Salmon Conservation Under Changing Conditions and with Freshwater-marine Carryover Effects

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Conservation management of endangered salmon in regulated rivers requires an understanding of drivers across life stages in freshwater and marine systems. Clear relationships between survival and environmental drivers can be difficult to identify with certainty, especially while environmental conditions are shifting regionally and through time. We presented on a series of papers that considered: 1) what shifting relationships among environmental indices can mean for predicting salmon responses (Gosselin et al. 2021a), and 2) the relative contributions of environmental, biological and anthropogenic drivers on smolt-to-adult survival (Gosselin et al. 2021b).

We first showed how correlations may be shifting in the last century across 42 freshwater, marine and climate indices in a study of 72 river sites where Chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*Oncorhynchus kisutch*) occur in the western USA. We found regional differences in correlations among indices, which had relatively greater associations with teleconnections in the Northwest and within types of environmental indices in the Southwest (Gosselin et al. 2021a). We also found changes in correlations across 10-year windows of timeseries likely influenced by climate phases and their direct influence on freshwater temperature and precipitation. Stronger and weaker correlations may occur through time when superimposing influences from multiple teleconnections that are in- or out-of-phase.

Fig. 1. A couple of different perspectives to consider when interpreting correlations of environmental indices.

We shared two perspectives that can be important to consider when interpreting correlations between indices (Fig. 1). From a climate-centric perspective, the correlations can represent how teleconnections set up conditions that migratory salmonids will experience as they enter different habitats. There could be one or a few convenient large-scale marine/climate indices that represent multiple local conditions. From a fish-centric perspective, the correlations could represent carryover or cumulative biological effects. For example, a fish could repeatedly experience high temperatures in the egg, fry, smolt, subadult, and adult stages. These two perspectives are also not necessarily mutually exclusive.

We then presented results from an examination of smolt-to-adult survival across four life stages (juvenile downstream; estuary; ocean; and adult upstream) and compared direct and carryover effects for ~400,000 individually tagged, wild, Chinook salmon from the Snake River (Pacific Northwest, USA; 2001–2016). We identified the most important effects from over 20 relationships examined in a hierarchical Bayesian mark-recapture model (Gosselin et al. 2021b). By analyzing the covariates in a unified model, we evaluated their relationships to survival within and across life stages in a common currency.

Fig. 2. Estimated regression coefficients (β) for direct and carryover effects on survival across three life stages. Thick horizontal lines represent medians, thin horizontal lines represent 90% credible intervals, and ends represent 99.8% credible intervals of posterior distributions (as Fig. 4 in Gosselin et al. 2021b).

Table 1. Marginal effect size (Δ_{dk}) of each predictor k on survival in stage d , computed by varying the predictor over its observed range while holding all other predictors constant at their sample means. All estimates are reported as posterior median and 90% credible interval. Bold represents 90% credible interval that does not include 0 (modified from Table S2 in Gosselin et al. 2021b).

Covariate		Δ_{dk}		
Name (units)	Range observed	Juvenile, river reach	Subadult, ocean reach	Adult, river reach
LGR river temperature (°C)	6.2–15.0	-0.66 (-0.85, -0.50)	-0.97 (-1.26, -0.68)	-
LGR River flow (kcfs)	26.8–188.8	0.81 (0.64, 1.01)	-0.01 (-0.28, 0.25)	-
LGR water spilled (%)	0–58.2	-0.13 (-0.28, 0.00)	-0.12 (-0.21, -0.05)	-
LGR juvenile fork length (mm)	55–155	0.78 (0.58, 0.99)	2.26 (1.91, 2.61)	-
SWE (inches)	9.5–24.0	-0.11 (-0.61, 0.44)	0.91 (0.13, 1.70)	-
PITPH (number of powerhouses)	1–4.7	-	-0.55 (-1.17, 0.14)	-
SSTarc (unitless)	-0.48–1.38	-	-1.67 (-2.70, -0.64)	-
BOA river temperature (°C)	6.7–22.6	-	-	-0.38 (-0.54, -0.26)
BOA river flow (kcfs)	79.2–501.5	-	-	0.19 (0.11, 0.29)
BOA water spilled (%)	0.6–65.2	-	-	-0.12 (-0.21, -0.05)

Across the direct effects examined in the juvenile downstream stage (Fig. 2a), the direct and carryover effects in the ocean stage (Fig. 2b), and the direct and carryover effects in the adult upstream stage (Fig. 2c; Table 1; modified from Gosselin et al. 2021b), the strongest marginal effect sizes indicated that marine conditions (i.e., sea surface temperature index, SSTarc) had a strong negative relationship with ocean survival. Yet, juvenile fish length in the river had comparable but positive marginal effect sizes with ocean survival (Fig. 2; Table 1; modified from Gosselin et al. 2021b). Fish length, river temperature, and the snow-water-equivalent (SWE) index had important direct and/or carryover associations to river and ocean survival. Furthermore, the freshwater index of dam powerhouse passage (PITPH) showed a negative but uncertain influence on ocean survival.

As conditions in freshwater and marine environments continue to change, it is important to continue existing monitoring programs, to understand underlying mechanisms, and to not rely only on correlations between environmental indices because they break down over time. These mechanisms will allow us to understand which relationships are relevant under certain climate phases and which mitigative strategies are likely to be robust under a changing climate. Furthermore, as the ocean continues to warm and exert relatively large impacts on salmonid survival (Crozier et al. 2021), it will be important to consider a diversity of mitigative options, including freshwater-marine carryover effects that may help increase ocean survival.

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