

# **Preliminary evaluation of alternative Sacramento River winter Chinook salmon control rules**

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## **1 Introduction**

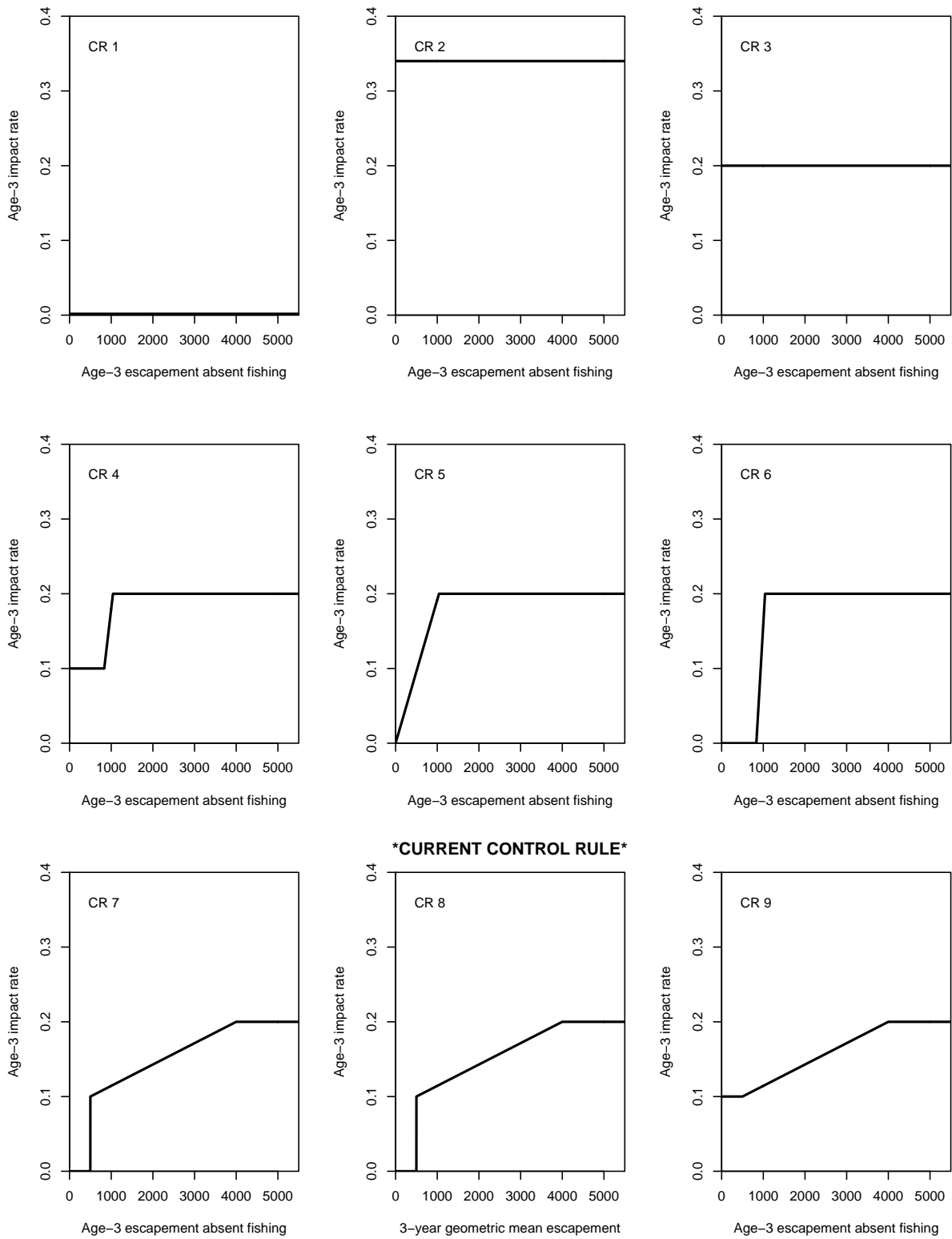
At the November 2015 Pacific Fishery Management Council (PFMC) meeting, the Council formed the Ad Hoc Sacramento River Winter Chinook Workgroup (hereafter Workgroup) and tasked the Workgroup with exploring and evaluating alternative fishery management frameworks for Sacramento River winter Chinook salmon (SRWC). The Workgroup identified three focal efforts, including: (1) develop methods for forecasting the abundance of SRWC, (2) develop a suite of potential control rules for the Council's consideration, and (3) evaluate the performance of these control rules with regard to conservation benefits and fishery costs using a Management Strategy Evaluation (MSE) approach. With regard to (1), abundance forecasting approaches were developed, presented at the October 2016 Methodology Review, and reviewed by the full Scientific and Statistical Committee (SSC) at the November 2016 PFMC meeting. With regard to (2), the Workgroup developed a suite of alternative control rules (Figure 1) which were adopted by the Council for further analysis at the September 2016 PFMC meeting. This report represents initial results from effort (3): evaluation of alternative control rules through MSE simulations.

The MSE model used to evaluate alternative SRWC control rules is a modified and updated

version of the MSE model previously used to inform the Reasonable and Prudent Alternative for the 2010 ocean fishery Biological Opinion (NMFS, 2010). Detailed descriptions of this model can be found in a companion report (O’Farrell, 2017) and Winship et al. (2012, 2013). A copy of Winship et al. (2012) can be found at [http://www.pcouncil.org/wp-content/uploads/SRWC\\_MSE\\_2012\\_02\\_28.pdf](http://www.pcouncil.org/wp-content/uploads/SRWC_MSE_2012_02_28.pdf). Parameter estimates used in the MSE were obtained by fitting a SRWC population dynamics model to female spawner and natural-origin fry data. The population dynamics model shares the same structure as the MSE operating model and is based on the model described in Winship et al. (2011, 2014). The MSE operating model and the population dynamics model were modified from the earlier versions in that a temperature covariate was added to the density dependent egg-to-fry survival rate. The population dynamics model was also re-fitted with updated data and therefore the parameters of the MSE operating model have been updated. Finally, an abundance forecasting module representing how forecasts would be made in practice was incorporated into the MSE. The *Base* forecast model described in O’Farrell et al. (2016) is implemented in the MSE simulations described here.

The suite of control rules evaluated in this report were approved as a draft range of control rules by the Council (Figure 1). Control rules 1–3 are constant age-3 impact rate ( $i_3$ ) strategies representing no fishing, historical impact rates (O’Farrell and Satterthwaite, 2015), and more contemporary impact rates (O’Farrell et al., 2012), respectively. Control rules 4–9 specify reductions in  $i_3$  from a maximum level of 0.20 as abundance declines. Control rule 8 is the status quo 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).

In this report I present results from a base case MSE and a series of alternative scenarios selected to evaluate the robustness of simulation results. Extinction risks were evaluated using a select subset of criteria previously identified for Central Valley salmonids (Lindley et al., 2007). Costs to fisheries were evaluated by computing the frequency of the allowable impact being scaled back from the maximum level of 0.20.



**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.

## 2 Methods

### 2.1 MSE

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, 2017). 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 the age-3 escapement absent fishing ( $E_3^0$ ) is made from simulated fry data, incorporating observation error, using the *Base* forecast model (O’Farrell et al., 2016). This forecast abundance 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 and implementation error. 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 herein are the result of 20,000 simulations of 100 years in duration, performed for each control rule scenario described below.

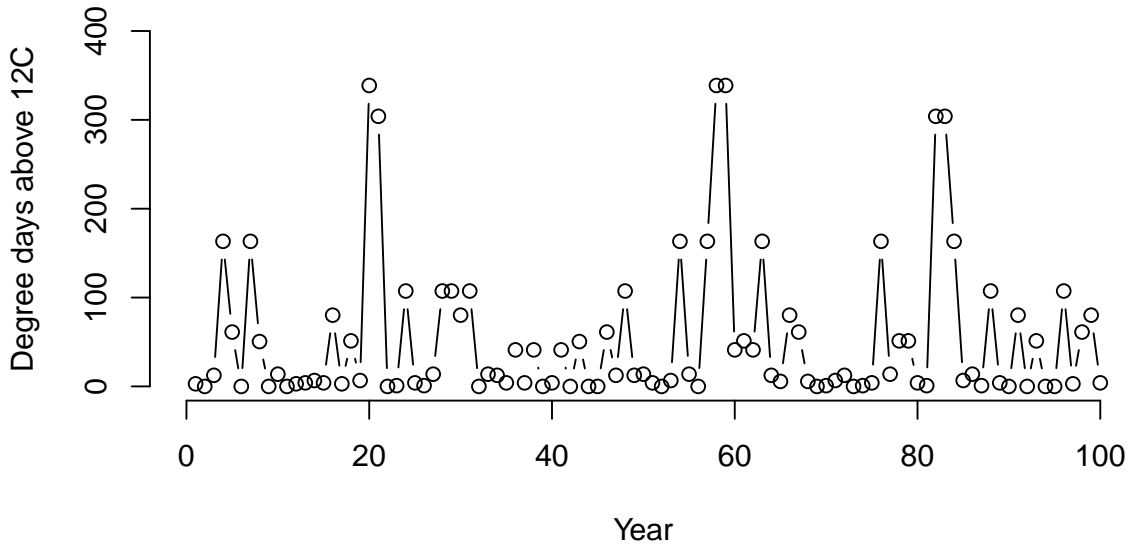
## 2.2 Simulation scenarios

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, 2017). 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. The temperature covariate is specified as a time series where “normal” years are punctuated by severe droughts. 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. Figure 2 provides an example time series of the river temperature covariate.



**Figure 2.** A single random example of the time series of the river temperature covariate to the maximum egg-to-fry survival rate parameter.

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 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.
5. The mean and 95 percent interval of the realized age-3 impact rate in years  $30 \leq t \leq 99$ .

### **3 Results**

Figure 3 displays performance measures across all control rules and scenarios.

#### **3.1 Base case**

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). These escapements were lower than those reported in Winship et al. (2012). Average escapement in the absence of fishing in Winship et al. (2012) was reported to be approximately 23,000–24,000 fish, while under the other control rules, mean spawner levels were approximately 13,000 fish. There was very little contrast between control rules 3–9 with regard to the mean number of spawners.

With regard to extinction risk for the population size criterion, the large majority of simulations resulted in a low risk of extinction. These results are consistent with those of Winship et al. (2012) for their base case with no autocorrelation assumed in the juvenile survival rates. The extinction risk proportions presented here for the population size criterion exceeded those in Winship et al. (2012) by minimal amounts, except for control rule 2 (their control rule 1). For control rule 2,

a constant impact rate of 0.37 was assumed while Winship et al. (2012) assumed an impact rate of 0.25. There was very little contrast between control rules 3–9 with regard to the proportion of simulations with either a moderate or high risk of extinction for the population size criterion.

For the catastrophe criterion, there was very little difference in extinction risk among the nine control rules. Each control rule had moderate/high extinction risk for approximately 40–50 percent of the simulations.

The proportion of simulations where the control-rule specified impact rate was at least 20 percent varied substantially between control rules. For control rules 4–6, impact rates were specified at the maximum level of 20 percent for a very high proportion of the simulations. In contrast, impact rates were scaled back much more frequently for control rules 7–9; specified impact rates were at the maximum level for approximately 60 percent of the simulations. There was an imperceptible difference between control rule 7 (which is informed by a forecast of abundance) and control rule 8 (which has the same form as control rule 7 but is informed by the three-year geometric mean of spawner escapement).

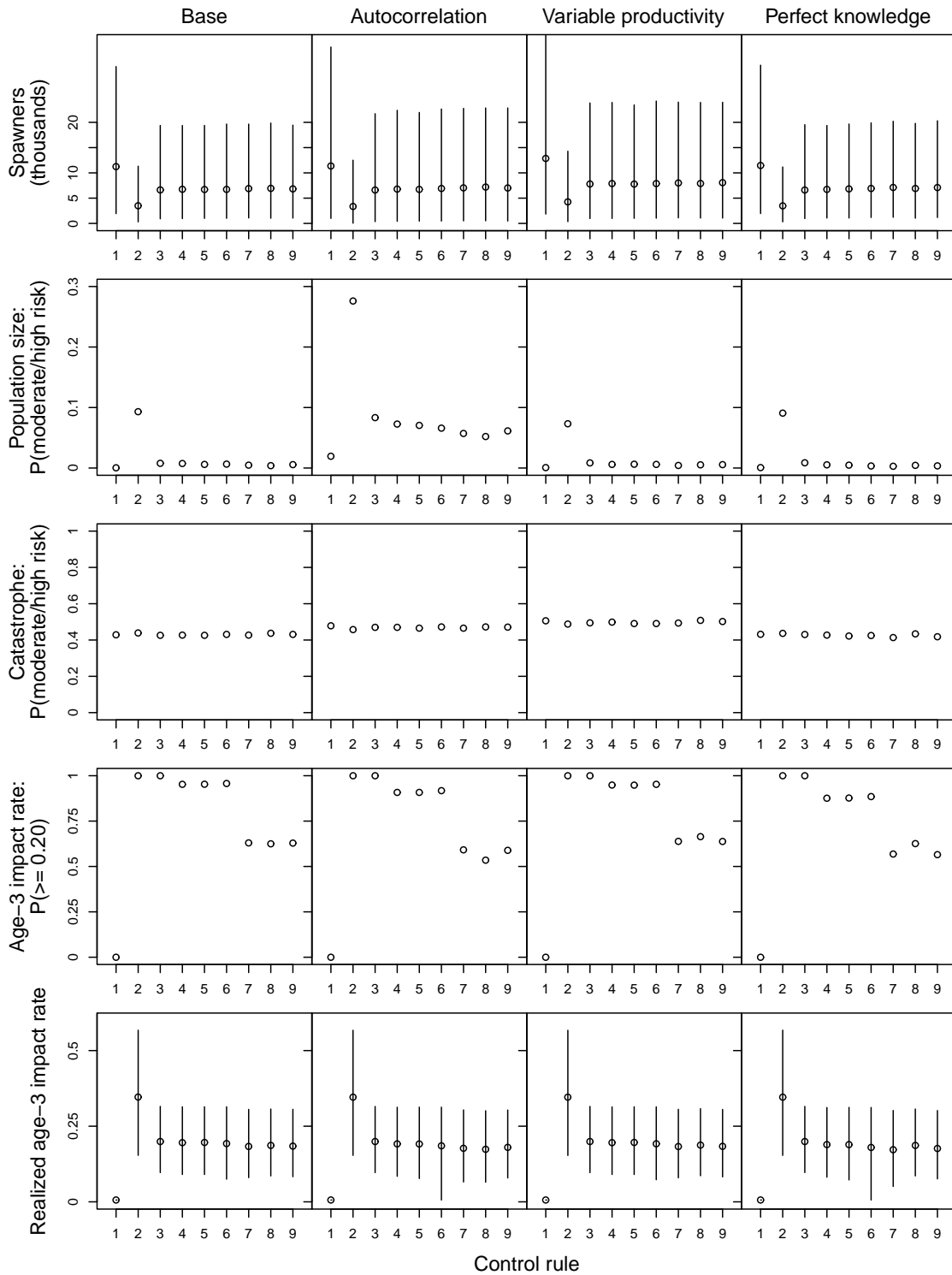
Realized impact rates were similar across control rules 3–9. While control rules 7–9 have impact rates scaled back more frequently than control rules 4–6, this did not translate into large differences in realized impact rates. This is likely due to the reductions in specified impact rates being relatively modest and the implementation error incorporated when computing realized impact rates given the allowable impact rates.

### **3.2 Autocorrelated juvenile survival rates**

Including temporal autocorrelation in the juvenile survival rates did not have an appreciable effect on mean spawner levels relative to the base case, though variability in the distribution of spawner abundance increased.

With regard to the population size risk criterion, the proportion of simulations with moderate or high risk of extinction was substantially higher than the base case. For control rules 3–9, a moderate or high risk occurred in 5 to 10 percent of the simulations. This result likely comes from





**Figure 3.** Performance measures evaluated for each of the nine control rules and four alternative scenarios. For the “Spawners” and “Realized age-3 impact rate” results the circles represent mean values and the 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 increased variance in the escapement time series, which is a product of runs of low or high escapement. There is some contrast in extinction risk among the abundance-based control rules, with control rule 4 having the highest risk and control rule 8 having the lowest risk.

For the catastrophe criterion, there was a small overall increase in the incidence of moderate or high risk of extinction relative to the base case. However, there was little contrast in risk across the control rules.

Age-3 impact rates were scaled back from the maximum level with greater frequency under the autocorrelation scenario. As with the base case, control rules 7–9 were scaled back more frequently than control rules 4–6. Control rule 8 resulted in the impact rate being scaled back most frequently among all control rules (nearly 50 percent of simulations).

Realized impact rates were comparable between the base case and autocorrelation simulations.

### **3.3 Variable productivity**

Incorporating the effect of periodic droughts through the temperature covariate in the egg-to-fry relationship had the effect of slightly increasing the mean abundance relative to the base case. The likely reason for this counterintuitive result is that the population experiences higher productivity for most years of the simulation (relative to the base case), which are punctuated by two-year periods with low productivity. The base case assumes a mean 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. Under this scenario, the population is driven both by catastrophes (serious droughts which result in warm water and low productivity) and bonanzas (cold water and high productivity).

For the population size criterion, the proportion of simulations resulting in moderate or high risks of extinction was very similar to the base case. There was little contrast among the abundance-based control rules.

For the catastrophe criteria, the proportions of moderate or high extinction risks were slightly higher relative to the base case and the autocorrelation scenario. There was little contrast among all of the control rules.

Specified impact rates were scaled back from the maximum of 20 percent at a similar frequency as the base case. However, control rule 8, which relies on the three year geometric mean of escapement, resulted in less frequent reductions in the allowable impact rate relative to control rules 7 and 9 (which rely on a forecast of  $E_3^0$ ).

Realized impact rates and their variability were comparable between the base case and variable productivity simulations.

### **3.4 Perfect knowledge of $E_3^0$**

In the case where  $E_3^0$  is known exactly, the mean and variability in the number of spawners was similar to the base case. Furthermore, there were negligible differences between the base case and the perfect knowledge scenario with regard to the population size and catastrophe criterion. There was little contrast in these performance measures between control rules 3–9.

Allowable impact rates for control rules 4–7 and 9 were scaled back more frequently than the base case when  $E_3^0$  was known without error. Control rule 8 predictably scaled back impact rates at the same rate as the base case.

Realized impact rates were slightly lower for the abundance-based control rules. Of note, the lower bound of the 95 percent intervals of the  $i_3$  distribution extends to lower values than the base case.

## **4 Discussion**

The MSE results suggest very little contrast among control rules 4–9 in the distribution of spawner abundance and the extinction risk criteria examined here. While the abundance-based control rules have a variety of forms and abundance levels at which the age-3 impact rate begins to be reduced, the differences in these control rules result only in small differences in mean realized impact rates and mean escapement. Furthermore, mean realized impact rates and escapement for abundance-based control rules are very similar to those for control rule 3 (a constant 20 percent impact rate).

Under most simulations, the specified impact rates for the abundance-based control rules are either 20 percent or decreased from that maximum level by only a small amount. Accounting for error in the implementation of the allowable impact rate also contributes to the similarity in mean realized impact rates across control rules 3–9.

There are substantial differences between control 4–9 with regard to the frequency at which the allowable impact rate is reduced from the maximum level of 20 percent. Under all scenarios, control rules 4–6 specified an age-3 impact rate of 20 percent under the large majority of simulations and there was little difference in this result between these control rules. In contrast, the allowable impact rate was specified to be 20 percent in a much smaller proportion of simulations for control rules 7–9. This result is intuitive since control rules 7–9 begin ramping down the allowable impact rate at much higher abundance levels than control rules 4–6.

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 abundance and incidence of high or moderate risk of extinction for the population size and catastrophe criteria.

## **5 Acknowledgments**

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