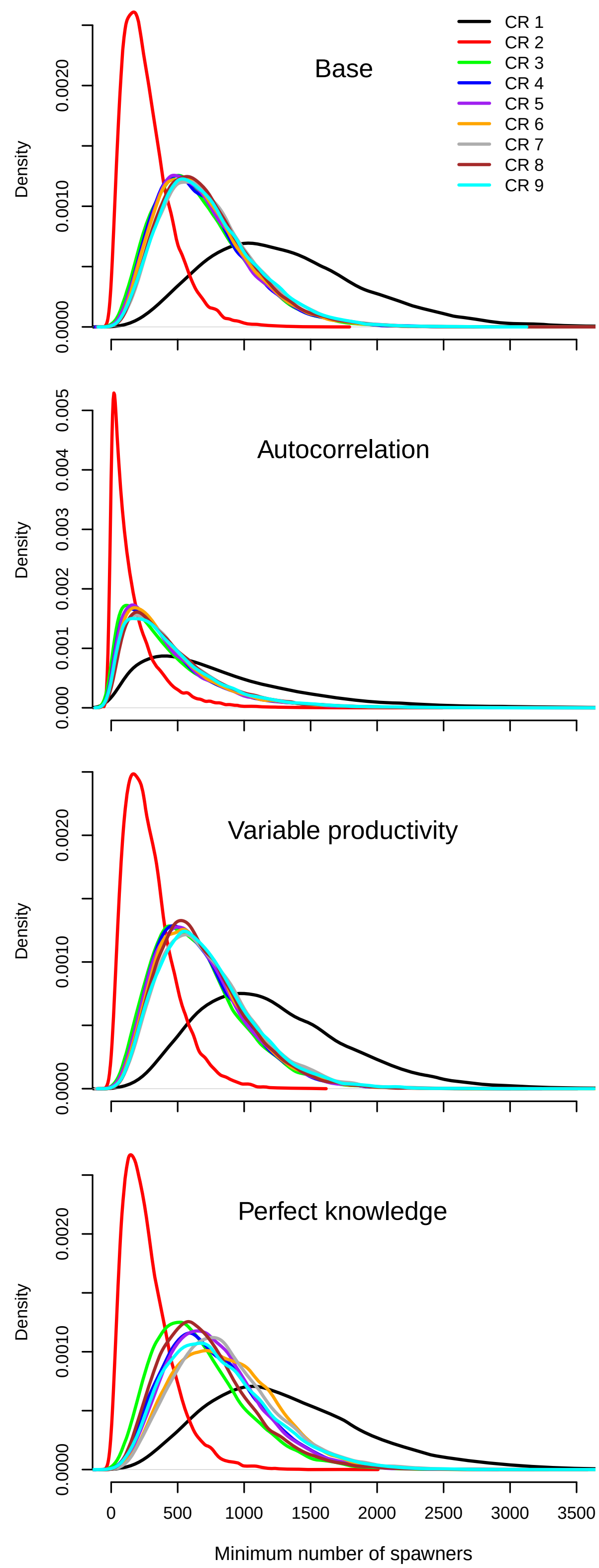

Figure 6. Distributions of the minimum number of spawners observed under each of the nine control rules and four simulation scenarios.

If the simulated number of spawners fell to 100 fish or less, the geometric mean of spawners over the following three years tended to be greater than 100 fish (Figure 7). An exception to this occurred for the Autcorrelation scenario, where the median of the geometric mean response for control rule 2 was < 100. For abundance-based control rules, there was little contrast between the conditional response. For the Autocorrelation scenario, there were a substantial number of instances when the number of spawners was ≤ 100 fish under all control rules. There were small differences in the median of the geometric mean response over control rules 4–9. For the other scenarios there were far fewer instances where spawners fell below the threshold, which likely contributed to the variable geometric mean responses. A coherent pattern in the response to crossing a low spawner threshold was not readily apparent.

4 Discussion

This report describes results of MSE simulations aimed at evaluating the trade offs between conservation and fishery outcomes for a variety of impact rate control rules. Results described here are consistent with those presented in O'Farrell (2017b) and at the April 2017 PFMC meeting. Base simulations have been confronted with an expanded series of alternative scenarios to evaluate the robustness of results to model selection.

Simulation results suggest modest differences between the abundance-based control rules in terms of the mean number of spawners and extinction risk for the population size and catastrophe criteria. Mean spawner levels for control rules 7–9 exceeded mean levels for control rules 4–6 consistently, but by a relatively small amount (Table A-1). There were, however, substantial differences between the abundance-based control rules in terms of the frequency and magnitude that the allowable age-3 impact rate was reduced from the maximum level of 0.20. The allowable impact rate was specified to be 0.20 in a much smaller proportion of simulations for control rules 7–9. This result is intuitive as control rules 7–9 begin reducing the allowable impact rate at much higher abundance levels than control rules 4–6.

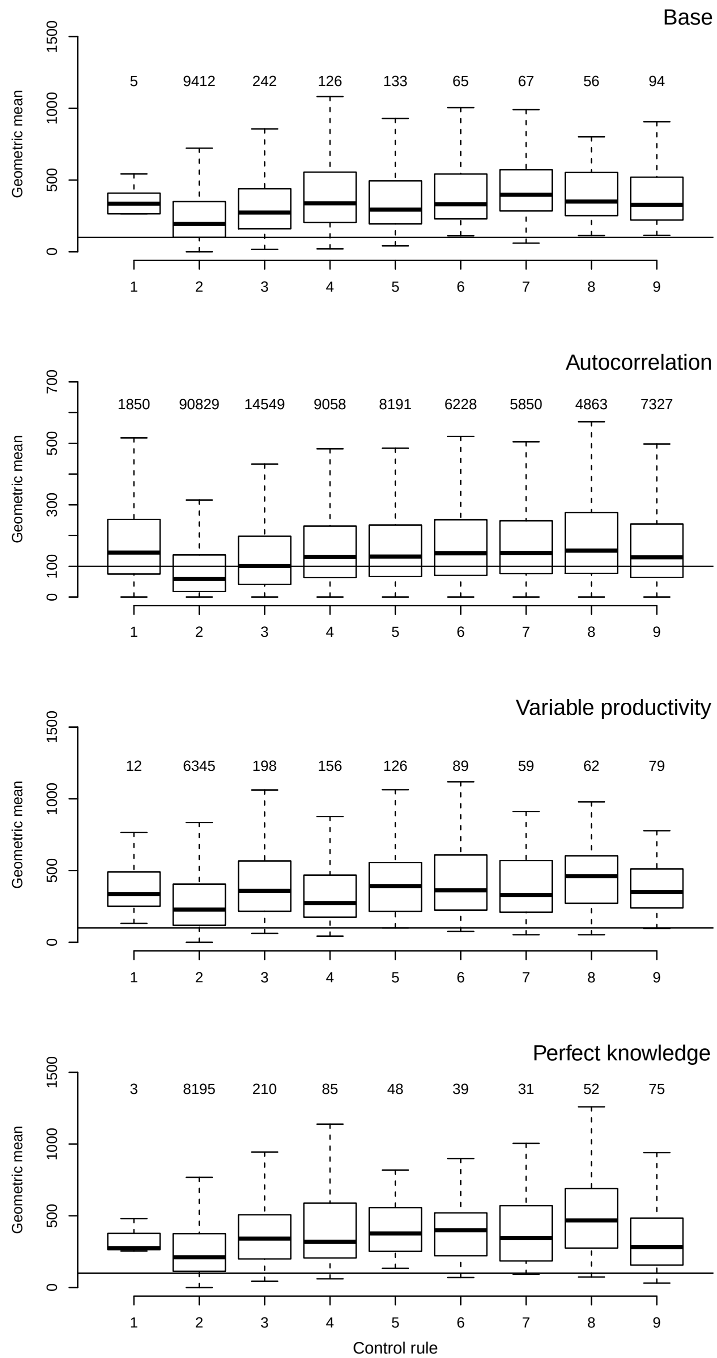

Figure 7. Boxplots summarizing the distribution of the geometric means of spawners computed over the three years following a simulated spawner level of ≤ 100 fish. Numbers above the boxplots denote the number of geometric means contributing to the boxplot (the number of instances when simulated escapement was ≤ 100 fish). Horizontal lines indicate the 100 fish threshold. Note differing y-axis scale for the Autocorrelation scenario.

Challenging the winter Chinook population with more difficult environments and thus longer, more frequent, and larger scale reductions in productivity predictably resulted in higher extinction risks and larger reductions in the allowable impact rate. It also resulted in small but notable levels in contrast in extinction risk between the abundance-based control rules, with control rules 7–9 (and occasionally 6) having lower risk than control rules 4 and 5.

Results from the perfect knowledge of E_3^0 scenario suggest that there is limited ability to reduce extinction risks by employing very accurate abundance forecasts. Highly accurate abundance forecasts would result in more frequent reductions in the allowable impact rate, though nearly equivalent mean spawner levels and incidence of high or moderate risk of extinction for the population size and catastrophe criteria. The choice of using the median or mode to characterize the central tendency of the abundance forecast distribution has little effect on the distribution of spawners but does have some bearing on fishery constraints. For control rules 7 and 9, the shape of the allowable impact rate distribution for the median case is a better approximation of the true case (impact rate distribution resulting from perfect abundance forecasts) than when the mode of the forecast distribution is used as the control rule input variable. In particular, the median of the impact rate distributions is 0.20 for both the median and true cases while it is less than 0.20 for the mode case. Impact rate distributions are similar across the three cases for control rules 4–6. We therefore recommend use of the median of the forecast distribution as the input variable for the control rules.

5 Acknowledgments

The Workgroup would like to thank Arliss Winship for the development of the initial MSE model that has been adapted for this application, and Noble Hendrix who was instrumental in the development of the SRWC abundance forecasting approach. We also appreciate the feedback on this and previous work provided by the Council, the Scientific and Statistical Committee, the Salmon Advisory Subpanel, and the Salmon Technical Team.

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Appendix A Tabular results

This appendix provides tabular results summarizing the MSE results that contributed to Figure 3. Table A-1 displays mean spawner abundance for each control rule and scenario combination. Table A-2 reports the proportion of simulations resulting in low, moderate, and high risk of extinction for the population size criterion (Lindley et al., 2007). Table A-3 reports the proportion of simulations resulting in low, moderate, and high risk of extinction for the catastrophe extinction risk criterion (Lindley et al., 2007). Table A-4 reports the proportion of instances across all simulations in years $30 \leq t \leq 99$ where the control rule specified age-3 impact rate fell into one of four bins. Table A-5 is equivalent to Table A-4 except results are presented for the impact rate realized by the simulated population.

Table A-1. Mean spawner abundance across control rules and scenarios. Scenario abbreviations include AC: Autocorrelation, VP: Variable productivity, and PK: Perfect knowledge.

	Scenario			
Control rule	Base	AC	VP	PK
1	11241	11369	12847	11459
2	3488	3365	4271	3482
3	6632	6612	7811	6616
4	6754	6793	7893	6735
5	6716	6727	7787	6823
6	6731	6916	7882	6915
7	6900	7031	8015	7115
8	6935	7186	7910	6912
9	6840	7014	8058	7101

Table A-2. Proportion of simulations resulting in high, moderate, and low risk of extinction for the populations size criterion across control rules and scenarios. Scenario abbreviations include AC: Autocorrelation, VP: Variable productivity, and PK: Perfect knowledge.

	Base			AC			VP			PK		
Control rule	Low	Mod	High	Low	Mod	High	Low	Mod	High	Low	Mod	High
1	1.000	0.000	0.000	0.981	0.019	0.000	0.999	0.001	0.000	0.999	0.001	0.000
2	0.907	0.091	0.002	0.724	0.224	0.052	0.927	0.072	0.001	0.909	0.090	0.001
3	0.992	0.008	0.000	0.917	0.079	0.005	0.992	0.008	0.000	0.991	0.009	0.000
4	0.992	0.008	0.000	0.927	0.070	0.003	0.994	0.006	0.000	0.995	0.005	0.000
5	0.994	0.006	0.000	0.930	0.068	0.002	0.994	0.006	0.000	0.995	0.005	0.000
6	0.994	0.006	0.000	0.934	0.064	0.002	0.994	0.006	0.000	0.997	0.003	0.000
7	0.995	0.005	0.000	0.943	0.056	0.001	0.996	0.004	0.000	0.997	0.003	0.000
8	0.996	0.004	0.000	0.948	0.051	0.001	0.995	0.005	0.000	0.996	0.004	0.000
9	0.994	0.006	0.000	0.939	0.059	0.002	0.994	0.006	0.000	0.996	0.004	0.000

Table A-3. Probability of high, moderate, and low risk of extinction for the catastrophe criterion across control rules and scenarios. Scenario abbreviations include AC: Autocorrelation, VP: Variable productivity, and PK: Perfect knowledge.

	Base			AC			VP			PK		
Control rule	Low	Mod	High	Low	Mod	High	Low	Mod	High	Low	Mod	High
1	0.571	0.427	0.002	0.522	0.468	0.011	0.494	0.499	0.007	0.569	0.430	0.001
2	0.561	0.435	0.004	0.542	0.442	0.016	0.512	0.478	0.010	0.563	0.432	0.005
3	0.574	0.424	0.002	0.530	0.458	0.013	0.506	0.486	0.008	0.569	0.428	0.002
4	0.573	0.424	0.003	0.530	0.458	0.012	0.501	0.492	0.007	0.573	0.425	0.002
5	0.574	0.424	0.002	0.534	0.455	0.011	0.509	0.484	0.006	0.578	0.420	0.002
6	0.569	0.429	0.002	0.528	0.459	0.013	0.509	0.483	0.008	0.575	0.424	0.001
7	0.573	0.425	0.002	0.534	0.454	0.012	0.506	0.487	0.006	0.587	0.412	0.001
8	0.563	0.435	0.002	0.528	0.460	0.012	0.492	0.500	0.008	0.566	0.432	0.003
9	0.569	0.429	0.002	0.529	0.459	0.012	0.498	0.493	0.009	0.582	0.416	0.002

Table A-4. Proportion of simulations in which the allowable age-3 impact rate falls within the specified bins. Bins include $i_3 = 0$, $0 < i_3 \leq 0.10$, $0.10 < i_3 < 0.20$, and $i_3 \geq 0.20$. Scenario abbreviations include AC: Autocorrelation, VP: Variable productivity, and PK: Perfect knowledge.

	Base				AC				VP				PK			
Control rule	0	0-0.1	0.1-0.2	0.2	0	0-0.1	0.1-0.2	0.2	0	0-0.1	0.1-0.2	0.2	0	0-0.1	0.1-0.2	0.2
1	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
2	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00
3	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00
4	0.00	0.03	0.01	0.95	0.00	0.07	0.02	0.91	0.00	0.03	0.02	0.95	0.00	0.10	0.03	0.88
5	0.00	0.01	0.03	0.95	0.00	0.04	0.05	0.91	0.00	0.01	0.04	0.95	0.00	0.05	0.07	0.88
6	0.03	0.01	0.01	0.96	0.06	0.01	0.01	0.92	0.03	0.01	0.01	0.95	0.09	0.01	0.01	0.88
7	0.01	0.00	0.36	0.63	0.03	0.00	0.38	0.59	0.01	0.00	0.35	0.64	0.04	0.00	0.39	0.57
8	0.00	0.00	0.37	0.62	0.03	0.00	0.44	0.54	0.00	0.00	0.33	0.66	0.00	0.00	0.37	0.63
9	0.00	0.01	0.36	0.63	0.00	0.04	0.38	0.59	0.00	0.01	0.35	0.64	0.00	0.05	0.39	0.57

Table A-5. Proportion of simulations in which the realized age-3 impact rate (accounting only for implementation error) falls within the specified bins. Bins include $i_3 = 0$, $0 < i_3 \leq 0.10$, $0.10 < i_3 < 0.20$, and $i_3 \geq 0.20$. Scenario abbreviations include AC: Autocorrelation, VP: Variable productivity, and PK: Perfect knowledge.

	Base				AC				VP				PK			
Control rule	0	0-0.1	0.1-0.2	0.2	0	0-0.1	0.1-0.2	0.2	0	0-0.1	0.1-0.2	0.2	0	0-0.1	0.1-0.2	0.2
1	0	1.00	0.00	0.00	0	1.00	0.00	0.00	0	1.00	0.00	0.00	0	1.00	0.00	0.00
2	0	0.01	0.11	0.88	0	0.01	0.11	0.88	0	0.01	0.11	0.88	0	0.01	0.11	0.88
3	0	0.06	0.47	0.48	0	0.06	0.47	0.48	0	0.06	0.47	0.48	0	0.06	0.47	0.48
4	0	0.07	0.47	0.46	0	0.09	0.47	0.44	0	0.07	0.47	0.46	0	0.10	0.47	0.42
5	0	0.07	0.47	0.46	0	0.10	0.46	0.44	0	0.07	0.47	0.46	0	0.11	0.46	0.43
6	0	0.09	0.45	0.46	0	0.13	0.43	0.44	0	0.09	0.45	0.46	0	0.15	0.42	0.42
7	0	0.11	0.51	0.39	0	0.13	0.50	0.37	0	0.11	0.51	0.38	0	0.16	0.50	0.35
8	0	0.09	0.51	0.40	0	0.15	0.51	0.35	0	0.09	0.51	0.41	0	0.09	0.51	0.40
9	0	0.10	0.51	0.39	0	0.12	0.52	0.36	0	0.10	0.51	0.38	0	0.13	0.52	0.35