## 2. Methods

### 2.1 Population Dynamics Model

We used an integrated population model (IPM) to estimate the influence of covariates on Yukon River Chum salmon productivity at multiple stages throughout their lifecycle. IPMs are a class of models well-suited to address the challenge of incorporating environmental predictors into population models (Schaub & Abadi 2011), as demonstrated by successful applications in mammal and bird conservation (Besbeas et al. 2002, Regehr et al. 2018). The flexible IPM framework allowed us to incorporate multiple data sources when estimating ecosystem covariate impacts on Fall Chum salmon survival. The IPM tracked cohorts of fall Chum salmon by brood year, *t*, life stages, *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 from their first winter to when they return to the Yukon river mouth and are vulnerable to terminal harvest, 3) “harvest”, which includes individuals that survived the marine environment and are intercepted in terminal commercial and subsistence fisheries, 4) “spawners”, which are the fish that return back to the spawning grounds and 5) “eggs”, the amount of eggs produced by spawners (Figure **XX**). We tracked cohorts based on their brood year and age class.

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

Nt,s=j= t,s=j\* Nt,s=e Eq. 4.1

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

Eq. 4.2

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 1) using an inverse logit function of basal productivity, , which represented the mean survival rate at low density.

Eq. 4.3

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

Upon surviving their first summer at sea, chum salmon migrate to the Eastern Aleutian Islands and Western Gulf of Alaska, where they spend up to five years at sea before returning to the Yukon River (Farley Jr et al. 2024). The first winter in the GOA is hypothesized as a critical life stage step where high mortality occurs, thus we estimated survival during the first winter at sea, t,s=m.  Survival during the first winter at sea was estimated using the Beverton-Holt transition function described above (Eq. 4.2) and the productivity parameter, which informs survival, was estimated conditional on environmental covariates described in Table 1 for the marine stage.

= t,s=m \* Nt,s=j Eq. 4.4

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

= Eq. 4.5

We assumed a cumulative natural mortality for ages 4-6, , where the annual mortality was fixed to 0.06, this represents the assumption that older fish had a higher marine mortality than younger fish (Beamish 2018), but that overall ocean mortality after the first winter at sea was low. The proportion of fish returning to the Yukon River from each brood year, was estimated as a Dirichlet hyper-distribution arising from a mean age at maturity probability vector, , with deviations determined by an inverse dispersion parameter. This parameter controlled the annual variation in maturity probability.

Eq. 4.6

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

Nt+a+1,s=c,a= Nt+a+1,s=r,a \*(Eq. 4.6

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

Ft+a+1 = Eq. 4.7

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

Nt+a+1,s=s,a= Nt+a+1,s=r,a- Nt+a+1,s=c,a Eq. 4.8

The number of eggs produced by each spawner was dependent on the proportion of females, P, which was fixed at 50% (Gilk et al. 2009), and age specific fecundity rates, Ea. Age specific fecundities were not available for Yukon River Chum salmon, but have been estimated for Chum in the neighboring Kuskokwim River (Gilk et al. 2009) regions, so we assume the following fecundities: where Age 2’s were 1800, Age 3’s 2351, Age 4’s 2902, and Age 5’s 3453, so that larger fish produced more eggs per spawner (Gilk et al. 2009).

Nt+a+1,s=e,a =Nt+a+1,s=s,a \*Ea\*P Eq. 4.9

### 2.2 Model Estimation

We fit the integrated population model to multiple datasets using Bayesian inference and implemented the model in STAN (Carpenter et al. 2017) using the rstan package in R (Stan Development Team 2024). The model was fit using 4 chains, 2000 warm up iterations and 4000 total iterations, we set the adapt-delta to 0.99 to force the model to take smaller steps when searching the parameter space. We diagnosed chain convergence using the Gelman-Rubin statistic (Brooks & Gelman 1998) and visually inspected coherence in the distribution of posterior samples from each chain using trace plots (Supplement figure XX). We used the priorsense package in R to evaluate how sensitive the posterior is to perturbations of the prior and likelihoods (Kallioinen et al. 2023).

Marine juvenile abundance estimated in the IPM were fit to a juvenile fall chum salmon index arising from data collected in the Northern Bering Sea (NBS) survey. The NBS survey is a collaborative survey run by ADFG, NOAA Alaska Fishery Science Center, the University of Alaska, Fairbanks (UAF) and the U.S. Fish and Wildlife Service (USFWS) to better understand the Northern Bering Sea Ecosystem (Murphy et al. 2021). The survey has collected a wide array of ecosystem information, including juvenile salmon abundance from surface trawls that are conducted at multiple stations across the NBS. The survey is conducted annually in Summer/Fall (typically between August and September), which is the termination of juvenile Chum salmon first summer at sea before they migrate to the GOA. Fish caught in this survey are allocated to genetic reporting groups, including Yukon Fall Chum.

To account for spatial and temporal survey imbalances, Chum salmon CPUE data were used to estimate a juvenile salmon index. A Vector Autoregressive Spatio-Temporal modeling approach was used to create an independent index of Yukon River fall chum salmon, and methods are detailed by Cunningham et al – check in with Curry, do I need to include methods here?). To translate the model estimated juvenile abundances to the scale of the observed juvenile abundances, we estimated a constant, *q*. We fit the model to the juvenile index ranging from brood years 2002 to 2022. Observation error was assumed as log-normally distributed:

Eq. 4.XX

Fall run Chum total return, harvest and spawner estimates for the Yukon River was provided by the Alaska Department of Fisheries and Game (ADFG) fall chum salmon run reconstruction (Fleischman & Borba 2009). A full discussion of the run reconstruction model is available in Fleischman and Borba 2009, the model methods have remained the same as the reconstruction model has been updated with new information. Spawner abundances were estimated based on data from escapement monitoring projects beginning in the 1970’s that covers 95% of the drainage and yields drainage wide estimates. Harvest data to inform the run reconstruction was compiled from commercial fish tickets and subsistence surveys. In the reconstruction, the total run size was assumed as the sum of the spawners and harvest. We fit the model to the return, harvest and spawner estimates ranging from brood years 2002 to 2022. We assumed observation error was log-normally distributed for all stages:

Eq. 4.XX

Eq. 4.XX

Eq. 4.XX

Age composition data that informed the run reconstruction was collected from lower river fisheries and test fisheries (Fleischman & Borba 2009). We fit the estimation model to age composition estimates provided by the run reconstruction. We used predicted run size by calendar year and age (Nt+a+1,s=r,a) to calculate the predicted proportions at age by calendar year (). The difference between the annual return age composition predicted by the model, *,* and the observed return age composition, was minimized by relating the two through a multinomial distribution.

### 2.3 Ecosystem Covariates

Covariates included in the IPM were gathered based support from peer reviewed literature (Table 1). All covariates were mean-scaled before they were included in the model. We considered four covariates hypothesized to impact juvenile salmon productivity from the egg stage to the end of their first summer at sea, including Yukon River flow rates, cumulative degree days for sea surface temperatures in the Northern Bering Sea, pollock recruitment index and the mean spawner size trend from the parent generation. We included the Yukon River mainstem mean flow for May and June for each brood year +1 with the hypothesis that increased river flow 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 flow rates in May and June are the most likely to impact juvenile feeding and address this hypothesis. We acquired monthly flow data (cubic feet per second) from a gage hosted by the USGS at Pilot Station, AK, along the Lower Yukon River (Table 1, Figure 1).

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 hypothesized a positive relationship between temperature and juvenile productivity, as suggested by empirical studies in the Bering Sea and bioenergetics modeling in Japan (Iino et al. 2022, Farley Jr et al. 2024). The hypothesized positive relationship may arise if warmer temperatures enhance juvenile salmon growth rates as they enter the marine environment which can reduce size selective mortality and lead to greater productivity (Beamish & Mahnken 2001, Farley Jr et al. 2024). To calculate CDD we used the daily mean NBS SST, publicly available on the Alaska Fisheries Information Network (AKFiN), summed from June to August for each year brood year +1 to align with when juvenile salmonids would experience the temperature conditions.

We included the EBS walleye pollock (*Gadus chalcogrammus*) recruitment index from the pollock stock assessment to represent changes in salmon prey availability during the first summer at sea (Ianelli et al. 2023). Young pollock represent a high-quality prey source for juvenile chum that is important for lipid accumulation and can lead to greater growth and productivity (Myers et al. 2009, Kaga et al. 2013, Farley Jr et al. 2024). While juvenile Chum salmon consume multiple fish species, forage fish typically have patchy distributions making them difficult to survey and estimate reliable indices, thus the pollock recruitment index represents robust prey index for juvenile Chum salmon. Finally, we included the mean trend in spawner size at age for spawners that returned during the juvenile brood year. 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, Feddern et al. 2024). 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 (Supplemental Table 1), we compiled Yukon River Chum salmon age and length data from 2000-2021.

We included an additional set of covariates in estimating survival for the adult marine life stage, which we considered as the end of the first summer at sea, when individuals leave the Bering Sea and typically head to the Gulf of Alaska and the Aleutian Peninsula, until the individuals are vulnerable to terminal harvest when they return to the Yukon River. Covariates included in the marine adult stage include CDD for sea surface temperatures in the Eastern Aleutian Islands, a fullness index, annual total Chum and Pink salmon hatchery releases (separately) from Alaska, Japan, Korea and Russia. We included winter Eastern Aleutian CDD to represent the temperature conditions that young Yukon River Chum salmon experienced during their first winter at sea, which is hypothesized as a critical survival bottleneck in the lifecycle (Farley Jr et al. 2024). To calculate CDD we used the daily mean E Aleutian SST, publicly available on the Alaska Fisheries Information Network (AKFiN), summed from November to February to represent winter conditions. We hypothesized a negative relationship between high CDD and productivity, as high temperatures can alter the prey base which is critical under higher metabolic demands of warm temperatures (Farley Jr et al. 2024).

We included a juvenile stomach fullness index (SFI), to represent the conditions fish are in when they begin their first winter at sea, we hypothesized that a higher SFI, which represents better fish condition, would be positively related to adult productivity. The SFI is estimated from fullness data collected by the NBS survey (discussed in more detail below) and the fullness data collection methods are detailed in Murphy et al 2021. Stomach fullness data are collected from salmon at each station and recorded on a per station basis. To account for differences in the survey through space and time and in the number of stomachs examined at each station, we used a generalized additive model to estimate a SFI. The model took the following form:

Eq. 4.10

where is the expected log SFI, for the i-th observation in space and time. We included an intercept to estimate mean SFI, , a factor year effect, to standardize SFI across years, , and a factor gear effect, to standardize SFI across gear types, . is a spatial field represented by a tensor product of B-splines for geospatial coordinates (: latitude, : longitude), which allowed for anisotropy in the smoothing process. The model was assessed for convergence and the residuals were assessed for homogeneity.

Finally, we included Chum and Pink hatchery release abundances, separately, from Alaska, Japan, Korea and Russia. We hypothesized a negative relationship between hatchery release abundances and adult marine productivity as increases in marine competition negatively impacts salmon stocks (Ruggerone et al. 2003, Cunningham et al. 2018, Scheuerell et al. 2020, Feddern et al. 2024). International hatchery release information is publicly available from the North Pacific Anadromous Fish Commission. [Discuss lags]

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