Direct and Carryover Effects of Freshwater, Marine and Fish Conditions on Juvenile, Ocean, and Adult Survival of Snake River Chinook Salmon

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Carryover effects are particularly relevant to mitigation strategies in river environments that aim to increase ocean survival. Since direct environmental effects in the ocean are not amenable to freshwater management intervention, understanding the relative magnitudes of carryover effects is important. Furthermore, evaluating covariates of juvenile and adult life stages in the same model facilitates comparison of their effects and their strength of evidence in a common currency. The objectives of this study are to: 1) quantify and assess the weight of evidence for direct and carryover effects on salmon survival, and 2) determine how river conditions affect the survival of both downstream juvenile and upstream adult migrants. Here we define “direct effects” on stage-specific survival as those related to conditions in the same life stage (or reach), and “carryover effects” as those related to conditions experienced in the previous life stage.

We examined how freshwater and marine environmental conditions and individual-level fish condition indices affect survival in three life stages: 1) downstream-migrating smolt, 2) ocean, and 3) upstream-migrating adult. We used fish detection data from passive integrated transponder (PIT) tagged wild spring/summer Chinook salmon originating upstream of Lower Granite Dam (LGR; Snake River, Washington, USA; ptagis.org). We analyzed individuals with passage timing and fork lengths observed at LGR in outmigration years 2002–2015. We tested the effects of the following stage-specific covariates: 1) juvenile stage: passage timing or river temperature, flow, percent spill and fish length measured at LGR, number of Snake River bypasses experienced, and snow-water-equivalent (SWE) index (Jorgensen et al. 2016); 2) ocean stage: sea surface temperature index (SSTarc) (Johnstone and Mantua 2014), North Pacific Gyre Oscillation (NPGO) index (Di Lorenzo et al. 2008), carryover effects from river environment (listed in previous stage), and number of hydrosystem bypasses experienced; and 3) adult stage: Bonneville Dam passage timing or river temperature, flow and percent spill (Fig. 1). Furthermore, for relevant reaches, we tested two passage-types in which juveniles had a run-of-river or barge-transported experience through the hydrosystem.

We applied a hierarchical Bayesian Cormack-Jolly-Seber (CJS) model to estimate probabilities of apparent survival (hereafter survival; ϕ) and detection (p) with covariates and annual random effects:

$$\text{logit}(\phi_{md}) = \mathbf{x}_{md}\boldsymbol{\beta}_d + \epsilon_{t[m]d} \quad \text{Eq. (1a)}$$

$$\epsilon_{td} \sim N(0, \sigma_d)$$

$$\text{logit}(p_{md}) = \mathbf{z}_{md}\mathbf{b}_d + e_{t[m]d} \quad \text{Eq. (1b)}$$

$$e_{td} \sim N(0, s_d)$$

where survival from site d to $d + 1$ ($d = 1, \dots, D - 1$) for capture history m ($m = 1, \dots, M$) in year t is a function of covariates $\mathbf{x}_{md}$ with regression coefficients $\boldsymbol{\beta}_d$, plus a random effect $\epsilon_{t[m]d}$ associated with the year of migration. The model for detection probability at site d is analogous. Detection sites, reaches, and associated covariates are depicted in Fig. 1. We fitted candidate models to the capture histories of PIT-tagged Chinook using Hamiltonian Monte Carlo algorithm implemented in Stan (mc-stan.org).

Fig. 1. Juvenile (blue), ocean (purple), and adult (green) reaches where apparent survival and detection probability were estimated. Covariates associated with survival and detection probabilities are represented with matching colors. Survivals were estimated in the juvenile reaches between Lower Granite (LGR), McNary (MCN), and Bonneville (BON) dams, and the estuary trawl (TWX), in the ocean reach, and in adult reaches between Bonneville (BOA), McNary (MCA), and Lower Granite (LGA) dams.

We calculated annual and interannual posterior medians of survival for each relevant reach that run-of-river and transported rear-type fish migrated through in the hydrosystem, estuary and ocean (Fig. 2). For the run-of-river fish, juvenile survival tended to be higher in the Snake reach (LGR-MCN) than in the mainstem Columbia reach (MCN-BON). Survival below the hydrosystem was relatively high to the estuary trawl, and low in the ocean (approx. 1%). Adult upstream survival (assumed equivalent to conversion rate) was lower in the Columbia reach than the Snake reach. For transported fish, survival from the point of release below BON to the estuary trawl was similar to that of run-of-river fish. Ocean survival and upstream adult survival both tended to be lower for transported fish than run-of-river fish.

Fig. 2. Posterior distributions of apparent survival of wild Chinook salmon across reaches and life stages for run-of-river fish (left) and transported fish (right). See Fig. 1 for acronym definitions. Thick and thin horizontal lines represent posterior medians and 90% credible intervals, respectively, of the interannual hyper-means. Points represent posterior medians of the annual values.

River and sea surface temperature indices generally showed the strongest relationships with survival across juvenile, ocean and adult reaches in our preliminary results. For run-of-river fish in the juvenile reaches, river temperature had a negative relationship with survival in the Snake reach but positive in the Columbia reach, which still equated to a negative influence overall through the hydrosystem. Flow, spill and fish length showed positive relationships with juvenile survival. Snow-water-equivalent effects were highly uncertain. In the ocean reach, SSTarc showed a strong negative influence (Fig. 3). Carryover effects were negative for river temperature, and positive for fish length and snow-water equivalent. In the adult reaches, river temperature showed negative relationships with conversion rates. Percent water spilled showed a negative effect in Columbia reach (BOA-MCA) but less so if any, in Snake reach (MCA-LGA). For transported fish, the SSTarc index also showed strong negative influences on survival of these fish (Fig. 3). The effects from juvenile fish length were positive and stronger than the other covariates tested for carryover effects. In the adult reaches, river temperature had negative influences. Percent water spilled also had a negative influence but primarily in Columbia reach.

Fig. 3. Posterior distributions of covariate effects (on the logit scale) of ocean survival for wild Chinook salmon with run-of-river (left) or transported (right) downstream passage experiences.

We advise caution in interpreting these preliminary results, given multicollinearity among covariates. Still, some strong patterns were evident. The strongest and clearest effect was from SSTarc. Compared to covariates of freshwater carryover effects, the SSTarc effect was stronger (e.g., log-odds ratio ranges: -0.3 to -1.6 for river temperature, -0.4 to -1.7 for both flow and spill, -0.5 to -1.8 for fish length). Even if there are large ocean effects, identifying carryover effects from the river environment will help inform river management. Given the ranges of conditions examined in the current study, the partial influence from decreasing river temperature could increase ocean survival from about 0.5% to 2.6% for run-of-river fish. Similarly, given the ranges observed, the partial influence from increasing SWE could increase ocean survival from about 0.5% to 2.2%, and the influence from increasing fish length could increase ocean survival from about 0.4% to 2.9% for run-of-river fish.

This study identified positive effects of fish length on juvenile and ocean survival. With the current model, we did not detect an effect from the number of hydrosystem bypasses on juvenile or ocean survival. These findings are consistent with a recent study (Faulkner et al. 2019) that also found positive effects of juvenile length on ocean survival, but weak negative effects (if any) from number of bypasses experienced.

River conditions in a given year are experienced by both juveniles migrating downstream and adults migrating upstream. However, the effects may not always be the same for both these life stages. River temperature mostly had negative effects on survival. Yet, increasing percent spill was found to be beneficial to juvenile survival while detrimental to adult conversion rates. Comparison of the effects on juveniles and adults would require further examination in a currency that accounts for high ocean mortality.

Overall, we found a clear negative effect from SSTarc on ocean survival. But despite this strong effect, we also detected negative and positive carryover effects from river temperature and fish length, respectively, on ocean survival. The current study finds support for river temperature and fish length as among the most important and controllable environmental and fish conditions that could help improve ocean survival via freshwater-marine carryover effects.

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