**Temporal Patterns in Chinook Salmon Migration Across Western Alaska Watersheds**

**Introduction:**

Chinook salmon populations are experiencing unprecedented declines across much of their range. This trend is especially severe in Western Alaska watersheds, which contain some of the world's last pristine Chinook habitat but have seen steep declines in returning Chinook and Chum salmon in recent years. Salmon from this region support lucrative commercial fisheries, contribute billions of dollars to regional and global economies, and have historically supported subsistence harvests for dozens of communities in the region. As runs have collapsed, however, many upstream communities have voluntarily reduced or ceased subsistence fishing altogether, triggering a region-wide crisis of food insecurity, cultural loss, and the potential disappearance of a critical economic resource. As a result, resource managers face the difficult task of designing management strategies which balancing ongoing harvest opportunities with the urgent need to rebuild salmon populations and strengthen their resilience to future perturbations.

There is growing recognition of the critical role that intrapopulation variability plays in fostering resilience at the ecosystem scale in both terrestrial and aquatic ecosystems. In salmon populations, substantial variation in both return timing and spatial distribution of habitat use produces significant complexity in life history strategies within and among populations. Overall population performance in salmon ecosystems is shaped by the statistical averaging of multiple distinct, semi-independent sub-units distributed across space and time. Weak or negative covariance among these stocks helps buffer the broader population against the poor performance of any individual subunit, whose success may fluctuate in response to a dynamic mosaic of multi-dimensional environmental conditions. This “portfolio effect” dampens ecosystem variability by distributing risk across its components, much in the same way that financial diversification of a portfolio spreads investment risk across sectors to reduce overall volatility. Ecosystems composed of numerous negatively or weakly correlated “assets” are therefore better equipped to withstand both localized and system-wide disturbances, as such events may favor some components while disadvantaging others. In many salmon populations, particularly those at lower latitudes, this natural complexity has been eroded due to poor management and anthropogenic impacts on salmon ecosystems (Griffiths et al., \_). As a result, many systems now exhibit increased synchrony across subunits, leading to greater covariance in performance and generating “boom-or-bust” cycles in ecosystem productivity. This homogenization increases ecosystem vulnerability, even if aggregate return numbers appear stable or even more productive than more diversified ecosystems in the short term. Consequently, long-term resilience is better assessed by the health and viability of contributing subunits rather than by total run size alone.

Efforts to rebuild and conserve the long-term resilience of Western Alaska Chinook salmon must therefore account for this spatiotemporal complexity and design management strategies which maintain it in the long term. These include designing harvest methods which consider both overall exploitation rate as well as the timing of harvest throughout the season. Strategies that concentrate harvest in periods of peak abundance (e.g., highest CPUE per day), for example, may fail to account for whether this peak consists of a mix of vulnerable, weak stocks or a single, more robust stock that can sustain higher exploitation. Instead, management strategy should aim to allow harvest opportunities on healthy stocks while minimizing the risk of overexploitation for co-migrating weak stocks. In practice, however, implementing such stock-specific management approaches requires detailed data on the spatiotemporal ecology of salmon populations; information that has historically been limited at sufficiently fine spatial and temporal scales.

In the absence of fine-scale data on stock-specific spatial ecology in Western Alaska, management strategies have largely relied on a coarse understanding of the spatiotemporal distribution of salmon across these basins. In the Yukon River Basin, for instance, management is based on several stock aggregates defined by the spatial resolution of available genetic baselines. As a result, large portions of the watershed are effectively treated as a single stock. For example, all Canadian-origin salmon are managed as one aggregate stock, despite the presence of multiple contributing sub-stocks that exhibit considerable variability in life history characteristics both within and across seasons (Connors et al., 2023) This oversimplification risks overlooking important ecological diversity critical for population resilience.

In the Kuskokwim river-basin, an alternative management strategy that has been implemented is the use of front-end closures, which allow an estimated number of early-returning fish to escape before harvest begins. While this approach does protect a subset of early migrants and helps ensure a minimum escapement, the proportional contribution of different sub-units within this closure window remains poorly understood. As a result, a front-end closure may either protect a diverse array of sub-units, thus preserving ecosystem variability, or primarily shield a single, large stock. In the latter case, long-term consequence may include degradation or extirpation of later-returning, weaker stocks, and a consolidation toward a single dominant life history strategy. This loss of diversity increases risk to the overall population by eroding the ecological portfolio that supports long-term resilience.

Advances in isotopic methods offer a promising tool to study fine-scale spatial patterns in remote ecosystems. In salmon, isotopic signatures are incorporated into ear stones, or otoliths; metabolically inert structures that record environmental information and can be analyzed post-mortem using laser ablation. Using these techniques, researchers estimate the natal origin of individual fish by comparing isotope ratios such as that of Strontium (⁸⁷Sr/⁸⁶Sr) recorded in otoliths to values measured or modeled across the landscape. In geologically diverse regions like Western Alaska, unique strontium isotope ratios are distributed across the riverscape at relatively fine spatial scales, enabling provenance estimates to the sub-basin or tributary scale. However, in very large systems such as the Yukon River Basin, redundant isotope signatures at multiple locations can limit the spatial resolution of otolith-based methods. Current best genetic baselines for Chinook salmon in this region using genetic stock identification (GSI) can estimate provenance at relatively coarse spatial scales, however, integrative approaches that explicitly combine genetic and isotope data can overcome these challenges and enabling the exploration of fine-scale spatiotemporal patterns even in Alaska’s largest river basins.

Here, we apply otolith-based methods to reconstruct within year spatiotemporal patterns for Chinook salmon in the Yukon and Kuskokwim River basins. Specifically, we aim to: (1) identify the spatiotemporal structure of returning populations in Alaska’s most productive salmon-bearing watersheds; (2) assess how this structure varies with overall run dynamics; and (3) evaluate the potential impacts of harvest strategies, including front-end closures, on stocks across these systems.

**Methods:**

**Sample set**

**Otolith Sample set**

We analyzed otoliths collected from two major Chinook salmon monitoring efforts in Western Alaska: the Bethel Test Fishery and the Lower Yukon Test Fishery. Samples were collected across multiple years—2017 through 2021 for the Bethel site, and 2015, 2016, 2017, 2018, and 2021 for the Lower Yukon site. From these collections, 250 otoliths were subsampled to represent the full duration of the Chinook salmon migration, with equal representation across early, middle, and late portions of the run. Otoliths were sectioned along the transverse plane, mounted on microscope slides, and polished to expose internal growth structures. Prepared samples were then sent to the University of Utah Strontium Isotope Laboratory for analysis using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Ablations were performed along a transect from the core of each otolith to just beyond the onset of marine growth, which was identified based on the presence of dark annuli. The analysis captured both strontium isotope ratios (⁸⁷Sr/⁸⁶Sr) and elemental concentrations (⁸⁸Sr), producing a continuous geochemical time series spanning early freshwater development through marine entry.

To isolate the region of the otolith corresponding to freshwater natal origin, we applied a manual selection protocol that considered several features. First, we identified a decline in ⁸⁸Sr concentrations associated with movement away from the embryonic core. Next, we used empirically derived estimates of the distance from the core to the expected natal origin region. Finally, we examined otolith morphology along the transect to identify transitions between early life stages. The resulting data were used to infer natal origin by comparing the measured ⁸⁷Sr/⁸⁶Sr values within this region to spatially explicit strontium isotope isoscapes developed for the Yukon and Kuskokwim river basins.

**Isoscapes:**

Isoscapes were produced of the Yukon and Kuskokwim river basins using spatial stream network modeling, which considers etc. etc.

**Bayesian Model and Priors**

Provenance estimates were produced using a probabilistic Bayesian framework which includes… bring in from the old paper. For samples in the Yukon river basin, a genetic prior was added which incorporates posterior values from genetic stock identification (Makhlouf et al., 2025). Additionally, spatial priors derived from the USGS intrinsic potential model— which synthesizes presence data from telemetry, manual counts, and habitat suitability—were applied to the highest and second highest order tributaries in each basin. This approach constrains assignments away from extensively sampled areas lacking evidence of Chinook spawning. Thresholding values were then assigned to keep only those values in the top 30% of posterior values.

**Polygon binning and conversion to point data**

**Resulting timeseries (25 reads per individual)**

**Analysis**

**Timeseries Analysis**

DFA of individual timeseries for each stock vs overall returns.

This will ideally pull-out underlying patterns in patterns grouped by stock.

Loadings by stock across space and time. Are later retuning stocks more variable, for example?

**Yukon genetics groups vs fine scale returns.**

IS there more variation in run timing across sub stocks within genetic groups vs genetic groups as a whole.

**Front end closure simulation**

How much “protection” is each stock afforded from a front end closure

**Qualitative/map description of CV/ mean across years but within quartile**

Are there places that are CONSISTANT for each quartile? i.e. Aniak ALWAYS comes in strong in Q1 and places that are present in a quartile but more variable. i.e. SOMETIMES Stony river shows up in Q1

**Results:**

**Discussion:**