### 2. Methods

#### 2.1 Population Dynamics Model

An integrated population model (IPM) was used to estimate the influence of environmental and ecological covariates on the survival of Yukon River fall Chum salmon at multiple stages throughout their lifecycle (Figure 1, Figure 2). IPMs, also called lifecycle models, are well-suited to address the challenge of incorporating environmental predictors into population models (Schaub & Abadi 2011), as demonstrated by successful applications in mammal, bird and fish conservation (Besbeas et al. 2002, Cunningham et al. 2018, Regehr et al. 2018, Crozier et al. 2021, DeFilippo et al. 2021). The flexible IPM framework incorporates multiple data sources to estimate ecosystem covariate impacts on fall Chum salmon survival. Data used to fit the IPM include juvenile abundance data from a marine survey in the Bering Sea, run reconstruction data from adult Chum salmon returning to the Yukon River to spawn, and environmental covariates spanning brood years 2002 – 2021. The model was fit within a Bayesian framework as described below.

The IPM tracked cohorts of fall Chum salmon by brood year, *t*, life stage, *s* and age, *a*. The model includes five stages for Yukon river fall Chum: 1) “eggs”, which tracks the amount of eggs produced by spawners, 2) “marine summer”, which tracks individuals from eggs to the end of their first summer in the marine environment, 3) “marine winter”, which tracks individuals from the end of their first summer past their first winter in the marine environment, 4) “total returns”, which tracks individuals after their first winter to when they return to the Yukon River mouth and are vulnerable to terminal harvest, and 4) “spawners”, which are the fish that escape harvest and make it to the spawning grounds and is equal to the difference between total returns and total terminal harvest (Figure 2).

The number of Chum salmon surviving from an egg to the end of their first summer in the ocean, Nt,s=j, depends on the number of eggs spawned in brood year, *t*, Nt,s=e and the 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 represents time-varying maximum survival rate in the absence of density-dependent compensation, and represents the carrying capacity, or the maximum number of individuals that could survive to the end of each life stage. The productivity parameter was estimated conditional on environmental covariates (Table 1) using an inverse logit function of basal productivity, , which represented the maximum survival rate (in logit space) at low density.

Eq. 4.3

Here, a matrix, of mean-scaled covariate values *c*, was multiplied by an associated coefficient vector, which described the influence of each covariate, *c*, on stage-specific survival rates. The time reference for each covariate value is offset from the brood year by a stage-specific value , indicating the appropriate calendar year of reference for the interaction between the Chum salmon cohort and the environmental or ecosystem process.

Upon surviving their first summer at sea, fall Chum salmon migrate to the Eastern Aleutian Islands and Western Gulf of Alaska (GOA), where they spend up to five years at sea before returning to the Yukon River (Farley et al. 2024). The first winter is hypothesized to be a critical period in the life stage of juvenile salmon (Beamish & Mahnken 2001, Farley Jr et al. 2007). Thus, we estimated survival from the first winter at sea to maturity, t,s=m using the Beverton-Holt transition function described above (Eq. 4.2). The productivity parameter, which informs the maximum survival rate, was estimated conditional on covariates as described in Table 1. Survival from the first winter at sea to maturity, t,s=m, was multiplied by the number of juvenile fish, Nt,s=j, to yield the number of fish that survive their first winter at sea and mature, .

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

The number of fish returning to the Yukon River are based on calendar year is indexed by . The number of returning fish, Ny,s=r,a, depended on age-structured natural mortality rates at ocean age , , and the proportion of fish that mature and return to spawn from each brood year at a given ocean age, .

= Eq. 4.5

We assumed a fixed natural mortality for fish with a total age of 3-6 years, , where the annual mortality rate was 0.06. This represents the assumption that older fish had a higher marine mortality than younger fish but that overall ocean mortality after the first winter at sea was low (Beamish 2018). The maturity schedule for Chum salmon was assumed to vary randomly over time, relative to an average maturity schedule. The proportion of fish maturing and returning to the Yukon River at each ocean age, from each brood year , was estimated with a Dirichlet hyper-distribution arising from a mean age-at-maturity probability vector, . Annual deviations from the mean age-at-maturity were determined by an inverse dispersion parameter, *D*.

Eq. 4.6

Returning fish, Ny,s=r,a, were subject to terminal harvest determined by annual fishing mortality in each calendar year , and age-specific selectivity, . The resulting catch-at-age in calendar year is:

Eq. 4.7

To allow ample flexibility in annual fishing mortality rates by calendar year. We estimated mean fishing mortality and process deviations around the mean, .

Eq. 4.8

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

Eq. 4.9

The number of eggs produced by each spawner, *,* was assumed to follow a Ricker function which includes parameters for the log of the maximum recruitment per spawner without density dependence, , for each age class and the strength of density dependence, (Ricker 1954, Hilborn 1985). The proportion of females, , was fixed at 50% (Gilk et al.2009).

Eq. 4.10

The lifecycle begins again by summing the number of eggs produced by each female spawner across age classes, which yields number of eggs produced in each brood year, .

Eq. 4.11

#### 2.2 Model Estimation

Data to which the IPM was fit included juvenile abundance data from marine surface trawl surveys conducted by the Alaska Department of Fish and Game (ADF&G) and NOAA National Marine Fisheries Service in the Bering Sea, run reconstruction model outputs describing adult Chum salmon returning to the Yukon River to spawn, and environmental covariates spanning brood years 2002 – 2022. The Yukon River fall Chum salmon run reconstruction model was developed and is implemented by the ADF&G and is informed by data collected through the extensive efforts of ADF&G and Department of Fisheries and Oceans Canada (DFO) monitoring and assessment programs (Fleischman & Borba 2009). We fit the IPM to these datasets using Bayesian inference using the STAN platform and implemented the model using the rstan package in R (Carpenter et al. 2017, R Core Team 2021, Stan Development Team 2024). Models were fit to data for each population separately, with four chains run for 12,000 iterations and a 50% burn in rate, resulting in 6,000 saved iterations with a thinning rate of 1/10. We used an adapt-delta of 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 trace plots to ensure all chains converged to a stationary distribution (Figure S2). We used the *priorsense* package in R to evaluate how sensitive the posterior distribution was to prior and likelihood perturbations (Kallioinen et al. 2023).-