### Methods

#### Study area and species

#### Data Sources

##### Juvenile abundance index

We use a juvenile Chum index based on NOAA’s Bering Arctic and Subarctic Integrated Survey (BASIS) to estimate survival from the spawner stage until when fish are captured and enumerated at the end of their first summer in the Bering Sea on the BASIS survey. The BASIS survey takes place annually in early Fall throughout the North and Southern Bering Sea (there are some spatially imbalanced years where the NBS or SEBS was not surveyed). Fish caught in this survey are allocated to genetic reporting groups, including western Alaska Chum (Bristol Bay, Yukon Summer and Kuskokwim River) and Yukon Fall Chum.

This index used Vector Autoregressive Spatio-Temporal modeling approach in creating an independent index of Yukon River fall chum salmon.

The index spans brood years 2000-2023.

##### Catch and spawner index

Summer and fall run Chum spawner estimates for the Yukon River is provided by the Alaska Department of Fisheries and Game (ADFG) (Fleischman & Borba 2009, Hamazaki & Conitz 2009). We used run reconstructions to inform the stock-recruit transition functions used in this chapter. Run reconstructions typically use escapement, catch, and age composition data to estimate the number of fish returning to freshwater based on their brood year (the year they emerged from eggs in freshwater). Run reconstructions can vary significantly in complexity depending on the goal of the reconstruction and the system-specific data availability. The Yukon rivers is the longest river in Alaska, and a transboundary river with headwaters in Canada. The massive size of this system makes it difficult to fully account for salmon traveling across such remote regions and consequently, Chum salmon on these rivers have low-data availability relative to other systems. These age-structured run reconstructions use maximum likelihood estimates to minimize negative log likelihoods estimate total run size, spawner abundance, and harvest. These models are thoroughly documented in the associated publications (Fleischman & Borba 2009, Hamazaki & Conitz 2009).

##### Population Process Model

The population model tracked cohorts of summer and fall Chum salmon by brood year, t, life stages, n, and stocks, s.

The model includes five life stages for Yukon river fall chum: 1) “juvenile” which tracks individuals from eggs to when they are at the end of their first summer in the marine environment 2) “ocean”, which tracks individuals by age class and applies an age specific natural mortality, 3) “returns”, which tracks individuals that survived the marine environment and are returning to the Yukon river, this stage considers instantaneous fishing mortality and removes individuals when they are intercepted in terminal commercial and subsistence fisheries, 4) “spawners”, which consider the amount of fish that return back to the spawning grounds and 5) “eggs”, the amount of eggs produced by spawners. We tracked cohorts based on the brood years.

The number of Chum salmon surviving from an egg to the end of their first ocean summer in brood year t+1, Nt+1,n=j,s,, depended upon the abundance of eggs that were spawned in brood year, t, Nt,n=e,s and the population-specific survival rate from eggs to ocean juveniles, t,n=j,s.

Nt,n=j,s= t,n=j,s\* Nt,n=e,s

The survival rate, t,n=j,s, was calculated using a Beverton Holt Transition function (Moussalli & Hilborn 1986).

where the productivity parameter represented time varying maximum survival rate without density dependence, and represented the carrying capacity, or the maximum number of individuals that could survive past that life stage. The productivity parameter was estimated conditional on environmental covariates (Table XX) using an inverse logit function of basal productivity, , which represented the mean survival rate at low density.

Eq. 4.2

Here, a matrix of covariate values c, were multiplied by an associated covariate coefficient, which described the relative influence of each covariate on population specific survival rates.

After surviving their first summer at sea, chum salmon migrate to the Gulf of Alaska and spend up to five years at sea before returning to the Yukon River (CITE). The first winter in the GOA is hypothesized as a critical life stage step where high mortality occurs, thus we estimate survival during their first winter at sea, t,n=w,s.  Survival during the first winter at sea in the Gulf of Alaska was represented by an environmentally mediated survival rate, t,n=m,s, and was estimated using the Beverton-Holt transition function described above (Eq. XX and XX). Similarly, the productivity parameter was estimated conditional on environmental covariates described in Table XX for the marine stage.

= t,n=w,s \* Nt,n=j,s Eq. 4.2

The number of fish returning to the Yukon River at time t+a+1, Nt+a+1,n=recruit,s,a, depended on age structured natural mortality rates, and the proportion of fish that return to spawn in each age class, .

= Eq. 4.2

We assumed a cumulative natural mortality for ages 4-6, , where the annual mortality was fixed at a low rate of 0.06 so fish that stayed in the ocean longer had a higher marine mortality than younger fish (Beamish 2018).

Returning fish, Nt+a=1,n=recruit,s,a, were subject to terminal harvest determined by annual fishing mortality, , and age-specific selectivity, .

Nt+a+1,n=catch,s,a= Nt+a+1,n=recruit,s,a \*(

To allow ample flexibility in annual fishing mortality rates, , we estimated mean fishing mortality and process deviations around the mean, .

Ft+a+1 =

Returning fish that were not captured in terminal fisheries were assumed to reach the spawning grounds and reproduce.

Nt+a+1,n=spawners,s,a= Nt+a+1,n=recruit,s,a- Nt+a+1,n=catch,s,a

The number of eggs produced by each spawner was dependent on the proportion of females, P, which was fixed at 50% (CITE), and age specific fecundity rates, Ea where Age 2’s were 1800, Age 3’s 2000, Age 4’s 2200, and Age 5’s 2400 (CITE), so that larger fish produced more eggs per spawner.

Nt+a+1,n=eggs,s,a =Nt+a+1,n=spawners,s,a \*Ea\*P

#### Ecosystem Covariates

The eight environmental covariates included in the survival analysis (Table XX) were collected based on hypotheses presented in peer reviewed literature regarding ecosystem processes that impact Chum salmon survival across different life stages.

We considered four covariates that may impact juvenile salmon productivity from the egg stage to the end of their first summer at sea, including Yukon River mainstem discharge, cumulative degree days for sea surface temperatures in the Northern Bering Sea, pollock recruitment index and the mean spawner size trend for the parent generation. We included the Yukon River mainstem mean discharge for May and June for each brood year +1 with the hypothesis that increased river discharge has a negative relationship with productivity as it makes juvenile foraging more difficult (Neuswanger et al. 2015). A majority of juvenile chum leave the lower Yukon River Delta by the end of June and occasionally into July, depending on ice break up phenology (Miller & Weiss 2023). Given this outmigration timing, Yukon River discharge rates in May and June are the most likely to impact juvenile feeding and address this hypothesis. We acquired monthly discharge data (cubic feet per second) from a gage hosted by the USGS at Pilot Station, AK, Pilot station is location along the Yukon River in the lower river region (Table XX, map XX).

We included Northern Bering Sea Summer (NBS) Cumulative Degree Days (CDD) to represent the temperature conditions preceding the NBS survey and represent ecosystem conditions for the first couple months this fish experience while at sea. We used the daily mean NBS SST, publicly available on the Alaska Fisheries Information Network (AKFiN), to calculate CDD. We hypothesized a positive relationship between temperature and juvenile productivity, as suggested by empirical studies in the EBS and bioenergetics modeling in Japan (Iino et al. 2022, Farley Jr et al. 2024). While not directly tested here, the proposed mechanism for warmer temperatures enhancing juvenile salmon productivity is that warmer temperatures can enable rapid growth, when sufficient food is available which leads to reduced size selective mortality and greater productivity (Beamish & Mahnken 2001, Farley Jr et al. 2024). We included the EBS walleye pollock (*Gadus chalcogrammus* ) recruitment index from the pollock stock assessment to represent changes in prey availability during the first summer at sea that may influence juvenile chum productivity (Ianelli et al. 2023). Young pollock represent a high-quality prey source for juvenile chum, compared to *Cnideria* spp. that are also found in juvenile chum stomachs, that is important for lipid accumulation increasing productivity (Kaga et al. 2013, Farley Jr et al. 2024). Finally, we included the mean trend in spawner size at age for spawners that returned during the brood year of the next juvenile generation. Nonlinear trends in chum salmon size at age can impact reproduction potential and effect productivity, we hypothesized a positive relationship between size and productivity where bigger fish produce more offspring and have greater reproductive success (Ohlberger et al. 2020, Oke et al. 2020). The Alaska Department of Fish and Game (ADFG) conducts standardized salmon escapement surveys across Alaska where they have recorded salmon length, sex and age since the 1990’s. This information is publicly available (Supplement xx), we compiled Yukon River Chum salmon age and length data from 2000-2023. Most surveys have not differentiated between summer or fall run chum salmon, so this covariate represents the mean size trend for summer and fall chum salmon. [actual methods for getting trends – gam, dfa?? I dont think what I currently do will fly]

#### Priors

“Preliminary data suggest that chum migrate as a mixed stock group, but proportions of each phenotype vary throughout the migration period [72]. The individual assignment of chum salmon to spring and fall stocks is not currently possible at a level of probability that meets management requirements. However, current research investigating temporal variations in the stock composition may still provide additional insight into the influence of hydrology and temperature on migration”

- Konzela, C.M.; Whittle, J.A.; Marvin, C.T.; Myurphy, J.M.; Howard, K.G.; Borba, B.M.; Farely, E.V.; Templin, W.D.; Guyon, J. Genetic Analysis Identifies Consisten Proportions of Season Life History Types in Yukon River Juvenile and Adult Chum Salmon. North Pac. Anadromous Fish Comm. 2016, 6, 439–450. [CrossRef]

-----THIS IS OLD FROM MY PROPOSAL---

I propose to develop a truncated life-cycle model based on a Beverton-Holt transition function that incorporates biological and physical environmental covariates to estimates of Chum salmon productivity to understand the relative influence of these process on changes in Chum salmon survival and abundance (Moussalli & Hilborn 1986). The model will be based on data from two life stages, a stage labeled FW which includes freshwater and early marine survival and is based on a marine juvenile survey, and a stage labeled S, which includes fish that survive from ocean-year 0 to spawn and is based on escapement and catch data (Figure 4.1). Model time-steps will be indexed based on calendar year; however, covariates will be matched based on brood-year which will inform the environmental conditions fish experienced during ocean entry. The stages are chosen based on stock-specific data availability throughout the lifecycle and to separate out early stage versus late-stage environmental effects on abundance. The Yukon River supports Chum salmon Summer and Fall runs, where the Fall runs tend to be larger and migrate to the ocean earlier than summer Yukon chum. Additionally, the marine genetic reporting groups can separate Yukon Fall chum from other Chum runs in the region, thus I will model two stock groups: Yukon Fall Chum, Yukon Summer Chum and Kuskokwim Chum salmon.

This model will focus on understanding processes in the early marine life stage, but also includes covariates for the secondary marine and spawner component. In this multistage model, the productivity and carrying capacity parameters for each stage , are estimated in a Beverton Holt transition function to calculate survival rate for each brood year t, stock s and stage, n, . This model takes the following form:

Eq. 4.1

Eq. 4.2

Eq. 4.3

Eq. 4.4

Eq. 4.5

Here, the relative number of spawning individuals is multiplied by the proportion of females in the spawning stock, , and the fecundity, to produce the total potential eggs, , for each calendar year, t and stock, s. Next, the survival rate for the freshwater/early marine stage, is multiplied by total potential eggs, , to yield EBS juvenile Chum abundance before their first winter at sea, . Fish estimated in this stage have survived to the first fall at sea where they are indexed by NOAA’s BASIS survey in Fall (termed Ocean Year-0). Next, survival rate for juvenile ocean year-0 to spawners, , is multiplied by the number of ocean age 0 fish, to yield relative number of spawning individuals . Productivity, is a function of the average survival rate across stocks, and the sum of environmental covariate effects, c. The coefficient for each stock s, life stage n and covariate c, will be multiplied by mean-scaled covariate time series within the covariate matrix, X (Hilborn and Walters 1992).

Prey Index and covariates

I will test multiple covariates at each life stage to understand relative contributions of physical and biological environmental processes to Chum salmon abundance (Figure 4.1). I intend to include nearshore degree days, mainstem river discharge, river ice break up timing and a marine prey index for the n = FW stage. I have described hypotheses and mechanisms in more detail for these covariates in table 4.1. I will develop a marine prey index for juvenile Chum during their first summer at sea within the juvenile Western AK Chum salmon spatial distribution (55°N to 64°N). These maps were developed by Cunningham et al. for the North Pacific Marine Fisheries Council. The marine prey index, as well as other FW stage covariates are represented within (Eq 4.2). This prey index will focus on relative abundance of copepods and amphipods that are abundant in juvenile Chum diets, such as Calanus spp and Themisto libellula as an indicator species for Chum salmon prey availability (Murphy et al. 2016). The species I will include are also diet for Chum prey, i.e. forage fish, when Chum become larger and piscivorous (Moulton 1997, Burril 2007). The initial intent was to use BEST-NPZ output to inform a hybrid Calanus spp prey index. However, conclusions from Chapter 1 indicate proceeding with caution when using BEST-NPZ as a temporal biomass index. Instead, I will utilize a zooplankton abundance dataset from the NBS collected by NOAA’s AFSC. This data set uses multiple gear types to survey the NBS zooplankton community in Fall from 2002 to 2023 (excluding 2020). Surveys used a vertically towed Juday net from 2002 to 2011 to capture smaller zooplankton and then they used paired bongo nets from 2011 to present. Most large zooplankton were collected using obliquely towed paired bongo nets; however, some samples were collected using an obliquely towed ring net from 2002 to 2011. Multiple surveys have tested the selectivity of these methods to understand potential data biases when switching between the two methods, they have concluded that they are comparable for Calanus spp (Gorbatenko & Dolganova 2007, Kimmel et al. 2023). Themisto libellula are only enumerated from the large zooplankton nets (60 cm diameter net using 333 μm and 505 μm mesh) in the dataset. To inform survival for the second life-stage component, n=Sp, I will include offshore degree days and hatchery origin Pink and Chum abundance within (Eq 4.3) (Table 4.1). Temperature can lead to stress and changes to metabolic rate as fish are staging to return to freshwater and spawn, this can negatively affect survival (Howard & von Biela 2023). Further, competition with hatchery fish can affect size and overall condition of returning fish (Tadokoro et al. 1996, Ohlberger et al. 2023).

Estimation and Likelihoods

I will fit the proposed model to stock-specific data using Bayesian methods, with a joint likelihood to allow the sharing of information between data rich and data limited stocks. This is advantageous as some AYK stocks are observed with greater precision than others (Schaub & Abadi 2011). The observation model will consist of two likelihood components using both life stage components (). Chum experience natural mortality across all life stages and they are also subject to subsistence and commercial fishing, in addition to pollock bycatch (Ianelli & Stram 2015). We assume this mortality is accounted for in estimates of . I will estimate model parameters within a Bayesian framework developed using STAN in R. I will evaluate convergence of the chains based on visual inspection of trace plots for each chain. I will use a posterior predictive check that estimates the Bayesian P-value to test whether the model can generate new observations that were similar or more extreme than the data. A Bayesian p-value between 0 and 1 indicates the model cannot generate new observations that properly resemble the data (Gelman 2005).

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