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ERRATUM

Erratum: Climate, Fire Regime, Geomorphology, and Conspecifics Influence the Spatial Distribution of Chinook Salmon Redds

We (Jacobs et al. 2021) analyzed an extensive 21-year data set of Chinook Salmon *Oncorhynchus tshawytscha* redd locations to (1) explain covariation between redd occurrence and environmental variables in the Middle Fork Salmon River (MFSR) and (2) leverage these relationships to predict changes in Chinook Salmon spawning habitat distribution under future climate scenarios. We have since discovered a small but consequential error in the process we used for applying future climate scenarios to our redd occurrence model in pursuit of our second objective: to predict the response of Chinook Salmon spawning to climate change. This error misrepresented variation in mean summer streamflow rates (hereafter, "summer flow") under the A1B emissions scenario (IPCC 2007) projected to 2040 and 2080 (Hamlet et al. 2013; Isaak et al. 2017), resulting in predictions that were driven primarily by stream temperature change and that underestimated the effects of summer flow changes. In our analysis, summer flow is an index of wetted stream size that may limit passage of large-bodied fish, such as Chinook Salmon. Once corrected, we found that predicted reductions in summer flows (averaging ~45% by 2040 and 60% by 2080 in the MFSR) strongly influenced the response of Chinook Salmon redd occurrence to future climate. Here, we have recreated Figures 3 and 4 from the original article, provided two additional figures, and updated our findings, which depart in important ways from some of what was originally presented in Jacobs et al. (2021). Specifically, we originally predicted that climate-driven changes in redd occurrence probabilities would be spatially heterogeneous but relatively small, with increasing occurrence probabilities in the highest-elevation reaches that were suboptimally cold and decreasing probabilities in warm, low-elevation reaches. Furthermore, we found positive effects of wildfire on redd occurrence that could be more influential than climate change. After correcting our error, we conclude that declines in summer streamflow strongly influence the response of redd occurrence probability to climate change and that wildfire may mitigate negative climate effects but is unlikely to wholly compensate for them. Importantly, we predict that Chinook Salmon habitat across the MFSR will remain plentiful (albeit less so) and of high quality, despite spatially heterogeneous losses predicted under climate change.

DESCRIPTION OF THE ERROR

To make sensible projections from an estimated statistical model under different covariate conditions, the scale of new covariate values must match that of the original variable. In our second objective (habitat projections under climate change), we made an error when transforming future flow variables to match the scale of the contemporary flow variable used to fit the original model. Our model was fitted using the z-scores of the natural logarithm of mean summer flow (Q) as a covariate (among other covariates, also transformed into z-scores):

$$z_{Q(i)} = \frac{\ln\left[Q_{(i)}\right] - \text{mean}[\ln(Q)]}{\text{SD}[\ln(Q)]}, \qquad (1)$$

where Q is the contemporary mean summer flow and SD is the standard deviation. The evaluation of model predictions under new flow scenarios (e.g., mean summer flow in 2040 under the A1B climate scenario [Q_{2040}]) necessitates that the new variable be transformed in the same way by the same quantities:

$$z_{Q_{2040}(i)} = \frac{\ln\left[Q_{2040(i)}\right] - \text{mean}[\ln(Q)]}{\text{SD}[\ln(Q)]}. \qquad (2)$$

We erred in the calculation of our 2040 and 2080 flow variables by standardizing the natural logarithm of the new flow variables by the mean and SD of the *untransformed* contemporary mean summer flow variable, followed by calculating the natural logarithm of the standardization:

$$z_{Q_{2040}(i)} = \ln\left\{\frac{\ln\left[Q_{2040(i)}\right] - \text{mean}(Q)}{\text{SD}(Q)}\right\}. \qquad (3)$$

This is incorrect for two reasons: (1) because $\ln[Q_{2040(i)}]$ was standardized by variables on the wrong scale and (2) because we log-adjusted after standardization. This error

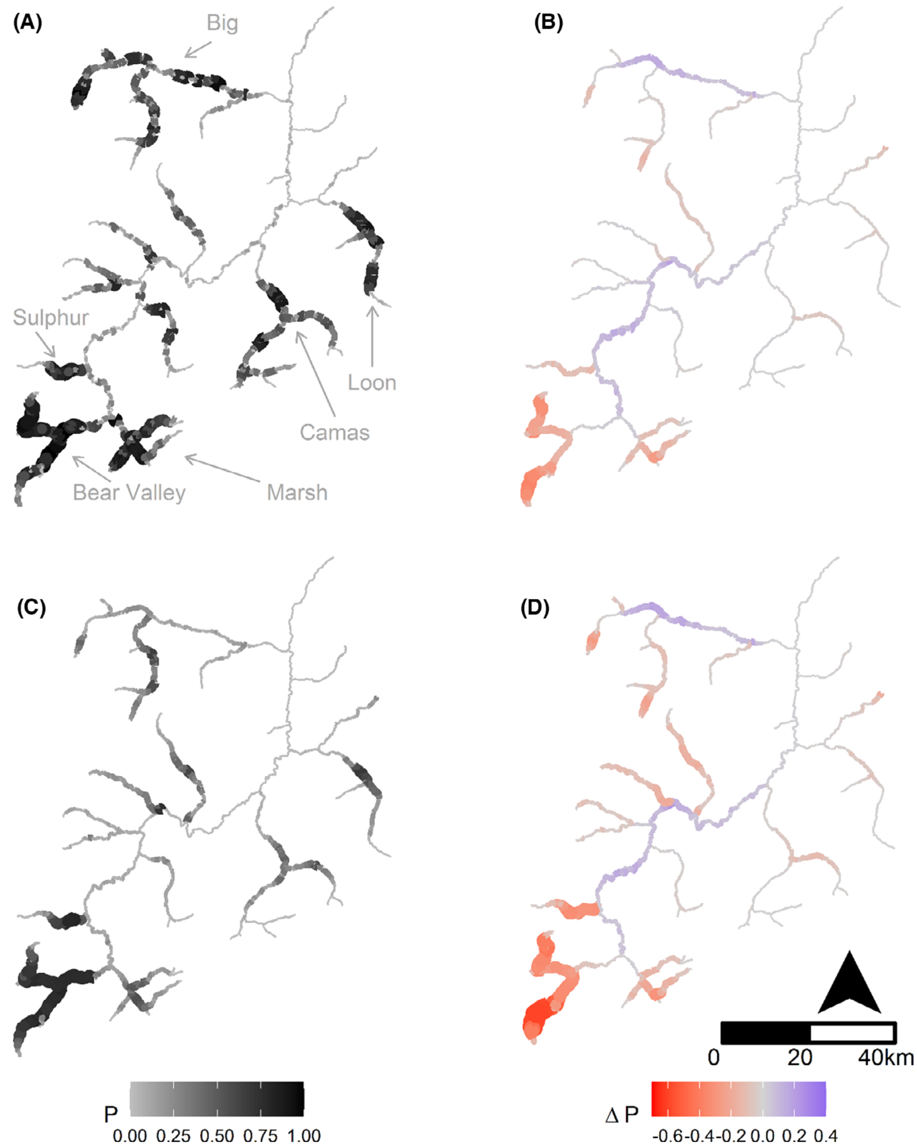

FIGURE 1. Maps describing redd occurrence across potential Chinook Salmon spawning habitats in the Middle Fork Salmon River (MFSR), Idaho. **(A)**, **(C)** Redd occurrence probability (P) is shown in terms of the observed proportion of years in which each reach was occupied by redds in the data set (A); and model-averaged prediction of P derived from the fixed-effect habitat–occurrence relationships in our top models (ignoring spatial random effects) under contemporary environmental conditions (C). **(B)**, **(D)** The predicted change in model-averaged redd occurrence probability (ΔP) between contemporary conditions and those projected for 2040 (B) and 2080 (D) for the A1B climate scenario (IPCC 2007), downscaled to the MFSR. In panels A and C, P scales with shading and size, where darker, larger line segments denote higher P. Climate-driven change in occurrence probability (ΔP) is the difference in occurrence probability between contemporary and projected conditions, such that negative values indicate predicted reductions in occurrence rate and positive values indicate increases. In panels B and D, ΔP scales with size and color from red (60% reduction) to gray (no change) to blue (40% increase). The locations of Big, Sulphur, Bear Valley, Marsh, Camas, and Loon creeks are indicated with gray text and arrows in panel A.

produced z-scores that averaged roughly −0.6 (or 0.6 SDs below contemporary conditions), with artificially low among-reach variation. Projections of future Chinook Salmon habitat from these incorrectly scaled flow variables (alongside *correctly scaled* future water temperature variables) were dominated by the effects of water temperature changes, with minimal effects of summer flow changes.

CHANGES TO RESULTS AND DISCUSSION

We recreated Figures 3 and 4 from the original article using the corrected flow scenario information (herein, Figures 1 and 2, respectively). We also provide two additional figures: Figure 3 compares the effects of future temperature and flow predictions independently and in combination, and Figure 4 illustrates predicted redd occurrence probabilities under each of our three climate scenarios. In

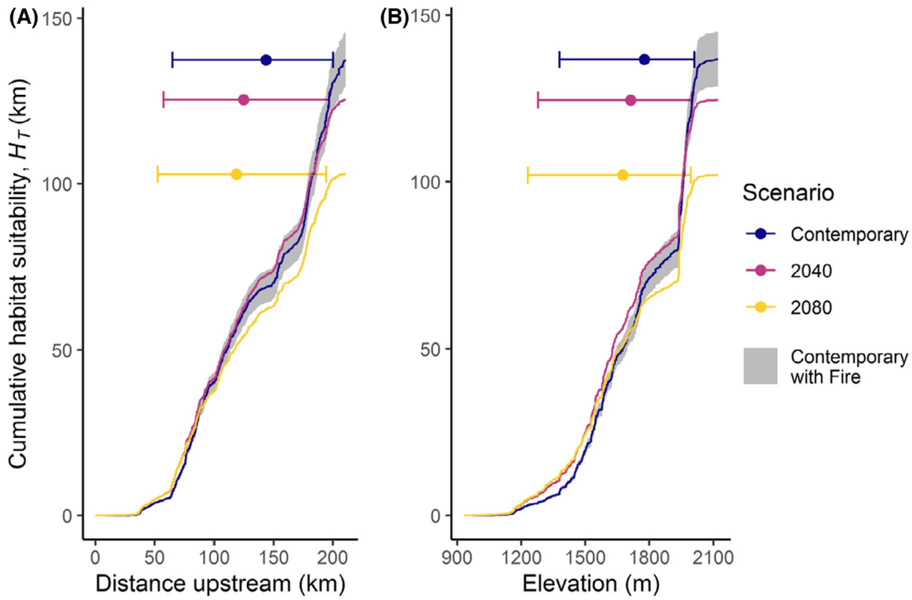

FIGURE 2. Cumulative distributions of H_T (length of stream weighted by the probability of occurrence of Chinook Salmon redds) in the Middle Fork Salmon River as a function of **(A)** distance upstream (km) and **(B)** elevation (m above sea level) for contemporary stream temperatures and mean summer flows (navy line) compared to those predicted for 2040 (purple line) and 2080 (gold line) using the A1B climate scenario (IPCC 2007). The gray band around the contemporary curve indicates the prediction space associated with ±1 SD in the within-year and 5-year fire variables (F_0 and F_5) for contemporary conditions, used to assess the relative effects of climate-driven changes in stream temperature and streamflow versus variation in fire under current climate conditions. Dot-and-whisker plots at the top of each panel illustrate the location on the *x*-axis variable of the median and 95th percentile range of H_T, plotted on the *y*-axis at the total cumulative value of H_T for that scenario.

contrast to our earlier findings, our present results suggest that climate change will strongly affect Chinook Salmon spawning and rearing habitats in the MFSR. In fact, there are reductions in habitat quality and redd occurrence for many MFSR reaches (Figure 1) that result in distributional changes across elevation and distance upstream (Figure 2). The results of our corrected climate forecast analysis generate three key observations: (1) the amount of high-quality habitat is predicted to decrease significantly with climate change; (2) increases in fire frequency should mitigate much—but not all—of the climate-driven habitat losses; and (3) the core distribution of Chinook Salmon spawning habitat in the MFSR will generally shift away from the headwater extremities of the network, expanding downstream and creating a more homogeneous distribution of habitat quality.

Habitat Losses

Our original article predicted that climate-driven shifts in the spatial distribution of high-quality habitat would result in only slight changes in the overall *amount* of high-quality habitat in the MFSR. In contrast, our revised analysis predicts that the MFSR will experience more substantial losses in the amount of high-quality habitat for Chinook Salmon spawning and rearing, driven primarily by climate-related reductions in summer flow (Figure 2). The predicted changes vary between subbasins, with some major tributaries experiencing relatively small and homogeneous declines in occurrence probability of redds (e.g., Camas and Loon creeks), while others are predicted to exhibit (1) strong homogeneous declines in redd occurrence probability (e.g., Sulphur Creek), (2) strong heterogeneous declines driven by losses in headwater habitats (e.g., Bear Valley subbasin), or (3) heterogeneous change (losses and gains) leading to a downstream shift in the location of high-quality habit (e.g., Big Creek; Figures 1, 4). We estimate that the resulting net change in habitat quality will lead to a decline in basinwide habitat of 10% in 2040 and 25% in 2080 based on the A1B emissions scenarios (IPCC 2007; Table 1).

Fire Benefits

The beneficial effects of wildfire for Chinook Salmon spawning and rearing habitat center on inputs of woody debris and spawning gravels. Fire may significantly mitigate climate-related habitat losses if fire frequency increases under climate change. Our simulations show that if average fire frequency increases across the basin by 1 SD, habitat quantity would increase by 6% under otherwise “contemporary” conditions, offsetting some of the habitat losses predicted from increased stream temperature and decreased summer flow for future climate scenarios (Table 1).

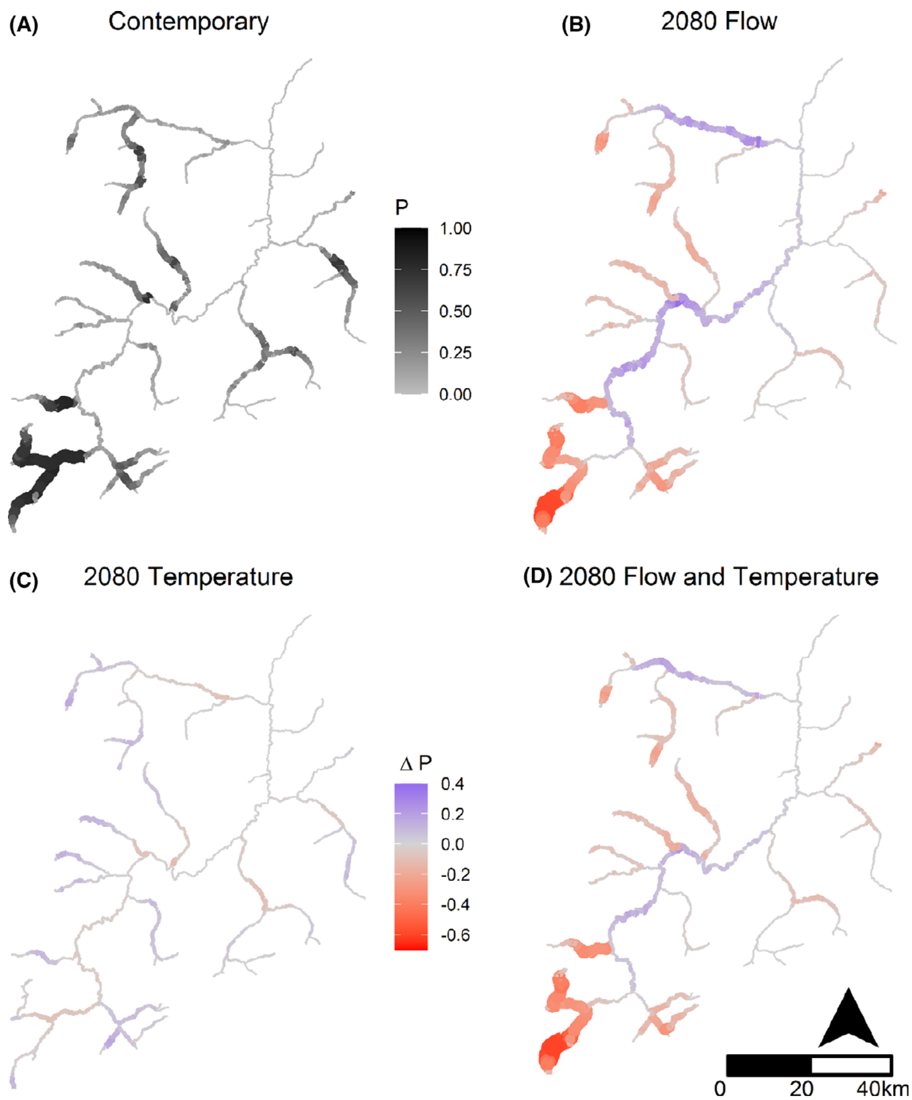

FIGURE 3. Comparison of the relative effects of summer streamflow reductions and stream temperature increases under the A1B climate scenario (IPCC 2007) for 2080, downscaled to the Middle Fork Salmon River: **(A)** redd occurrence probability (*P*) derived from our top models under contemporary environmental conditions; **(B)** change in redd occurrence probability (ΔP) for predicted summer streamflows in 2080 and contemporary stream temperature, (**C**) predicted temperatures in 2080 and contemporary flows, and (**D**) the combined effects of predicted flows and temperatures in 2080. In panel A, *P* scales with shading and size, where darker, larger line segments denote higher *P*. In panels B–D, ΔP scales with size and color from red (60% reduction) to gray (no change) to blue (40% increase).

Shifting Distribution

In Jacobs et al. (2021), we erroneously predicted net increases in redd occurrence probability at the upstream extent of the Chinook Salmon spawning distribution and corresponding declines further downstream, primarily due to changes in thermal suitability. However, the opposite is predicted when climate-related reductions in summer flow are properly accounted for in our corrected analysis. Under future climate scenarios for 2040 and 2080, redd occurrence probability declines most strongly in the furthest upstream (headwater) reaches that currently host high-quality habitat (Figures 1, 4). Also, in contrast to the results presented in Jacobs et al. (2021), higher-order, main-stem reaches are predicted to support gains in redd occurrence probability, though occurrence probabilities in the furthest downstream reaches of the basin remain low (Figure 1). Our models suggest that such gains are due to a nonlinear relationship between summer streamflow and redd occurrence probability, such that moderately sized streams are better suited for Chinook Salmon spawning than very large or very small streams (as we discussed in Jacobs et al. 2021). Comparison of the relative effects of climate-driven temperature increases and summer flow reductions for the year 2080 demonstrates competing effects of habitat loss/gain,

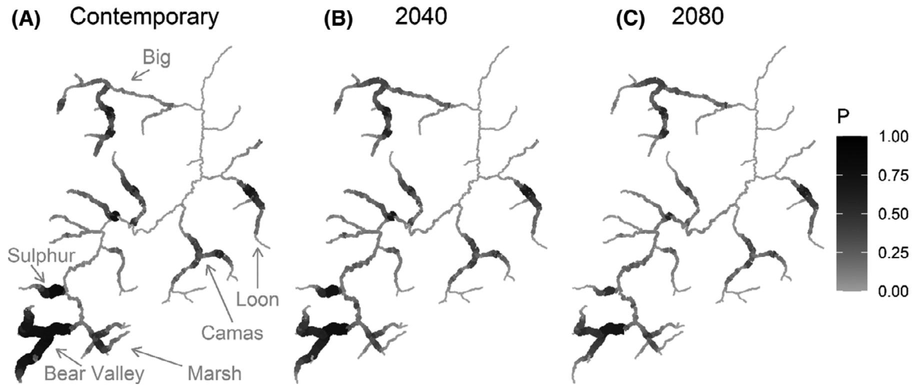

FIGURE 4. Predicted Chinook Salmon redd occurrence probability (P) under **(A)** contemporary conditions; and under climate change projections for **(B)** 2040 and **(C)** 2080. All panels show the expected P across Middle Fork Salmon River reaches, where darker grays and heavier lines indicate higher P. The locations of Big, Sulphur, Bear Valley, Marsh, Camas, and Loon creeks are indicated with gray text and arrows in panel A.

TABLE 1. Estimates of total high-quality habitat in the Middle Fork Salmon River (MFSR) under the A1B climate scenario (IPCC 2007) for 2040 and 2080 compared to contemporary wildfire effects defined in terms of ±1 SD in the within-year and 5-year fire variables (F_0 and F_5) outlined in Jacobs et al. (2021). The variable H_T is the total amount of high-quality habitat (km) predicted for the basin, produced by summing reach-specific habitat quantity index values ($\sum H_{T[i]}$); %Δ is the percentage difference in H_T from the Contemporary scenario; and %Flow is the average percentage difference in mean summer flow due to climate change across MFSR reaches relative to the Contemporary scenario.

Scenario	H_T(km)	%Δ	%Flow
Contemporary	137		
A1B, 2040	124	−10	−45
A1B, 2080	102	−25	−60
Contemporary, +1 SD Fire	145	+6	
Contemporary, −1 SD Fire	129	−6	

although with summer flow dominating the predicted changes in redd occurrence probability (Figure 3).

Our revised analysis indicates that many streams in the MFSR will remain coldwater refuges for Chinook Salmon in the face of a warming climate. However, the effect of summer flow reductions is likely to reduce this buffer, leading to net losses of habitat in some high-elevation tributary streams. Despite these losses, substantial high-quality habitat will remain in many subbasins. For instance, although some reaches in the Bear Valley subbasin (the southwesternmost drainage in Figures 1, 3, and 4) are predicted to sustain some of the largest reductions in habitat quality, several reaches in this subbasin will retain high probabilities of redd occurrence even with the predicted reductions in summer flow. Fire may mitigate some but not all habitat quality losses associated with future climate change (Table 1), which is a reasonable prediction given that the primary benefits of wildfire for salmon habitat are to replenish woody debris and spawning gravels rather than to mitigate flow reductions. In streams that retain sufficient summer flow for Chinook Salmon to access them, we predict that habitat quality in the MFSR will remain very high due to minor effects of warming on stream temperature and excellent physical habitat attributes. However, declining summer flows may prevent some adult salmon from reaching high-quality habitats in the upstream extremities of the network if those streams become too small. Importantly, reductions in stream depths and widths under future climate scenarios are likely to vary substantially among streams. Additional work is necessary to empirically determine whether flow reductions will prevent future access to the smallest high-elevation streams in which large-bodied Chinook Salmon currently spawn.

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