APPENDIX MS2013-03. OCEAN CONDITIONS AND SELECTED MANAGEMENT OPTIONS ON THE POPULATION DYNAMICS OF WENATCHEE RIVER SPRING CHINOOK SALMON

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EXECUTIVE SUMMARY

Ocean conditions have a large influence on salmon population dynamics, and predicting future impacts of climate change on salmon populations requires forecasting ocean conditions and consideration of the implications for abundance and persistence of populations. However, there is much uncertainty regarding the implications of climate change on local and basin-scale oceanography. Lacking downscaled climate-ocean models relevant to salmon, we can consider a range of ocean condition scenarios, and evaluate to what extent potential management options can compensate for poor ocean conditions. Here I apply scenarios for climate and management actions, focusing on responses of Wenatchee River spring Chinook salmon, a population listed as endangered under the Endangered Species Act. Predictions of population responses are available from a stochastic Leslie matrix-type salmon life cycle model that combined scenarios of simulated future ocean conditions with estimated effects of management actions that affected freshwater (prespawning adults, and rearing juvenile fish), mainstem (smolt migration through the Federal hydropower system) and estuary (avian predation). Scenarios for ocean conditions consisted of alternative percentages of years when ocean conditions during early ocean entry by salmon were favorable (negative mean annual Pacific Decadal Oscillation [PDO] values) and unfavorable (positive PDO values) for survival. Compared to a benchmark scenario, median spawners and carrying capacity declined with worsened ocean conditions. When we applied management actions individually, freshwater survival increases had the strongest effect on mitigating for poor ocean conditions compared to the mainstem hydropower dam and estuary survival improvements. Taken together, both freshwater, mainstem, and estuary management actions offset the effects of some moderate declines in ocean condition, but not the poorest ocean conditions considered in these scenarios. Future salmon life cycle modeling should consider other aspects of potential future ocean conditions, such as the frequency and magnitude of bad and good PDO periods, upwelling, and ocean variability.

BACKGROUND/INTRODUCTION

Ocean conditions have a large influence on salmon population dynamics (e.g., Koslow et al. 2002; Scheuerell and Williams 2005; Wells et al. 2008; Burke et al. 2013), and predicting future impacts of climate change on salmon populations requires forecasting ocean conditions and consideration of the implications for abundance and persistence of populations. These ocean conditions are a function of both regional and basin-scale processes (e.g., Mantua et al. 1997; Peterson et al. 2012). For instance, Jorgensen et al. (2013) and Crozier et al. (2013), respectively, have identified coastal upwelling and the Pacific Decadal Oscillation (PDO) as correlates of ocean survival for Chinook salmon (*Oncorhynchus tshawytscha*) populations in the US Pacific Northwest. Wells et al. (2008) found that Chinook salmon in the Smith River, California benefited from cool ocean temperatures and strong upwelling, wind stress, and a strong California Current. A critical question for decision makers is whether potential management actions can buffer or offset changes to these regional and basin-scale drivers that may stem from climate change.

There is much uncertainty regarding the implications of climate change on local and basin-scale oceanography. At the scale of the entire subarctic North Pacific Ocean, Schindler and colleagues (2008) note that increases in salmon production over the last several decades are linked to cool, productive ocean conditions, which may not persist under warming trends due to climate change. King et al. (2011) summarize potential implications of climate change in the California Current, and conceptual linkages between climate change and the potential response of Chinook salmon. King and colleagues summarize ensemble results from global circulation models, which suggest the potential for slight warming by year 2050, and some minor increases in upwelling intensity, particularly in the northern California Current. They identify risks of climate change to Chinook salmon, specifically the potential for a weakened California Current that could depress fecundity and increase mortality, and for ocean warming to favor northern populations over southern populations. These authors and Hollowed et al. (2013) note the difficulty in inferring local patterns from coarse scale global circulation models, and they point to the need for downscaled, finer resolution oceanographic modeling. Downscaled oceanographic models, forced by coarser scale global circulation models under IPCC CO_2 emissions scenarios, are in progress but not yet available for the marine environment. This contrasts with more extensive downscaling of global circulation models that has been applied to freshwater portions of Chinook salmon habitat (Battin et al. 2007; Crozier et al. 2008; Beechie et al. 2012).

In lieu of downscaled climate-ocean models for salmon, we can consider a range of ocean condition scenarios, and can evaluate to what extent potential management options can compensate for poor ocean conditions for salmon. This approach is consistent with the use of scenarios for ecological assessment and planning (Millenium Ecosystem Assessment 2005; Alcamo 2008) and with the need to identify management options that are robust to a range of uncertain future ocean conditions. Management options might include freshwater habitat restoration, which could improve survival of adult spawning fish and the juvenile freshwater rearing stage, modifications to hydropower operations, and a reduction in avian predation of juvenile outmigrants in the Columbia River estuary.

Here I apply these scenarios for climate and management actions, focusing on responses of Wenatchee River spring Chinook salmon, a population listed as endangered under the Endangered Species Act. Predictions are available from a life cycle model being developed by a team of researchers as a part of the Adaptive Management Implementation Plan (AMIP) of the 2008 Federal Columbia River Power System Biological Opinion (FCRPS

Biop) (Jorgensen et al. 2013). Life cycle models are useful tools to explore environmental change and resource management options on species population dynamics. The 2008 FCRPS Biop used life cycle models of Pacific salmonid populations to examine the effects of hydropower system dam operations on population viability under a range of future climate and hydropower system operations scenarios. The AMIP, an addition to the 2008 FCRPS Biop, called for an extension of these models to include more populations, and to include several types of effects, including habitat mitigation actions, and climate (Zabel et al. 2013). The work below considers habitat actions and climate, as well as management actions related to hydropower and avian predation.

STOCHASTIC LIFE CYCLE MODEL AND SCENARIOS

In this section we briefly describe the model, outline a few model scenarios, and provide and discuss some preliminary results.

THE MODEL

The Wenatchee spring Chinook life cycle model framework is built from a Leslie matrix age-structured population model for stream-type spring Chinook salmon (Zabel et al. 2006; ICTRT and Zabel 2007; Jorgensen et al. 2013). It tracks population numbers across five life stage classes through time: parr, smolts, ocean residence (from one to three years), and tributary spawners (four and five year old fish that spent two and three years, respectively, in the ocean). The following is a brief description of the model, but see ICTRT and Zabel (2007) and Jorgensen et al. (2013) for more details. The model is coded and runs in the R statistical and programming environment (R Development Core Team 2013).

The number of individuals at time $t+1$ is represented by $\mathbf{n}$, which is a 5 x 1 vector of the number of individuals at each of five life stages, and is a product of a 5 x 5 transition matrix, $\mathbf{A}(t)$, the dimensions of which reflect the five life stages incorporated into the model and the entries of which change with t, and the number of individuals in each of the life stages, $\mathbf{n}$, at time t:

$$\mathbf{n}(t+1) = \mathbf{A}(t) \cdot \mathbf{n}(t).$$

The elements in each row of $\mathbf{A}(t)$ determine the transition of individuals at one life stage progressing through to the next life stage, from one row in the $\mathbf{n}(t+1)$ matrix down to the next:

$$\mathbf{A}(t) = \begin{bmatrix} 0 & 0 & 0 & b_4 \cdot s_A \cdot F_4(t) & s_A \cdot F_5(t) \\ s_2 & 0 & 0 & 0 & 0 \\ 0 & s_3(t) & 0 & 0 & 0 \\ 0 & 0 & (1-b_3) \cdot s_o & 0 & 0 \\ 0 & 0 & 0 & (1-b_4) \cdot s_o & 0 \end{bmatrix}.$$

The s_is are the survival probabilities of moving from one life stage to the next. s_2 is the survival probability of parr to the smolt stage (moving from one-year-old fish to two years old). $s_3(t)$ is the survival probability of the transition of fish from two to three years old, the period in which fish leave freshwater and enter the estuary and ocean, corresponding to their first year of ocean residency. The s_3 term accommodates stochasticity and varies in time and according to scenarios of climatic and ocean conditions. s_o represents the subsequent annual probability of ocean survival, which was fixed at 0.80 (TRT and Zabel 2007). The proportion of three and four year olds leaving the ocean and returning to spawn (their breeding propensities) are noted by b_3 and b_4, thus, the proportion of three and four year old fish remaining in the ocean is given by $(1 - b_3)$ and $(1 - b_4)$. s_A is the survival of adults from Bonneville dam to the spawning grounds, and is a product of upstream survival through the Columbia River mainstem dam system, s_u, survival after in-river harvest, $(1 - h_r)$, and survival from the upper-most dam to the Wenatchee basin, s_{sb}. Fecundity in some cases for some fish species may be different for spawning fish of different ages, and the model can accommodate this differential with a fecundity multiplier, the F_i terms.

Table 1: Parameter inputs for the Wenatchee River spring Chinook salmon matrix-type model for three major production areas: Chiwawa River, Nason Creek, and the White River.

Parameter	Chiwawa River	Nason Creek	White River
Spawner(t) -to- parr$(t+1)$ Beverton-Holt "a"	353.437	328.490	154.318
Spawner(t) -to- parr$(t+1)$ Beverton-Holt "b"	0.000298	0.005	0.005
$\sigma^2{}_1$	0.412	0.600	1.04
ϕ_1 (variance term)	0.1	---	---
Parr-smolt survival[1]	0.6	0.6	0.6
Hydrosystem survival	0.525	0.525	0.525
s_3 (first ocean year)	Stochastic variable, dependent on relationship to ocean conditions	Stochastic variable, dependent on relationship to ocean conditions	Stochastic variable, dependent on relationship to ocean conditions
s_o (ocean survival for years after s_3)	0.8	0.8	0.8
b_3 (propensity of 3 year olds to breed)	0.046	0.046	0.046
b_4 (propensity of 4 year olds to breed)	0.514	0.514	0.514
h_r (in-river harvest rate)	0.09	0.09	0.09
s_u (Bonneville-to-basin survival rate)	0.794	0.794	0.794
s_{sb} (pre-spawning survival rate)	0.9	0.9	0.9
Initial abundance of 4 and 5 year old tributary spawners (geometric mean of 2008-2012 counts)	406	148	38

[1]Parr-smolt survival measures survival from exiting the tributaries until reaching the mainstem Columbia, derived in original matrix model.

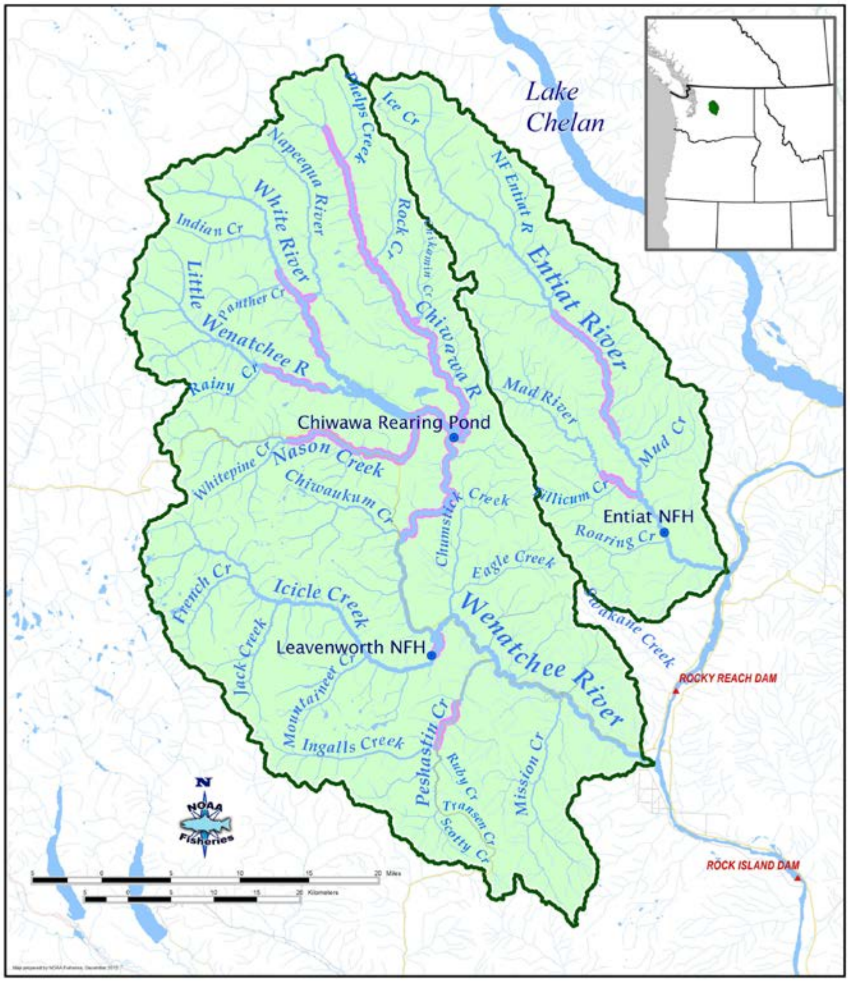

Figure 1: Wenatchee and Entiat River basins, with areas of recent spring Chinook salmon spawning and rearing indicated with highlights (in pink).

MULTIPLE PRODUCTION AREAS

We developed this life cycle model to incorporate three of the major fish production areas in the Wenatchee River basin representing the vast majority of fish production: Chiwawa River, Nason Creek, and the White River (Fig. 1). At the present time, we include three of these in the model: Chiwawa River (parameters as in the 2007 report, and shown in Table 1), Nason Creek, and the White River (parameters for both are reported in Table 1). The model essentially functions as though there are alternative transition matrices, $\mathbf{A}(t,j)$, and population vectors, $\mathbf{n}(t,j)$, for each production area, j, with production-area-specific parameters where appropriate or where data were available to estimate them (Table 1). As the model moves through time, each of the production areas' life stage transition survival calculations are handled separately, and the numbers of fish within the age classes in each of the $\mathbf{n}(t,j)$ vectors were summed to create one $\mathbf{n}(t)$ vector representing the entire Wenatchee population, which was used for calculations of overall population metrics such as the geometric mean of spawners, mean recruits per spawner, and for calculations of extinction probabilities (see explanations of these in "Model Output Response Measures" section below). As a consequence of the spatial coverage of the model's structure, we have implicitly begun to encompass two of several juvenile life history strategies. For example, juveniles from Nason Creek typically migrate to and rear in the mainstem Wenatchee River, rather than remain in their tributary to rear until they begin to migrate to the ocean. This alternative life history strategy can often lead to differential survival as they progress through subsequent freshwater and ocean life stages. As we develop the model further we will more explicitly incorporate juvenile life history variation.

SPAWNER-TO-PARR TRANSITION AND SURVIVAL

There is density dependence built into the spawner to subsequent parr transition, which was estimated for three of the five production areas by fitting a density-dependent Beverton-Holt (B-H) relationship to spawners and subsequent parr, s_1; $\mathrm{parr}(t+1) = \left(a \cdot S(t)\right)/\left(1 + b \cdot S(t)\right)$. B-H estimates of "$a$" and "$b$" parameters for the Chiwawa River fish were from the ICTRT and Zabel (2007) Wenatchee matrix-type model, and derived by dividing recruits by the product of prespawning survival, smolt-to-adult return rates, and parr-to-smolt survival; $\mathrm{parr}(t+1) = R_t/\left(s_{sb} \cdot \mathrm{SAR}_{t+2} \cdot s_{p-s}\right)$. Chiwawa River estimates included a Box-Cox transformation as a way to deal with the heteroscedasticity in the data (the σ_1^2 and ϕ_1 parameters; see Zabel et al. 2006 and ICTRT and Zabel 2007 for details). Nason Creek and White River B-H models were fitted to spawner and parr estimates from those subbasins (Washington Department of Fish and Wildlife, unpublished data). The short spawner and parr time series for Nason Creek and the White River didn't allow the Box-Cox transformation and estimation of these parameters, thus the s_1 function for these production areas was of the simpler form without the Box-Cox transformation. In place of those in Table 1 for Nason Creek and White River we report the variance, σ^2, of the B-H fits.

MODEL OUTPUT RESPONSE MEASURES

The following model output summary metrics are reported:

- Xth percentile of spawner abundance at time t = 100 years, taken across runs. The percentiles are X = 5%, 50% (median), and 95% ($N_{t,5\%}$, $N_{t,50\%}$, $N_{t,95\%}$).
- Geometric mean (taken across runs) of low (L), medium (M), and high (H) (calculated across years within a run) of spawner abundance, where $\bar{N}_{\mathrm{L}}$ = the 5th percentile, $\bar{N}_{\mathrm{M}}$ = the 50th percentile, and $\bar{N}_{\mathrm{H}}$ = the 95th percentile within a run.
- Probability of quasi-extinction for simulations that ran t = 100 years ($\mathrm{pr(QE)}_t$). We calculated the probability that the population would fall below 50 spawners in a moving average of four years.

We calculated two additional population dynamics metrics in response to these scenarios for purposes of comparison with other reports of this model's output on different sets of scenarios. They included productivity at low spawner abundance and carrying capacity. To calculate these metrics we first produced spawner and recruit data from model simulations for a given scenario. We ran several iterations (n = 10), and then combined all these data together. We then fit the following Beverton-Holt relationship to these data:

$$R_t = \frac{a \cdot S_t}{1 + b \cdot S_t} \cdot \exp(\varepsilon_t), \ \ \varepsilon \sim N(0, \sigma^2),$$

where R_t and S_t are recruits and spawners, respectively, in brood year t, a and b are model parameters, and with a multiplicative lognormal error term, ε_t. The parameter a represents maximum productivity (recruits per spawner) at low abundance, and a/b represents the maximum asymptotic recruitment. From these fits, we reported carrying capacity, K, at equilibrium population abundance where $R = S$, which is equal to $(a - 1)/b$. In some cases K was negative which indicated unfavorable conditions, as presented in the model by detrimental combinations of scenarios and parameter values. Negative K values were reported as "NA."

Taken together, these output metrics give a snapshot of the health of a population in response to a given set of environmental and management actions.

We ran simulations for t = 100 years and for each scenario we repeated model runs for n = 1,000 times to obtain a robust estimate of quasi-extinction probabilities.

SCENARIOS: FUTURE OCEAN CONDITIONS

Ocean conditions enter the life cycle model in survival during the third year of life, $s3$, when fish migrate out of their natal tributary basin and enter the estuary and ocean and begin their ocean residency period. We do not have direct measurements of $s3$, however we can estimate it from annual measurements of smolt-to-adult survival, SAR. We estimated $s3$ from SAR data and, treating $s3$ as a response variable, we found relationships between $s3$ and ocean indices (ICTRT and Zabel 2007; Kendall et al. 2013). For Wenatchee spring Chinook salmon, spring coastal upwelling (April and May; Pacific coastal upwelling index at 45°N 125°W) and river transit time to reach the estuary were important drivers of $s3$ (ICTRT and Zabel 2007; Jorgensen et al. 2013; Kendall et al. 2013).

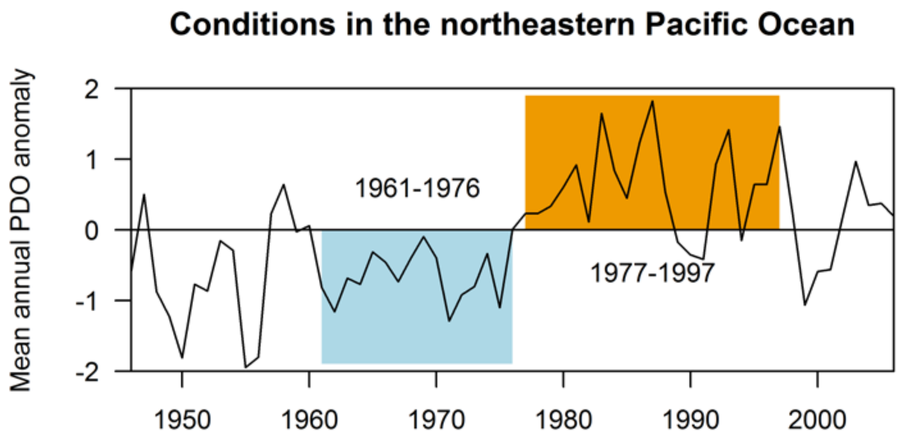

Figure 2: Ocean conditions as measured by Pacific Decadal Oscillation anomalies in recent years, with relative periods of favorable (cooler ocean surface waters, 1961-1976; blue) and unfavorable (warmer ocean surface waters, 1977-1997; orange) conditions for Pacific salmon survival in the ocean used to develop scenarios of future ocean conditions.

For the future ocean conditions scenarios, we developed time series of ocean indices for periods composed of differing amounts of "good" and "bad" periods as measured by the Pacific Decadal Oscillation anomaly index (PDO, Fig. 2; Mantua et al. 1997; http://jisao.washington.edu/pdo/PDO.latest). These time series determined third year survival, *s*3. We focused on PDO as a measure of ocean conditions to remain consistent across the ocean conditions scenarios for Chinook salmon life cycle modeling included in this report (see Crozier and Zabel, this report). Negative PDO values indicate cooler northeastern Pacific Ocean surface waters and promote conditions favorable to salmon ocean survival, whereas positive PDO values indicate warmer northeastern Pacific Ocean surface waters which are associated with conditions generally unfavorable to salmon survival in the ocean (e.g., Mantua et al. 1997; Peterson et al. 2012; Fig. 2). Our time series consisted of different percentages of good and bad years taken from these time periods (Fig. 2): 20% bad; 40% bad; 60% bad; 80% bad; 100% bad. We interleaved the good and bad year blocks (approximate 15 and 20 yr blocks, respectively; Fig. 2) to achieve the desired scenario compositions for time series of 100 years in length; thus, except for the 20% and 100% bad scenarios, blocks of bad and good years alternated through the series. In addition to these scenarios, we also ran a scenario encompassing good and bad periods and the intervening years (1946-2006; Jorgensen et al. 2013). During each run of 100 years in the model, the model randomly chose a starting point in the ocean time series as one part of the model's procedure to introduce stochasticity into third year survival (ICTRT and Zabel 2007). Due to this random starting process the time series were duplicated and stacked as necessary to allow the model to complete each 100 yr run.

The model's procedures for estimating third year survival from ocean conditions as well as the scenarios of future ocean conditions we describe above were the same as those of Crozier and Zabel (this report).

SCENARIOS: MANAGEMENT LEVERS

We combined future ocean conditions scenarios with several resource management scenarios (Table 2). These included:

Freshwater habitat improvements (s_{sb} and s_1 survival)

These parameter perturbations were used as a proxy for habitat improvements through freshwater restoration actions in adult spawning and juvenile rearing reaches, which could impact returning adult fish prior to spawning (prespawning mortality, s_{sb}) and the spawner-to-parr stage (s_1). Presently, we are developing relationships between freshwater habitat actions and fish survival. Therefore, habitat improvements were simulated by increasing survival at these life stages, and as Wenatchee model development continues, these perturbations will be replaced with relationships between freshwater habitat characteristics and in-basin survival estimates.

Improved survival in mainstem and estuary

We explored population dynamics in response to improvements in downstream smolt survival through the FCRPS dams (applied to s_2). In the same scenario, we also applied a multiplier on survival in the estuary (applied to s_3) that estimated a reduction in avian predation on smolt in the estuary (Paulsen and Zabel 2013).

Table 2: Resource management scenarios included in this study.

Survival stage	Change
Prespawning and spawner-parr (s_{sb} and s_1) survival[1,2]	+10%
FCRPS survival (s_2) and avian predation[2]	+10% FCRPS, and -50% reduction in avian predation

[1]Survival changes were applied to survival of spawners from the last dam to their tributaries (s_{sb}) and to the number of parr in $t+1$ produced by spawners in t (s_1) simultaneously.
[2]No decrement was applied to these survivals.

COMBINED EFFECTS OF FUTURE OCEAN CONDITIONS AND MANAGEMENT ACTIVITIES

The benchmark scenario consisted of typical regime shifts in ocean conditions observed over the last ~60 years, with approximately 46% unfavorable and 54% favorable years of ocean conditions for salmon from 1946-2006 as measured by the number of positive and negative PDO anomalies (Fig. 2). Median spawner abundance over the 100 year simulations was 860 individuals. The probability of quasi-extinction was small, only

0.001. However, interpretation of extinction probability as presented here must be done with care. Extinction probability in this analysis was defined solely on the frequency of falling below a low abundance threshold level (below 50 spawners in a four-year moving average). Abundance is one of several metrics used to determine species viability and population persistence (McElhany et al. 2000; ICTRT 2007). Taking into account additional measures of population persistence (i.e., abundance, productivity, spatial structure, and diversity), a recent assessment rated this population to have a high risk of extinction (ICTRT 2007; UCSRB 2007). Therefore below I focus more on metrics of abundance than of extinction.

In the absence of new management actions, ocean conditions alone drove median spawner abundance ($N_{100,\,50\%}$,) down by over 40% in the worst-case ocean scenario (Table 3). Across the range of ocean conditions tested, poorer ocean conditions led to reduced numbers of median spawners and a slightly increased probability of extinction. Carrying capacity also declined with worsening ocean conditions. Although we observed declining spawner abundance with increasingly unfavorable ocean conditions, there were little to no increase in extinction probabilities. Certainly, the combined effects of poor ocean conditions with detrimental impacts from freshwater residency, mainstem and estuary occupancy periods could have severe impacts on this population.

As management actions were applied, median spawners generally increased relative to scenarios where there were no management actions (Table 3). Response metrics generally mirror patterns in median spawner abundance, so I focus on median spawner abundance below. In the absence of changes in ocean condition, freshwater habitat actions improved median spawner abundance by approximately 30%, while improved survival during dam passage and in the estuary improved these population metrics by approximately 15%. Combining both types of actions led to nearly additive (~45%) improvements in these metrics.

Neither management actions improving freshwater habitat, nor actions to improve survival in the mainstem and the estuary, could completely reverse the impacts of the most extreme declines in ocean condition. Although freshwater habitat actions could improve median spawner abundance, habitat actions could not reverse the decline in median spawner abundance (relative to benchmark scenario) caused by the two worst ocean conditions scenarios (80-100% bad years; Table 3). Similarly, although mainstem FCRPS improvements combined with reduced avian predation in the estuary led to increased median spawner abundance, these actions could not compensate for the three worst ocean condition scenarios (60%-100% bad years).

Combining both types of management actions, under the historical ocean conditions, led median spawner abundance to increase by more than 40% (Table 3). Under the worst ocean conditions, the combination of freshwater with mainstem and estuary survival improvements had the least reduction in median spawners (~-20%) of any of the other scenario. When ocean conditions were poor at most 60% of the time, these combined management actions allowed median spawner abundance to remain above the benchmark level of median spawner abundance. Under the worst ocean conditions (80-100% poor conditions), these combined management actions led to declines in median spawner abundance and other population metrics, relative to the benchmark scenario.

DISCUSSION

The results above suggest that if climate change increases the frequency of years with positive PDO, which are generally unfavorable to salmon survival in the ocean, the management actions considered may be able to buffer the Wenatchee River spring Chinook population to a limited extent. Drastic increases in the frequency of poor ocean conditions, i.e. positive PDO for >60% of years, could not be countered by the management actions tested – thus a key question is to what extent such poor ocean conditions are expected to occur. Improved downscaled climate-ocean modeling is needed to better forecast likely future patterns in basin-scale metrics such as PDO, as well as measures of local productivity.

The management actions tested here led to substantial increases in abundance of this Chinook population. Encouragingly, these actions were modest, involving 10% improvements in survival rates and 50% reductions in avian predation. Thus there appears to be some scope for management of Wenatchee River Chinook salmon to adapt to declining ocean conditions, though we do not evaluate the costs, tradeoffs, or other additional mitigating actions.

In the work above, the positive phase of the PDO is used as a proxy to identify years with poor ocean conditions for salmon in general. Consistent with this, Crozier et al (2013) found that PDO was a significant predictor of survival during ocean residency of some Chinook salmon stocks. However, for Wenatchee spring Chinook salmon, survival was better predicted by upwelling intensity (Jorgensen et al. 2013). Therefore, for the Wenatchee population, in addition to several other Columbia River salmon and anadromous trout populations (Kendall et al. 2013), future downscaled predictions of upwelling are particularly critical; simulations that increase frequency of years with poor upwelling may depress the population more than the simulations here that increased frequency of years with positive PDO.

Our modeled ocean conditions were developed from a recent period of observations which included cold and warm periods. However, it is difficult to predict future ocean conditions, and it is uncertain whether variability in ocean conditions will be analogous to or different from the period we used to develop our scenarios. Recent conditions in the further recent past (to 1900) had relatively more years of transition between warm and cold conditions (Fig. 3). A more variable ocean combined with more frequent and persistent warm periods could increase extinction probability. We did not explore changes in ocean variability, but this is an important aspect that should be addressed in assessing the effects of future ocean conditions on salmon with life cycle models.

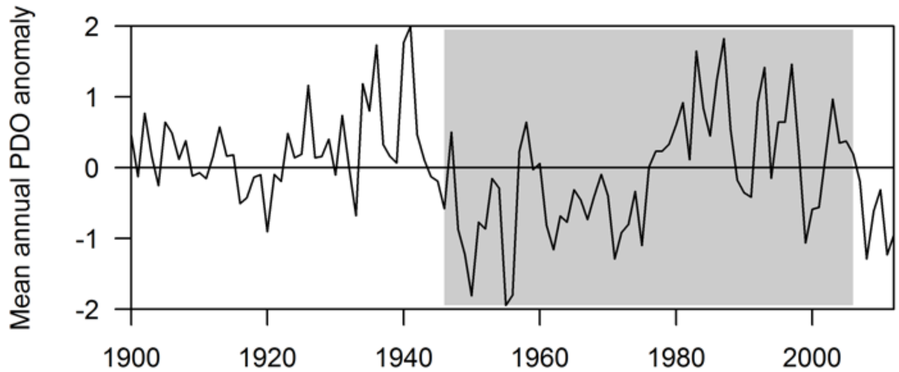

Figure 3: PDO anomaly from 1900-2012, with the time period used in this study to construct scenarios of future ocean conditions boxed in gray.

Table 3: Estimated impacts of management actions on the number of Wenatchee River basin wild spring Chinook salmon spawners using a life cycle model that incorporated scenarios of simulated future ocean conditions. The geometric mean of the number of wild spawners for the five year period 2005-2009 (from the Salmon Population Summary database https://www.webapps.nwfsc.noaa.gov/apex/f?p=261:home:0) was 576 spawners.

Ocean conditions	Avian predation	FCRPS survival	Freshwater survival	$N_{100,\,5\%}$	$N_{100,\,50\%}$	$N_{100,\,95\%}$	$\bar{N}_{100,\,5\%}$	$\bar{N}_{100,\,50\%}$	$\bar{N}_{100,\,95\%}$	$\Pr(QE)_{100}$	K	R/S_{low}
Benchmark												
Historical	current	current	current	210	860	3979	323	843	2790	0.001	754	1.58
Altered ocean condition												
20% bad	current	current	current	220	822	3074	317	817	2177	0.002	879	1.58
40% bad	current	current	current	188	737	2907	276	735	1978	0.005	704	1.84
60% bad	current	current	current	168	632	2662	241	642	1804	0.001	654	1.97
80% bad	current	current	current	136	549	2257	211	542	1512	0.009	633	1.50
100% bad	current	current	current	123	493	1872	196	486	1214	0.008	518	1.45
Freshwater habitat actions												
Historical	current	current	+10%	280	1111	4996	423	1098	3652	0	857	1.57
20% bad	current	current	+10%	291	1049	3920	399	1052	2838	0	947	1.52
40% bad	current	current	+10%	238	901	3455	337	908	2470	0	943	1.92
60% bad	current	current	+10%	221	859	3465	317	860	2411	0	759	2.09
80% bad	current	current	+10%	172	668	2768	252	666	1894	0.001	583	1.92
100% bad	current	current	+10%	158	606	2380	246	607	1504	0.001	574	1.43
Mainstem hydrosystem and estuary actions												
Historical	-50% reduced	+10%	current	251	1004	4633	377	989	3395	0	1110	2.46
20% bad	-50% reduced	+10%	current	267	976	3756	375	985	2627	0	NA	0.92
40% bad	-50% reduced	+10%	current	213	826	3278	312	832	2252	0.001	622	1.88
60% bad	-50% reduced	+10%	current	195	734	2993	276	736	2086	0	638	1.56
80% bad	-50% reduced	+10%	current	163	642	2631	241	639	1835	0.003	646	1.87
100% bad	-50% reduced	+10%	current	139	541	2214	222	547	1355	0.004	415	1.40
All management actions combined												
Historical	-50% reduced	+10%	+10%	303	1226	5477	458	1202	4041	0	1264	1.76
20% bad	-50% reduced	+10%	+10%	351	1254	4668	481	1261	3381	0	980	1.62
40% bad	-50% reduced	+10%	+10%	280	1055	4055	393	1056	2873	0	973	2.92

Ocean conditions	**Avian predation**	**FCRPS survival**	**Freshwater survival**	$N_{100,\,5\%}$	$N_{100,\,50\%}$	$N_{100,\,95\%}$	$\bar{N}_{100,\,5\%}$	$\bar{N}_{100,\,50\%}$	$\bar{N}_{100,\,95\%}$	$\Pr(\mathrm{QE})_{100}$	K	R/S_{low}
60% bad	-50% reduced	+10%	+10%	257	970	3916	357	979	2759	0	896	2.07
80% bad	-50% reduced	+10%	+10%	206	811	3338	307	806	2287	0	748	2.05
100% bad	-50% reduced	+10%	+10%	183	700	2690	282	698	1738	0.001	443	1.56

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