

**Influence of stock-specific migration rate variability
on mixed-stock harvest rates for at-risk Fraser River
Chinook salmon (*Oncorhynchus tshawytscha*)**

**by
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Abstract

Accurately reconstructing mixed-stock catches in the Fraser River is paramount for managing fisheries that can intercept or target at-risk Fraser River Chinook salmon (*Oncorhynchus tshawytscha*). However, reconstruction models assume constant in-river migration rates despite a growing body of evidence that Chinook salmon display some of the most variable in-river migration rates of all the Pacific salmon species. I used a spatially explicit, individual based model of Chinook salmon migration and fisheries in the Fraser River to simulate how small changes in migration rate variability affected stock-specific catch outcomes and proportional catch outcomes under a fixed in-river harvest scenario involving three separate stocks, including two at-risk stocks. For the Chilko Summer 5₂, Quesnel Summer 5₂, and South Thompson 4₁ stocks tested, increasing migration rate variability led to significantly lower catch outcomes (down 5.9%, 8.1%, and 16.6%, respectively). Increasing migration rate variability did not significantly affect each stocks proportional catch. My results provide valuable insights to managers, highlighting the significance of understanding how migration rate variability influences catch outcomes for at-risk Chinook salmon in the Fraser River. Additionally, these results underscore the importance of integrating migration rate variability into stock assessment models.

Keywords: Fraser River; Chinook salmon; migration rate; catch outcomes; mixed-stock fisheries

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1. Introduction

Returns of Chinook salmon (*Oncorhynchus tshawytscha*) play a vital cultural, ecological, and economic role in the Fraser River watershed and associated communities. In 2019, the Committee on the Status of Endangered Wildlife in Canada evaluated 11 Fraser River Chinook salmon stocks as at-risk, with 7 of them classified as endangered (COSEWIC, 2018). During their adult freshwater migration to spawning grounds, these at-risk Fraser Chinook stocks are subject to mixed-stock fisheries as they overlap temporally and spatially with viable, abundant salmon stocks (English et al., 2007; Dobson et al., 2020). As climate change progresses, factors that significantly influence their migration rate like water temperature and discharge (Damborg et al., 2020; Goniea et al., 2006; Salinger & Anderson, 2006) are likely to change and become more variable (Morrison et al., 2002; Shrestha et al., 2012). Variability in migration rates is not currently considered in models reconstructing catch of these at-risk stocks (English et al., 2007; Dobson et al., 2020). Managers often do not have the data to consider how variable migratory rates could affect by-catch of at-risk Chinook in mixed stock fisheries. Considering migration variability of at-risk Chinook stocks during their freshwater migration in a simulation study could provide managers with the information they need to proceed with fisheries, while protecting those stocks with lower productivity.

The interaction between unfavorable environmental conditions and human-induced pressures are contributing to challenges in both freshwater and marine survival (Beamish et al., 1995; Crozier et al., 2021; Hinch et al., 2021; Mantua et al., 2009). Despite this, consumer demand for wild salmon continues and the fisheries that supply them create economic value. Fishery managers are obligated to make complex decisions that satisfy fisheries objectives for viable Fraser salmon stocks, recovery objectives that may arise through the Species at Risk Act (SARA) (Government of Canada, 2002) or stock rebuilding provisions of Bill C-68 (Government of Canada, 2019) for at-risk Fraser Chinook stocks. Mixed-stock fisheries risk over-exploiting less productive stocks co-occurring during fisheries openings and can reduce overall resiliency of the collective population (Hilborn et al., 2003; Satterthwaite & Carlson, 2015; Schindler et al., 2010). Conversely, not taking advantage of mixed-stock fisheries due to conservation concerns means the loss of important cultural and economic opportunities to communities along the Fraser River. In 2008 and 2012, DFO imposed a series of restrictions on First Nations,

commercial, and recreational fisheries exploiting or intercepting Fraser Chinook to directly address their conservation concern (Dobson et al., 2020 Appendix A). Despite these restrictions, many stocks continue to decline in abundance. In part, this is attributed to exploitation as by-catch during mixed-stock fisheries (Dobson et al., 2020).

Chinook salmon exhibit some of the most complex life history strategies of all Pacific salmon (Groot and Margolis, 1991) with frequent variation in adult migration timing and migration behaviour (Boggs et al., 2004; Quinn, 2007). Migration behaviour for Chinook salmon encompasses migration timing, swim speed, fallback, holding behaviour, and thermal refugia use (Boggs et al., 2004; Hasler et al., 2012a; Hasler et al., 2012b, Quinn, 2007). Migratory behaviour of salmonids in general are not well understood, in part due to the difficulties associated with collecting information in the aquatic environment where access and visual observations are limited (Brönmark et al., 2014). Variation in migration rates however, are better understood from extensive freshwater telemetry studies (Damborg et al., 2020; Goniea et al., 2006; Salinger & Anderson, 2006). Migratory data are crucial to managing migratory, exploited species like Pacific salmon – models coupled with migratory data can help distinguish between the effects of natural drivers and harvest impacts (Hilborn & Walters, 1992; Freshwater et al. 2021).

Adult freshwater migration is a critical life stage for Chinook salmon, as they navigate complex river systems to reach their spawning grounds. Chinook salmon display a wide range of migration rates among river systems, run timing groups, and stocks, as well as temporally and spatially within stocks (Eiler et al., 2015; Hasler et al., 2012a; Hasler et al., 2012b; Keefer et al., 2004). For example, 21 stocks of Chinook salmon returning to the Yukon River system from 2002 to 2004 displayed migration rates ranging from 27.9 km d⁻¹ to 65.7 km d⁻¹ (Eiler et al. 2015), while 12 stocks of Chinook salmon returning to the Columbia River system from 1998 to 2002 displayed median migration rates from 9.8 km d⁻¹ to 38.5 km d⁻¹. While information on migration timing and river entry timing for Upper Fraser Chinook becomes more refined (Parken et al. 2008, Freshwater et al. 2021), data and associated studies on in-river migration rate and migration behaviour of Fraser Chinook stocks are confined to lower Fraser Chinook stocks with relatively short migration distances (Bass et al., 2019; Teffer et al., 2018) compared to Fraser Chinook returning to the middle and upper Fraser River or the Thompson River and its tributaries.

Migration rate variability

In-river migration rate is influenced by physiological limits on swim performance, migration behaviour, fisheries interactions, and in-river environmental conditions (Bass et al., 2019; Bernard et al., 1999; Geist et al., 2003; Quinn, 2007). Migration rate variability can come from any one of these components or combinations thereof. Studies on the free flowing Yukon River have found that some Chinook salmon stocks will increase their migration rate as they near the end of their migration in tributaries (Eiler et al., 2014; Eiler et al., 2015). Within stock variation of migration patterns and rates can be substantial for Yukon Chinook (Eiler et al., 2015), with bigger and later-arriving Chinook tending to migrate faster (Twardek et al. 2022). Peterson et al. (2017) found high interannual variation in migration rates linked to precipitation levels in the San Joaquin and Stanislaus River in California. Literature suggests that Chinook salmon migration behaviour that influences their migration rate is highly variable and dynamic – assuming fixed migration rates in fisheries models for large reaches of river while assessing Fraser River Chinook may not be adequate to effectively manage them.

Physiological characteristics like oxygen consumption rates, aerobic capacity, anaerobic capacity, recovery capacity, and thermal performance govern how fast Chinook salmon can migrate in different thermal conditions (Clark et al., 2008; Farrell et al., 2003; Van Wert et al., 2023). Chinook salmon, like other Pacific salmon species, have a high aerobic capacity (Kraskura et al., 2024). Lab studies involving adult Chinook salmon have shown their critical swim speed to be between 2.0 and 2.3 body lengths per second (Geist et al., 2003, Kraskura et al., 2024). Limited field studies have measured adult Chinook salmon bursting at speeds 481.58 cm/s or 2.0 body lengths per second, which is lower than other Pacific salmon species (Kraskura et al., 2024). One study showed that Chinook salmon can have a high recovery capacity in controlled settings with almost no negative effects to their aerobic capacity (Randall et al., 1987) - more recent literature supported by field studies suggests, however, that factors leading to excessive anaerobic metabolism can lead to migration failure and mortality (Birnie-Gauvin et al., 2023). Resting adult lower Fraser Chinook salmon show a critical thermal maximum of 25°C for Chinook >4 kg and 27°C for Chinook <4 kg as indicated by lower arterial and venous oxygen levels (Clark et al., 2007). Larger, resting Fraser Chinook switched to anaerobic metabolism above 25°C (Clark et al., 2007). Temperature changes during in-river migration can

dramatically alter some Fraser Chinook stocks migration ability - stock specific differences in thermal performance affect their migration ability and thereby migration rate (Van Wert, 2023). Fraser Chinook stocks with lower thermal tolerance exhibited by increased mortality, reduced aerobic capacity, and a reduced recovery capacity after anaerobic activity (Van Wert, 2023), all of which would likely lead to decreasing migration rates or altered migration behaviour (Rand et al., 2006; Strange et al. 2012). Swimming Columbia River spring chinook salmon exhibit increased oxygen consumption rates with rising temperature and swim speed, consistent with other Pacific salmon (Geist et al., 2003). Telemetry studies in Alaska and on the Columbia River have found that some Chinook salmon stocks significantly slow their migration rates as they enter tributaries of river systems and when temperatures reach above 20°C (Moses et al., 2019; Goniea et al., 2006). Physiological characteristics of Chinook salmon in response to changing thermal conditions are important to consider when thinking about migration rate variability.

Migration behaviour and its interaction with fisheries can also influence migration rate. Chinook salmon that experience fishery capture or handling tend to migrate slower, travel smaller distances, and sometimes “fallback” downstream (Bass et al., 2019; Bernard et al., 1999; Teffer et al., 2018). Fallback, which is thought to be uncommon in other species of Pacific salmon (Quinn, 2007), complicates estimation of migration rates (Keefer et al., 2006). For example, adult Chinook salmon in the lower Fraser River showed a 78% fallback rate post capture by fishwheel for radio-tagging (LGL Limited, 2010). In the heavily dammed Columbia River, another tagging study found substantial fallback variation among individually tagged Chinook, with some individuals cumulatively falling back over 1000 km during upstream adult migration, while other individuals did not fall back at all (Keefer et al., 2006). Literature shows that Chinook salmon migration rate variability is influenced by many factors, including their propensity to fallback. Given that Chinook salmon exhibit a wide range of possible migration rates and can fallback, I want to answer the question – how does migration rate variability and fallback influence the number of Chinook salmon caught under a fixed harvest plan?

The objective of this study is to determine whether catch and peak arrival timing to spawning grounds are influenced by migration rate variability. I used a simulation model as a mechanistic approach for estimating how stock-specific migration rate variability impacts catch and peak arrival timing for three Fraser River Chinook salmon stocks. I utilized the Fraser River Salmon Management Model (FRSMM), a spatially explicit,

boxcar/individual-based model, to simulate the movement and catch of migrating adult Chinook salmon. I used the same migration rate data from DFO's Chinook Run Reconstruction Model to parameterize FRSMM. Understanding the implications of such variability is crucial for developing effective management strategies that balance conservation needs with sustainable fisheries practices. If migration rate variability significantly influences catch, this study could help managers understand its importance in planning future management scenarios.

2. Methods

Background on populations and fisheries

Fraser River Chinook salmon are classified into 4 Management Units (MUs), Spring 5₂, Summer 5₂, Spring 4₂, and Fall 4₁, which describe their dominant life history age and freshwater residency structure and run-timing (DFO, 2021). I chose to examine the Chilko Summer 5₂, Quesnel Summer 5₂, and South Thompson Summer 4₁ Chinook stocks. The Chilko and Quesnel stocks are part of the Middle Fraser Stream Summer population, which is listed as Threatened by COSEWIC (DFO, 2018). The South Thompson Summer 4₁ stock is not listed by COSEWIC and represents one of the most abundant Fraser Chinook stocks outside of the Lower Fraser. Peak arrival timing at the Fraser River mouth of summer run Fraser Chinook starts in late May, peaks in mid-July, and ends in mid-September. On average, temperatures are highest in the Fraser River in early August (Patterson et al., 2007). Summer Fraser Chinook co-migrate with Early Stuart, Early Summer, and Summer run Sockeye salmon and pink salmon. While at-risk Fraser Chinook stocks no longer have dedicated fishery openings, they are subject to by-catch in mixed-stock fisheries targeting sockeye and pink salmon and in Chinook directed recreational and food, social, and ceremonial fisheries (Dobson et al., 2020, LGL Limited, 2010).

Data

I obtained information on migration rate, total run size, spawning ground arrival timing, and spatially explicit weekly fishery harvest rates for all three stocks from Fisheries and Oceans Canada (DFO) Fraser River Stock Assessment group in their Chinook Run Reconstruction Model (L. Weir, personal communications, October 7, 2022). The fixed in-river harvest scenario I chose used weekly harvest rates in the same locations at the same times as the Chinook Run Reconstruction Model output for the year 2012. Fisheries were located along the entire length of the selected stocks migration routes, including commercial, First Nations, and recreational harvest. The majority of fishing effort in the model took place in lower Fraser gillnet fisheries for all three stocks (Figure 1). I used total run size data and environmental data from the year 2012 for my simulation. Mean daily temperature from thirteen stations along the Fraser River were provided by the DFO

Environmental Watch Program (website: <https://www.pac.dfo-mpo.gc.ca/science/habitat/frw-rfo/index-eng.html>). Discharge data were accessed from Water Survey of Canada (website: <https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey.html>).

FRSMM model

The Fraser River Salmon Management Model (FRSMM) is a spatially explicit, boxcar model with an individual-based model run in parallel to track cumulative impacts of migration conditions on migrating salmon (Springford, 2012). FRSMM represents groups of migrating adult salmon using boxcars and simulates individual BOTS (BOTS are Objects for Tracking States). In FRSMM, boxcars represent the movement of aggregate groups of salmon, which are stock, time, and location specific. BOTS, which are randomly generated individual fish from a stock and following the same rules as the boxcar, are used to record cumulative effects of exposure to temperature related mortality (Carter, 2014; Straight, 2021). The model uses discrete 12-hr timesteps and 10-km spatial increments called reaches, starting at Mission, BC and ending at stock-specific spawning grounds. Catch in FRSMM is location and time specific – harvest rates are applied over a series of timesteps to simulate the short openings and intensive effort of in-river fisheries. Previous research using FRSMM has looked at Fraser Sockeye acute and cumulative temperature related mortality and the effects of spatial location of in-river fisheries on harvest targets (Carter, 2014; Straight, 2021). Previous research using FRSMM has focused only on Sockeye salmon.

The following two sections describe how I used FRSMM to assess whether catch is affected by migration rate variability of three Fraser River Chinook salmon stocks in a fixed, in-river harvest scenario by altering the spread parameter of the multinomial logit movement sub-model in FRSMM. The movement sub-model is a reach specific, stochastic multinomial logit model parameterized with stock-specific migration rates. To simulate stock-specific migration variability, I varied the spread parameter of the movement sub-model in FRSMM across 5 different values over 100 simulations for the three stocks of Fraser Chinook salmon chosen. Unlike previous research using FRSMM, I did not examine temperature related mortality or stress as part of my simulation – this study focusses only on the relationship between variable migration rates and catch.

Movement

FRSMM has a movement sub-model that is reach/location specific. The movement sub-model is a stochastic, multinomial logit model parameterized with stock-specific migration rates. Simulating movement involves generating transition probabilities based on the average movement rate and spread, and randomly distributing the total number of fish present in reach r at time t to a new set of reaches at time $t + 1$.

Transition probabilities θ_i ($i = 1, 2, \dots, 9$) are used to represent the proportion of fish present in location i at time $t - 1$ that move to 9 possible new locations in one time step. In my simulation the 9 possible new locations are represented by cutpoints c_i ($-1, 0, 1 \dots 8$). Cutpoints represent the number of reaches that a fish will travel at time t , meaning that a BOT can travel one reach backwards (10km) or up to 8 reaches forward (80km) in one 12-hr timestep. Transition probabilities are computed using an ordered multinomial logit model defined by an average response variable y , which is the stock and reach specific migration rate, and a spread parameter σ_j , which determines the range of reaches over which fish will spread around the expected reach. Specifically, when σ_j varies it affects the steepness of the curve produced by the logistic function; a larger value of σ_j makes the curve steeper, and a smaller value of σ_j makes it flatter. This means that, as σ_j increases, the transition from 0 to 1 in the output of the inverse logit function is more abrupt and that small changes to the input $\left(\frac{y-c_i}{\sigma_j}\right)$ (Equation 1) result in the probability distribution for potential new reaches being spread out over a larger area around the expected reach (Figure 2, Figure 3, Figure 4, and Figure 5). My simulations y assumes movement is independent of temperature and discharge, and that cutpoints are equally spaced. As such, a cumulative probability distribution is computed for each cutpoint c_i

$$\theta_i = \begin{cases} 0 & i = 0 \\ 1 - \text{logit}^{-1}\left(\frac{y-c_i}{\sigma_j}\right) & 1 < i < r \\ 1 & i = r \end{cases} \quad \text{Equation 1}$$

Then, the probability of moving from reach r to reach $r + c_i$ is computed for each i by taking differences between the cumulative probabilities,

$$\theta_i = \begin{cases} \theta_i & i = 1 \\ \theta_i - \theta_{i-1} & i > 1 \end{cases} \quad \text{Equation 2}$$

Finally, the total number of fish $N_{t,r}$ present in reach r at time t is re-distributed among potential new reaches r to $r + c_9$ via random draw from a multinomial distribution,

$$N_{t+1,r,r+c_9} \sim \text{Multinomial}(N_{t,r}, \theta_{r:r+c_9}) \quad \text{Equation 3}$$

where the notation $r:r + c_9$ indicates a vector of reaches from r to $r + c_9$. BOTS move according to the same rules except that the multinomial draw uses a sample size of 1.

Sensitivity analysis

I performed a sensitivity analysis of the spread parameter σ_j in the movement sub-model to simulate variability in migration rate using FRSMs movement sub-model. The spread parameter σ_j distributes BOTS across a wider range of reaches when it is higher, making the probability of fallback higher, but also the probability of jumping more than 1 cutpoint ahead also higher (Equation 1). Increasing σ_j simultaneously increases migration rate variability, the chance of fallback, and the mean migration rate. I varied σ_j across five values, $\sigma_j = 0.1, 0.25, 0.5, 0.75, 0.9, 1, 5, 10,$ and 20 performing 100 simulations per spread parameter value. These σ_j values, starting with a very low σ_j value representing as little variation as possible in FRSM, were chosen to see if small changes or large changes to migration rate variability caused significant differences in total catch and peak arrival timing.

I performed a one-way analysis of variance (ANOVA) and post hoc tests on a composite dataset containing all the FRSMM simulation outputs for catch and peak arrival timing to spawning grounds for each σ_j value to investigate the variation between different σ_j values on catch and peak arrival timing for the three Fraser Chinook stocks and all three stocks combined. The data were tested for normality and homogeneity of variances prior to analysis. I also performed an analysis of covariance (ANCOVA) and post-hoc tests to investigate the effect of σ_j and the three Chinook stocks on the proportional catch of each stock. All statistical analyses were performed using R version 4.1.1 (R Core Team, 2021).

3. Results

The mean total catch output from my simulation for Chilko Summer 5₂ under the base model scenario of $\sigma_j = 1$ was 521 and the mean peak arrival date to spawning grounds was September 16. The mean total catch for Quesnel Summer 5₂ under the base model scenario of $\sigma_j = 1$ was 177 and the mean peak arrival date to spawning grounds was October 14. The mean total catch for South Thompson Summer 4₁ under the base model scenario of $\sigma_j = 1$ was 1273 and the mean peak arrival date to spawning grounds was October 20.

In my sensitivity analysis, higher migration variability lead to a reduction in overall simulated catch for all three stocks ($F_{8, 2691} = 55.74, p < 0.01$) (Table 1; Figure 5, Figure 6). Significant differences were observed in multiple comparisons (Tukey's HSD), specifically, the comparisons between σ values of 0.9 and 0.25 ($p = 0.03$), 0.75 and 0.1 ($p < 0.01$), 10 and 0.1 ($p < 0.01$), 20 and 0.1 ($p < 0.01$), 5 and 0.1 ($p < 0.01$), 0.75 and 0.25 ($p = 0.58$), 0.9 and 0.25 ($p = 0.03$), 10 and 0.25 ($p < 0.01$), 20 and 0.25 ($p < 0.01$), 5 and 0.25 ($p < 0.01$), 10 and 0.5 ($p < 0.01$), 20 and 0.5 ($p < 0.01$), 5 and 0.5 ($p < 0.01$), 10 and 0.75 ($p < 0.01$), 20 and 0.75 ($p < 0.01$), and 20 and 10 ($p < 0.01$) (Table 2).

Variability in migration rate had a large effect on simulated catch for the Chilko Summer 5₂ ($F_{8, 891} = 4128, p < 0.01$), Quesnel Summer 5₂ ($F_{8, 891} = 1410, p < 0.01$), and South Thompson Summer 4₁ ($F_{8, 891} = 12062, p < 0.01$) stocks (Table 3). Higher migration rate variability lead to lower catch estimates for each stock. For both the Chilko Summer 5₂ and Quesnel Summer 5₂ stocks, the mean simulated catch of fish significantly differed between all pairs of σ values, except for the comparison between σ values of 0.5 and 0.1 and between 0.1 and 0.75 for the Chilko Summer 5₂ stock (Table 4), and the comparison between σ values of 0.5 and 0.1 and between σ values of 0.75 and 1 for the Quesnel Summer 5₂ stock (Table 5). For the South Thompson Summer 4₁ stock, I found significant differences between all levels of σ , except for the comparison between 0.1 and 0.25 and between 1 and 0.75 (Table 6). These results suggest that the σ value had a significant impact on the simulated catch for the chosen Fraser Chinook stocks, particularly for individual stocks, with some σ values corresponding with significantly higher or lower catches compared to others (Figures 7, 8, 9, 10, 11 and 12).

Higher values of migration variability σ lead to a reduction in peak arrival timing for all three stocks combined ($F_{8, 2691} = 86.25, p < 0.01$) (Table 7). Significant differences were observed in multiple comparisons (Tukey's HSD), specifically, the comparisons between σ values of 0.25 and 0.1 ($p = 0.01$), 10 and 0.1 ($p < 0.01$), 20 and 0.1 ($p < 0.01$), 5 and 0.1 ($p < 0.01$), 0.5 and 0.25 ($p < 0.01$), 0.75 and 0.25 ($p < 0.01$), 0.9 and 0.25 ($p < 0.01$), 1 and 0.25 ($p < 0.01$), 10 and 0.25 ($p < 0.01$), 20 and 0.25 ($p < 0.01$), 5 and 0.25 ($p < 0.01$), 10 and 0.5 ($p < 0.01$), 20 and 0.5 ($p < 0.01$), 5 and 0.5 ($p < 0.01$), 10 and 0.75 ($p < 0.01$), 20 and 0.75 ($p < 0.01$), 10 and 0.9 ($p < 0.01$), 20 and 0.9 ($p < 0.01$), 10 and 1 ($p < 0.01$), 20 and 1 ($p < 0.01$), 5 and 10 ($p < 0.01$) and 5 and 20 ($p < 0.01$) (Table 8).

Variability in migration rate also had a large effect on the peak arrival date for the Chilko Summer 5₂ ($F_{8, 891} = 1559, p < 0.01$), Quesnel Summer 5₂ ($F_{8, 891} = 1458, p < 0.01$), and South Thompson Summer 4₁ ($F_{8, 891} = 693, p < 0.01$) stocks (Table 9). Higher migration rate variability lead to a decrease in the peak arrival time estimates for each stock and an increase in the mean migration rate. As examples on either extreme of the σ value chosen – for $\sigma = 0.1$, the Chilko Summer 5₂ traveled an average of 15.8km/day, the Quesnel Summer 5₂ traveled 20.3 km/day, and the South Thompson 4₁ stock traveled 15.2 km/day. For $\sigma = 20$, the Chilko Summer 5₂ traveled an average of 25km/day, the Quesnel Summer 5₂ traveled 37.9 km/day, and the South Thompson 4₁ stock traveled 17.6 km/day. For both the Chilko Summer 5₂ and Quesnel Summer 5₂ stocks, the mean simulated peak arrival time significantly differed between all pairs of σ values (Table 10, 11, and 12). These results suggest that the σ value had a significant impact on the peak arrival time for the chosen Fraser Chinook stocks, particularly for individual stocks, with increasing σ values leading to earlier mean peak arrival times (Figures 13, 14, 15, 16, 17, and 18).

There was no significant effect of migration rate spread on the proportion of simulated catch of each stock ($F_{1, 9} = 0.00, p = 1.00$) (Table 13). Stock is the primary predictor of the proportion of simulated catch ($F_{2, 9} = 10294.98, p < 0.01$). the effect of σ and stock on the proportion of simulated catch ($F_{2, 9} = 5.82, p = 0.02$) depends on the specific stock (Table 13). However, the size of this interaction is smaller than that of the main effect of stock, suggesting that stock is a stronger predictor overall. Finally, the lack of significant effect of σ on the proportion of simulated catch indicates that this variable may not be useful in predicting catch proportions in this context. A bar plot was created to visualize the mean proportional catch values for each σ value, which were used as the

covariate in the ANCOVA. As shown in Figure 19, there appears to be a slight trend of decreasing mean proportional catch with increasing σ values, although the difference between the σ values is small.

Total catch estimated by the Chinook Run Reconstruction Model for the Chilko Summer 5₂ was 1816, 895 for the Quesnel Summer 5₂, and 14,209 for the South Thompson Summer 4₁. My simulations mean total catch for Chilko Summer 5₂ ranged from 574 ($\sigma = 0.25$) to 217 ($\sigma = 20$) (Figure 6 and Figure 9). The Quesnel Summer 5₂ ranged from 193 ($\sigma = 0.25$) to 70 ($\sigma = 20$) (Figure 7 and Figure 10). The South Thompson Summer 4₁ ranged from 1,404 ($\sigma = 0.25$) to 461 ($\sigma = 20$) (Figure 8 and Figure 11). Note that the Chinook Run Reconstruction Model included intensive fisheries in Area 29, Steveston, and Deas Island for the year 2012, which I did not for my analysis (Figure 1). Separating out those fisheries catch in the Chinook Run Reconstruction model from their reconstructed total catch was not possible for comparison.

The Chinook Run Reconstruction model had a peak arrival date for the Chilko Summer 5₂ as August 30, the Quesnel Summer 5₂ as September 26, and South Thompson Summer 4₁ as October 14. My simulations mean peak arrival date for Chilko Summer 5₂ ranged from September 25 ($\sigma = 0.25$) to August 21 ($\sigma = 20$) with $\sigma = 10$ coming the closest to the Chinook Run Reconstruction Model date at August 25 (Figure 13 and Figure 16). The Quesnel Summer 5₂ mean peak arrival date ranged from October 23 ($\sigma = 0.25$) to September 17 ($\sigma = 20$) with $\sigma = 10$ coming the closest to the Chinook Run Reconstruction Model date at September 20 (Figure 14 and Figure 17). The South Thompson Summer 4₁ mean peak arrival date ranged from October 22 ($\sigma = 0.25$) to October 12 ($\sigma = 20$) with $\sigma = 10$ coming exactly on the Run Reconstruction Model date at October 14 (Figure 15 and Figure 18).

Compared to the Chinook Run Reconstruction model, my simulations catch estimates were lower (Dobson et al., 2020). Peak arrival timing from my simulation was most similar to the Chinook Run Reconstruction Model's estimated peak arrival time for all three stocks at $\sigma = 10$ (Chilko Summer 5₂ at August 25, Quesnel Summer 5₂ at September 20, and the South Thompson Summer 4₁ October 14). According to my simulation, and comparing to the Chinook Run Reconstruction Model, a spread parameter value of $\sigma = 10$ best characterizes the migration rate variability and mean migration rate for each stock.

4. Discussion

My results suggest that higher migration rate variability leads to significantly lower catch outcomes and earlier peak arrival times to spawning grounds for Fraser River Chinook salmon stocks under a fixed in-river harvest plan. While the results of previous studies have found that Chinook salmon display diverse and variable in-river migratory behaviour and migration rates (Eiler et al., 2015; Moses et al., 2019; Goniea et al., 2006), no studies have yet looked at the relationship between migration rate variability with a chance of fallback and catch outcomes for Fraser River Chinook. These findings have implications for the management of mixed-stock fisheries, especially concerning at-risk Chinook stocks and the need to balance conservation objectives with sustainable fisheries practices.

Small changes in migration rate variability can affect how many fish are caught in a realistic mixed-stock harvest scenario. Temperature (Geist et al., 2003; Goniea et al., 2006; Moses et al., 2019; Van Wert, 2023), fisheries interactions (Bass et al., 2019; Bernard et al., 1999; Teffer et al., 2018), and precipitation levels (Peterson et al., 2017) affect migration rates of Chinook salmon. Salinger and Anderson (2006) found that PIT tagged adult Chinook salmon in the Columbia and Snake Rivers displayed a wide range of migration rates for 9 km/day to over 60km/day, with a mean migration rate of 35 km/day. In a study analyzing radio-tagging data, Keefer et al. (2004) found different Chinook stocks returning to the Columbia River and its tributaries had median migration rates ranging from 9 km/day to 38 km/day, again with large spreads in migration rates within stocks. These telemetry studies found much larger spreads in possible migration rates than what my simulation examined – even more pronounced effects to catch may be possible with more realistic spreads in possible migration rates. Consequently, it is important for fisheries managers to consider the specific migration factors that influence the magnitude of migration rate variability of each stock when designing management strategies or developing run reconstruction models. My analysis suggests that Fraser Chinook salmon stocks may be differentially vulnerable to mixed-stock fisheries depending on which σ values characterize the variability in their migration rate. Notably, some pairs of σ values led to significantly different catch outcomes (Figure 7, 8, 9, 10, 11, and 12, Table 2 and Table 4). For the Chilko Summer 5₂, Quesnel Summer 5₂ and the South Thompson Summer 4₁ stocks, significant differences were observed between most σ values; however, the values of σ in which they differed varied. Each stock responds differently to

changes in factors that influence migration rate and behaviour, emphasizing the need for tailored management approaches that account for the unique characteristics of each stock.

When comparing my simulations output using FRSM to the Chinook Run Reconstruction Model, my catch estimates were lower. This is most likely because I chose to start my simulation in Mission as previous FRSM studies have done (Carter, 2014; Straight, 2021), I did not include gill net fisheries in Area 29, Steveston, and Dease Island that were included in the Chinook Run Reconstruction model. Fishery area specific total harvest data was not made available to me by stock, only by MU aggregate in the Chinook Run Reconstruction Model outputs. As such, a direct fishery to fishery comparison is not possible. Future simulations using FRSM could include the missing Area 29, Steveston, and Dease Island fisheries to understand if FRSM is underestimating fish even when those fisheries are included. Additionally, a sensitivity analysis altering Chinook stocks arrival timing in the Chinook Run Reconstruction could be done as a way of varying migration rates to compare catch outcomes when varying the other model.

The σ value of 10 represented the best estimate based on mean peak arrival times to spawning grounds for all three Fraser Chinook stocks in FRSM when comparing to the Chinook Run Reconstruction's peak arrival to spawning grounds dates (Figures 17, 18, and 19). This could represent the level of migration rate variability most associated with the Chinook Run Reconstruction model, or it could be the mean migration rate when $\sigma = 10$ is more similar to the Chinook Run Reconstruction's. This is odd considering that the Chinook Run Reconstruction's migration rates were used directly as the response variable in FRSM's movement sub-model (Equation 1). Additional differences between FRSM and the Chinook Run Reconstruction model should be examined to see which underlying assumptions are driving these differences in peak arrival to spawning grounds timing.

The FRSM movement sub-model was parameterized to distribute fish from between 1 reach backwards to 8 reaches forwards every timestep. Herein, increasing the spread parameter σ in the movement sub-model (Equation 1), and thus the migration rate variability, in the multinomial logit model led to a higher likelihood of distributing individuals to larger cutpoint values (Figure 2). This resulted in larger reach distances covered by the individuals in the model. Additionally, the model restricted fallback (movement backward)

to only one reach, while migration forward could be extended over multiple reaches. Consequently, increasing σ lead to a higher proportion of individuals migrating faster and covering larger distances. The decreased catch observed with increased migration rate variability can be attributed to individuals spending less time in the intensive gill net fisheries of the lower Fraser River due to faster migration (Figure 1). This aligns with the interpretation that increasing σ results in more rapid movement of individuals through the river system, reducing the time they spend in areas where they can be caught. The spread of possible reaches that BOTS could travel per 12 hr. timestep was increased to a maximum of 8 cutpoints, or 80 km. Given that the maximum migration rates for adult Chinook salmon in other systems is roughly 60 km/day (Salinger and Anderson, 2006; Eiler et al., 2015), 80 km per timestep may appear as too high an assumption. However, the nature of the multinomial logit model constrained mean migration rates to never exceed realistic numbers when σ was as high as 20. It will be important to validate whether the predicted spread of migration rates from my simulation are accurate for each stock with telemetry studies.

Individual stock was the primary predictor of the proportion of simulated catch, not the migration rate variability. My results suggests that the proportion each stock is caught as an aggregate remains stable as the migration variability increases. However, this constant proportionality (Figure 20) is not surprising given that the same spread parameter values were used for all stocks in the ANCOVA. Further sensitivity analyses should compare proportional catch when stocks exhibit different spread parameter values. This additional analysis could reveal whether or not some stocks are more vulnerable to catch under different migration variability scenarios. Fisheries managers should consider these interactions when developing strategies to mitigate the potential negative effects of mixed-stock fisheries on at-risk Chinook stocks.

Limitations and assumptions

My analysis focused on three specific Chinook salmon stocks and used a simplified representation of migration rate variability through the σ parameter in the FRSSM movement sub-model. The multinomial logit model used in FRSSM is a simple way of representing migration variability and incorporating a chance of fallback; however, it does not explicitly parameterize effects of bottlenecks, discharge, or temperature on migration rate. FRSSM has a sub model that simulates a bottleneck by increasing the multinomial

logit transition probabilities around a reach where you specify a bottleneck to exist, but it did not effectively represent bottlenecks despite repeated testing and altering. Other factors that can influence migration rate like diel patterns and depth behaviour during migration should also be explored (Keefer et al., 2019).

In FRSM, the run timing of stocks through fisheries is assumed to be fixed. Run timing assumptions within the model determine the allocation of harvest impacts among stocks, therefore bias in assumed parameters or variability due to environmental factors could introduce uncertainty into the results of this study. All stocks are assumed to have equal catchability to the in-river fisheries they pass through in the model. Given that South Thompson 4₁ Chinook are on average smaller than returning Summer 5₂ Chinook and the inherent size-selectivity of gillnet gear, this assumption may not be appropriate (Dobson et al., 2020). Previous studies on Sockeye and Chum salmon have shown gillnet catch efficiency may increase exponentially with fork length and that gillnets can lead to selective pressures on spawning ground for smaller fish (Fukuwaka et al., 2008; Hamon et al., 2000). Additionally, the fixed-harvest plan used in my analysis may not accurately reflect current in-season harvest plans, which are often dynamic based on in-season stock assessment determinations. However, this information could readily be updated in new model runs of FRSM.

Recommendations for future work

My analysis focused on the movement sub-model, whereas previous FRSM analyses examined Sockeye salmon in-river mortality as influenced by temperature (Carter, 2014; Straight, 2021). Chinook salmon also experience mortality related to thermal changes in the Fraser River (Bass et al., 2019). Temperature related mortality studies of the Fraser, Columbia, Snake, Klamath, and Willamette Rivers suggest that Chinook salmon exhibit considerable stock specific variability in thermal tolerance while migrating in-river (Bass et al., 2019; Bowerman et al., 2021, Keefer et al. 2015, Keefer et al., 2018; Van Wert et al., 2023). Future research assessing stock specific thermal tolerances of at-risk Fraser Chinook salmon would be useful and could be parameterized and incorporated into a future analysis using FRSM. The probability and distance of fallback may be more extreme than my simulation examined - some chinook in the Columbia River have been found to fallback over 1000km cumulatively over their entire upstream migration (Keefer et al., 2005). In river bottlenecks, created by different flow regimes, can also impact

migration rate and success (Cooke et al., 2004; Macdonald et al. 2010). As explained previously, FRSMM's bottleneck function did not work properly represent this challenge. Rebuilding the existing bottleneck function in FRSMM or modeling bottleneck effects on catch could be important to understand how differential flow regimes in the Fraser influence migration rate variability and catch.

In general, fisheries interactions in FRSMM encompass only reach specific harvest rates. As such, estimates of catch induced mortality could be underestimated in FRSMM as fishing related incidental mortality (FRIM) is not examined (Patterson et al. 2017). Incorporating a gear specific FRIM model into a future analysis could reveal the magnitude of underestimation of fishing related mortality. My research focused only on the Chilko Summer 5_2 , Quesnel Summer 5_2 and the South Thompson Summer 4_1 stocks - incorporating spring 5_2 Chinook could be valuable in future research as well.

FRSMMs movement sub-model does not explicitly tie temperature to migration rates or migration rate variability. Studies on Columbia River Chinook suggest that Chinook salmon significantly slow their migration rates as temperatures go above 20°C (Dionne et al., 2019; Goniea et al., 2006, Moses et al., 2020; Salinger & Anderson, 2006). One study examining the effects of water temperature and discharge on adult salmon migration swim speed and delay compared different model types against PIT tag data to see which model type best fit the data (Salinger & Anderson, 2006). Salinger & Anderson (2006) found that broken linear models best fit they PIT tag data they had collected on migrating adult salmon. It is possible that the multinomial logit model used to represent movement in FRSMM may not represent fine scale migration movement of Fraser Chinook salmon as effectively as other model types – future research could compare telemetry data to different model types as Salinger & Anderson did (2006) and to fixed migration rate models like the Chinook Run Reconstruction Model (Dobson et al. 2020). Fine scale telemetry data for fish that migrate past Hell's Gate is apparently sparse (Dobson et al., 2020); biotelemetry work that aims to assess how temperature or other factors influence Fraser chinook migration rates would reduce uncertainty for managers interested in understanding these stocks.

The challenge of limited data and high variability in migration rate should be addressed when examining in-river fisheries interaction for at-risk Fraser Chinook stocks. DFO uses test fisheries paired with genetic stock identification (GSI) and coded wire tag

(CWT; mass marking of juveniles from different natal stocks with unique tag identifications) to get precise run timing windows for river entry timing for Fraser Chinook stocks (Parken et al., 2008); however, the precision does not extend upriver to migration rates of specific stocks en-route to spawning grounds. Currently, stock assessment and forecasting for Chinook salmon stocks in the Fraser River assumes constant stock specific in-river migration rates determined from limited test fishery data paired with GSI and CWT data (Dobson et al. 2020, Lauren Weir, DFO, personal communications).

The data on stock-specific migration rates at fine spatial and temporal scales in-river and on marine approaches that are often incorporated into local fisheries management decisions are not always publicly available (DFO, 2019; Freshwater, 2021). All data for my analysis was pulled from the DFO Chinook Run Reconstruction Model. Inquiry regarding the origins of the stock and reach specific migration rate data revealed uncertainty in the data's origin. In general, robust information on fish movements in large rivers is often limited due to the effort and costs associated with implementing large-scale monitoring programs over extended distances and periods of time (Eiler et al., 2015). Modern biotelemetry has been used effectively on migrating salmon to determine fine scale migration behaviour in a range of environmental conditions (Hinch et al., 2002; Keefer et al., 2004; Eiler et al., 2015). Using biotelemetry to collect quality in-river migration data has the capacity to substantially increase our understanding of Chinook salmon movements on a scale large enough to be useful to fishery managers.

Conservation implications

Managing mixed-stock fisheries is a trade-off between conserving at-risk stocks and meeting harvest objectives. My results provide insights into what factors can influence how this balance could be achieved. By considering the specific migration dynamics of each stock and incorporating this information into fisheries management plans, it may be possible to reduce the by-catch of at-risk Chinook while still allowing for the sustainable harvest of more abundant stocks. One of the primary conservation implications of this study is that even small changes in migration behavior can significantly affect stocks catch levels. Given the precarious status of these stocks and managers obligations to conserve and rebuild wild stocks (COSEWIC, 2018; DFO, 2005), it is imperative that managers are clear about their harvest objectives for mixed-stock fisheries that overlap with the run

timing of at-risk Chinook stocks. The incorporation of migration rate variability in managers' models may illuminate better harvest strategies to align with harvest objectives.

Climate change is forecast to impact Pacific salmon in the Fraser watershed significantly, with elevated water temperatures likely to increase freshwater mortality and slow migration rates (Crozier, 2020; Patterson et al., 2007, Hague et al., 2011; Strange et al., 2010; Strange et al. 2012). Increase in water temperatures and discharge are also forecasted to reduce homing and increase energy expenditure for Columbia Chinook (Connor et al. 2019). Increased variability in migration rates and an increase in water temperature could lead to greater stressors during fisheries capture and increased catch of Chinook salmon (Teffer et al., 2018). As mixed-stock fisheries risk over-exploiting less productive stocks and undermining portfolio effects of mixed-stock diversity (Hilborn et al. 2003; Satterthwaite & Carlson, 2015), the effects of increased mortality and migration rate variability due to climate change should be considered by managers. These findings underscore the importance of adopting tailored management strategies for each Chinook salmon stock. Conservation efforts should be designed to account for the unique characteristics of each stock, considering factors like migration timing, migration behaviour, and response to fishery capture. Given the dynamic nature of migration behavior proposed by this study and the future effects of climate change, an adaptive management approach could be warranted. Fisheries managers could continuously monitor and assess the behavior of Chinook salmon stocks and adjust management measures accordingly. This flexibility allows for a more proactive response to changing migration patterns and helps prevent over-exploitation of at-risk stocks. This study also highlights the critical need for improved data collection, data documentation for current models, and research efforts focused on in-river migration behavior of Chinook salmon. More comprehensive and detailed data on the movements of these fish can enhance the precision of fisheries management models and allow for a better understanding of the factors influencing migration rate variability. Future research should focus on collecting accurate field data on Fraser Chinook migration rates and migration behaviours to inform evidence-based management decisions.

Conclusion

In conclusion, this study highlights the significance of migration rate variability in the context of mixed-stock fisheries for Fraser River Chinook salmon. The results emphasize

the need for stock-specific management strategies that account for the unique migration behaviors of individual stocks. This work provides fisheries managers with information that can help them consider these factors when making decisions to ensure the conservation of at-risk Chinook stocks while maintaining sustainable fisheries practices. This research contributes to our understanding of how migration dynamics impact the catch outcomes in mixed-stock fisheries and provides valuable insights for effective fisheries management in the Fraser River watershed.

Tables

Table 1 One-way ANOVA results for effects of σ on simulated catch for all stocks.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
σ	8	77295776.78	9661972.10	55.74	<0.0001
Residuals	2691	466435464.13	173331.65		

Table 2 Tukey multiple comparisons of means for simulated catch and all stocks displaying the difference in means, lower and upper confidence intervals, and adjusted p-values for multiple comparisons.

	term	contrast	null.value	estimate	conf.low	conf.high	adj.p.value
1	σ	0.25-0.1	0.00	17.72	-87.80	123.25	1.00
2	σ	0.5-0.1	0.00	-8.54	-114.06	96.98	1.00
3	σ	0.75-0.1	0.00	-48.27	-153.79	57.26	0.89
4	σ	0.9-0.1	0.00	-92.30	-197.83	13.22	0.14
5	σ	1-0.1	0.00	-48.27	-153.79	57.26	0.89
6	σ	10-0.1	0.00	-416.11	-521.64	-310.59	<0.0001
7	σ	20-0.1	0.00	-457.92	-563.44	-352.39	<0.0001
8	σ	5-0.1	0.00	-137.46	-242.98	-31.94	<0.0001
9	σ	0.5-0.25	0.00	-26.26	-131.79	79.26	1.00
10	σ	0.75-0.25	0.00	-65.99	-171.51	39.53	0.58
11	σ	0.9-0.25	0.00	-110.03	-215.55	-4.50	0.03
12	σ	1-0.25	0.00	-65.99	-171.51	39.53	0.58
13	σ	10-0.25	0.00	-433.84	-539.36	-328.31	<0.0001
14	σ	20-0.25	0.00	-475.64	-581.16	-370.12	<0.0001
15	σ	5-0.25	0.00	-155.18	-260.71	-49.66	<0.0001
16	σ	0.75-0.5	0.00	-39.73	-145.25	65.80	0.96
17	σ	0.9-0.5	0.00	-83.76	-189.29	21.76	0.25
18	σ	1-0.5	0.00	-39.73	-145.25	65.80	0.96
19	σ	10-0.5	0.00	-407.57	-513.10	-302.05	<0.0001
20	σ	20-0.5	0.00	-449.38	-554.90	-343.85	<0.0001
21	σ	5-0.5	0.00	-128.92	-234.44	-23.40	<0.0001
22	σ	0.9-0.75	0.00	-44.04	-149.56	61.49	0.93
23	σ	1-0.75	0.00	-0.01	-105.52	105.52	1.00
24	σ	10-0.75	0.00	-367.85	-473.37	-262.32	<0.0001
25	σ	20-0.75	0.00	-409.65	-515.17	-304.13	<0.0001
26	σ	5-0.75	0.00	-89.19	-194.72	16.33	0.18
27	σ	1-0.9	0.00	44.04	-61.49	149.56	0.93
28	σ	10-0.9	0.00	-323.81	-429.33	-218.29	<0.0001
29	σ	20-0.9	0.00	-365.61	-471.14	-260.09	<0.0001
30	σ	5-0.9	0.00	-45.16	-150.68	60.37	0.92
31	σ	10-1	0.00	-367.85	-473.37	-262.32	<0.0001
32	σ	20-1	0.00	-409.65	-515.17	-304.13	<0.0001
33	σ	5-1	0.00	-89.19	-194.72	16.33	0.18
34	σ	20-10	0.00	-41.80	-147.33	63.72	0.95
35	σ	5-10	0.00	278.65	173.13	384.18	<0.0001
36	σ	5-20	0.00	320.46	214.93	425.98	<0.0001

Table 3 One-way ANOVA results for effects of σ on simulated catch for each stock.

	term	df	sumsq	meansq	statistic	p.value	CU
1	σ	4.00	233827.01	58456.75	119.13	<0.0001	Chilko 5.2
2	Residuals	495.00	242895.01	490.70			
3	σ	4.00	29620.45	7405.11	46.71	<0.0001	Quesnel 5.2
4	Residuals	495.00	78468.52	158.52			
5	σ	4.00	4279633.17	1069908.29	865.21	<0.0001	S. Thompson 4.1
6	Residuals	495.00	612114.24	1236.59			

Table 4 Tukey multiple comparisons of means for simulated catch and Chilko 5.2 displaying the difference in means, lower and upper confidence intervals, and adjusted p-values for multiple comparisons.

	term	contrast	null.value	estimate	conf.low	conf.high	adj.p.value	CU
1	σ	0.25-0.1	0.00	33.69	24.58	42.80	<0.0001	Chilko 5.2
2	σ	0.5-0.1	0.00	-6.82	-15.93	2.29	0.33	
3	σ	0.75-0.1	0.00	-16.03	-25.14	-6.92	<0.0001	
4	σ	0.9-0.1	0.00	-31.37	-40.48	-22.26	<0.0001	
5	σ	1-0.1	0.00	-16.03	-25.14	-6.92	<0.0001	
6	σ	10-0.1	0.00	-291.91	-301.02	-282.80	<0.0001	
7	σ	20-0.1	0.00	-327.46	-336.57	-318.35	<0.0001	
8	σ	5-0.1	0.00	-58.73	-67.84	-49.62	<0.0001	
9	σ	0.5-0.25	0.00	-40.51	-49.62	-31.40	<0.0001	
10	σ	0.75-0.25	0.00	-49.72	-58.83	-40.61	<0.0001	
11	σ	0.9-0.25	0.00	-65.06	-74.17	-55.95	<0.0001	
12	σ	1-0.25	0.00	-49.72	-58.83	-40.61	<0.0001	
13	σ	10-0.25	0.00	-325.60	-334.71	-316.49	<0.0001	
14	σ	20-0.25	0.00	-361.15	-370.26	-352.04	<0.0001	
15	σ	5-0.25	0.00	-92.42	-101.53	-83.31	<0.0001	
16	σ	0.75-0.5	0.00	-9.21	-18.32	-0.10	0.05	
17	σ	0.9-0.5	0.00	-24.55	-33.66	-15.44	<0.0001	
18	σ	1-0.5	0.00	-9.21	-18.32	-0.10	0.05	
19	σ	10-0.5	0.00	-285.09	-294.20	-275.98	<0.0001	
20	σ	20-0.5	0.00	-320.64	-329.75	-311.53	<0.0001	
21	σ	5-0.5	0.00	-51.91	-61.02	-42.80	<0.0001	
22	σ	0.9-0.75	0.00	-15.34	-24.45	-6.23	<0.0001	
23	σ	1-0.75	0.00	-0.00	-9.11	9.11	1.00	
24	σ	10-0.75	0.00	-275.88	-284.99	-266.77	<0.0001	
25	σ	20-0.75	0.00	-311.43	-320.54	-302.32	<0.0001	
26	σ	5-0.75	0.00	-42.70	-51.81	-33.59	<0.0001	
27	σ	1-0.9	0.00	15.34	6.23	24.45	<0.0001	
28	σ	10-0.9	0.00	-260.54	-269.65	-251.43	<0.0001	
29	σ	20-0.9	0.00	-296.09	-305.20	-286.98	<0.0001	
30	σ	5-0.9	0.00	-27.36	-36.47	-18.25	<0.0001	
31	σ	10-1	0.00	-275.88	-284.99	-266.77	<0.0001	
32	σ	20-1	0.00	-311.43	-320.54	-302.32	<0.0001	
33	σ	5-1	0.00	-42.70	-51.81	-33.59	<0.0001	
34	σ	20-10	0.00	-35.55	-44.66	-26.44	<0.0001	
35	σ	5-10	0.00	233.18	224.07	242.29	<0.0001	
36	σ	5-20	0.00	268.73	259.62	277.84	<0.0001	

Table 5 Tukey multiple comparisons of means for simulated catch and Quesnel 5.2 displaying the difference in means, lower and upper confidence intervals, and adjusted p-values for multiple comparisons.

	term	contrast	null.value	estimate	conf.low	conf.high	adj.p.value	CU
37	σ	0.25-0.1	0.00	7.70	2.47	12.93	<0.0001	Quesnel 5.2
38	σ	0.5-0.1	0.00	-2.94	-8.17	2.29	0.72	
39	σ	0.75-0.1	0.00	-8.49	-13.72	-3.26	<0.0001	
40	σ	0.9-0.1	0.00	-15.06	-20.29	-9.83	<0.0001	
41	σ	1-0.1	0.00	-8.49	-13.72	-3.26	<0.0001	
42	σ	10-0.1	0.00	-100.22	-105.45	-94.99	<0.0001	
43	σ	20-0.1	0.00	-112.39	-117.62	-107.16	<0.0001	
44	σ	5-0.1	0.00	-25.56	-30.79	-20.33	<0.0001	
45	σ	0.5-0.25	0.00	-10.64	-15.87	-5.41	<0.0001	
46	σ	0.75-0.25	0.00	-16.19	-21.42	-10.96	<0.0001	
47	σ	0.9-0.25	0.00	-22.76	-27.99	-17.53	<0.0001	
48	σ	1-0.25	0.00	-16.19	-21.42	-10.96	<0.0001	
49	σ	10-0.25	0.00	-107.92	-113.15	-102.69	<0.0001	
50	σ	20-0.25	0.00	-120.09	-125.32	-114.86	<0.0001	
51	σ	5-0.25	0.00	-33.26	-38.49	-28.03	<0.0001	
52	σ	0.75-0.5	0.00	-5.55	-10.78	-0.32	0.03	
53	σ	0.9-0.5	0.00	-12.12	-17.35	-6.89	<0.0001	
54	σ	1-0.5	0.00	-5.55	-10.78	-0.32	0.03	
55	σ	10-0.5	0.00	-97.28	-102.51	-92.05	<0.0001	
56	σ	20-0.5	0.00	-109.45	-114.68	-104.22	<0.0001	
57	σ	5-0.5	0.00	-22.62	-27.85	-17.39	<0.0001	
58	σ	0.9-0.75	0.00	-6.57	-11.80	-1.34	<0.0001	
59	σ	1-0.75	0.00	-0.00	-5.23	5.23	1.00	
60	σ	10-0.75	0.00	-91.73	-96.96	-86.50	<0.0001	
61	σ	20-0.75	0.00	-103.90	-109.13	-98.67	<0.0001	
62	σ	5-0.75	0.00	-17.07	-22.30	-11.84	<0.0001	
63	σ	1-0.9	0.00	6.57	1.34	11.80	<0.0001	
64	σ	10-0.9	0.00	-85.16	-90.39	-79.93	<0.0001	
65	σ	20-0.9	0.00	-97.33	-102.56	-92.10	<0.0001	
66	σ	5-0.9	0.00	-10.50	-15.73	-5.27	<0.0001	
67	σ	10-1	0.00	-91.73	-96.96	-86.50	<0.0001	
68	σ	20-1	0.00	-103.90	-109.13	-98.67	<0.0001	
69	σ	5-1	0.00	-17.07	-22.30	-11.84	<0.0001	
70	σ	20-10	0.00	-12.17	-17.40	-6.94	<0.0001	
71	σ	5-10	0.00	74.66	69.43	79.89	<0.0001	
72	σ	5-20	0.00	86.83	81.60	92.06	<0.0001	

Table 6 Tukey multiple comparisons of means for simulated catch and South Thompson 4.1 displaying the difference in means, lower and upper confidence intervals, and adjusted p-values for multiple comparisons.

	term	contrast	null.value	estimate	conf.low	conf.high	adj.p.value	CU
73	σ	0.25-0.1	0.00	11.78	-2.71	26.27	0.22	S. Thompson 4.1
74	σ	0.5-0.1	0.00	-15.86	-30.35	-1.37	0.02	
75	σ	0.75-0.1	0.00	-120.28	-134.77	-105.79	<0.0001	
76	σ	0.9-0.1	0.00	-230.48	-244.97	-215.99	<0.0001	
77	σ	1-0.1	0.00	-120.28	-134.77	-105.79	<0.0001	
78	σ	10-0.1	0.00	-856.21	-870.70	-841.72	<0.0001	
79	σ	20-0.1	0.00	-933.90	-948.39	-919.41	<0.0001	
80	σ	5-0.1	0.00	-328.09	-342.58	-313.60	<0.0001	
81	σ	0.5-0.25	0.00	-27.64	-42.13	-13.15	<0.0001	
82	σ	0.75-0.25	0.00	-132.06	-146.55	-117.57	<0.0001	
83	σ	0.9-0.25	0.00	-242.26	-256.75	-227.77	<0.0001	
84	σ	1-0.25	0.00	-132.06	-146.55	-117.57	<0.0001	
85	σ	10-0.25	0.00	-867.99	-882.48	-853.50	<0.0001	
86	σ	20-0.25	0.00	-945.68	-960.17	-931.19	<0.0001	
87	σ	5-0.25	0.00	-339.87	-354.36	-325.38	<0.0001	
88	σ	0.75-0.5	0.00	-104.42	-118.91	-89.93	<0.0001	
89	σ	0.9-0.5	0.00	-214.62	-229.11	-200.13	<0.0001	
90	σ	1-0.5	0.00	-104.42	-118.91	-89.93	<0.0001	
91	σ	10-0.5	0.00	-840.35	-854.84	-825.86	<0.0001	
92	σ	20-0.5	0.00	-918.04	-932.53	-903.55	<0.0001	
93	σ	5-0.5	0.00	-312.23	-326.72	-297.74	<0.0001	
94	σ	0.9-0.75	0.00	-110.20	-124.69	-95.71	<0.0001	
95	σ	1-0.75	0.00	-0.00	-14.49	14.49	1.00	
96	σ	10-0.75	0.00	-735.93	-750.42	-721.44	<0.0001	
97	σ	20-0.75	0.00	-813.62	-828.11	-799.13	<0.0001	
98	σ	5-0.75	0.00	-207.81	-222.30	-193.32	<0.0001	
99	σ	1-0.9	0.00	110.20	95.71	124.69	<0.0001	
100	σ	10-0.9	0.00	-625.73	-640.22	-611.24	<0.0001	
101	σ	20-0.9	0.00	-703.42	-717.91	-688.93	<0.0001	
102	σ	5-0.9	0.00	-97.61	-112.10	-83.12	<0.0001	
103	σ	10-1	0.00	-735.93	-750.42	-721.44	<0.0001	
104	σ	20-1	0.00	-813.62	-828.11	-799.13	<0.0001	
105	σ	5-1	0.00	-207.81	-222.30	-193.32	<0.0001	
106	σ	20-10	0.00	-77.69	-92.18	-63.20	<0.0001	
107	σ	5-10	0.00	528.12	513.63	542.61	<0.0001	
108	σ	5-20	0.00	605.81	591.32	620.30	<0.0001	

Table 7 One-way ANOVA results for effects of σ on simulated peak spawning grounds arrival timing for all stocks.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
σ	8	756904.27	94613.03	86.25	<0.0001
Residuals	2691	2951992.46	1096.99		

Table 8 Tukey multiple comparisons of means for simulated peak spawning grounds arrival timing and all stocks displaying the difference in means, lower and upper confidence intervals, and adjusted p-values for multiple comparisons.

	term	contrast	null.value	estimate	conf.low	conf.high	adj.p.value
1	σ	0.25-0.1	0.00	10.18	1.79	18.57	0.01
2	σ	0.5-0.1	0.00	-1.28	-9.67	7.11	1.00
3	σ	0.75-0.1	0.00	-3.77	-12.16	4.63	0.90
4	σ	0.9-0.1	0.00	-7.02	-15.41	1.37	0.19
5	σ	1-0.1	0.00	-3.77	-12.16	4.63	0.90
6	σ	10-0.1	0.00	-38.64	-47.03	-30.24	<0.0001
7	σ	20-0.1	0.00	-42.22	-50.62	-33.83	<0.0001
8	σ	5-0.1	0.00	-11.06	-19.46	-2.67	<0.0001
9	σ	0.5-0.25	0.00	-11.46	-19.85	-3.07	<0.0001
10	σ	0.75-0.25	0.00	-13.95	-22.34	-5.55	<0.0001
11	σ	0.9-0.25	0.00	-17.20	-25.59	-8.81	<0.0001
12	σ	1-0.25	0.00	-13.95	-22.34	-5.55	<0.0001
13	σ	10-0.25	0.00	-48.82	-57.21	-40.42	<0.0001
14	σ	20-0.25	0.00	-52.40	-60.80	-44.01	<0.0001
15	σ	5-0.25	0.00	-21.24	-29.64	-12.85	<0.0001
16	σ	0.75-0.5	0.00	-2.49	-10.88	5.91	0.99
17	σ	0.9-0.5	0.00	-5.74	-14.13	2.65	0.46
18	σ	1-0.5	0.00	-2.49	-10.88	5.91	0.99
19	σ	10-0.5	0.00	-37.36	-45.75	-28.96	<0.0001
20	σ	20-0.5	0.00	-40.94	-49.34	-32.55	<0.0001
21	σ	5-0.5	0.00	-9.78	-18.18	-1.39	0.01
22	σ	0.9-0.75	0.00	-3.25	-11.65	5.14	0.96
23	σ	1-0.75	0.00	-0.01	-8.39	8.39	1.00
24	σ	10-0.75	0.00	-34.87	-43.26	-26.48	<0.0001
25	σ	20-0.75	0.00	-38.46	-46.85	-30.06	<0.0001
26	σ	5-0.75	0.00	-7.30	-15.69	1.10	0.15
27	σ	1-0.9	0.00	3.25	-5.14	11.65	0.96
28	σ	10-0.9	0.00	-31.62	-40.01	-23.22	<0.0001
29	σ	20-0.9	0.00	-35.20	-43.60	-26.81	<0.0001
30	σ	5-0.9	0.00	-4.04	-12.44	4.35	0.86
31	σ	10-1	0.00	-34.87	-43.26	-26.48	<0.0001
32	σ	20-1	0.00	-38.46	-46.85	-30.06	<0.0001
33	σ	5-1	0.00	-7.30	-15.69	1.10	0.15
34	σ	20-10	0.00	-3.59	-11.98	4.81	0.92
35	σ	5-10	0.00	27.57	19.18	35.97	<0.0001
36	σ	5-20	0.00	31.16	22.77	39.55	<0.0001

Table 9 One-way ANOVA results for effects of simulated peak spawning grounds arrival timing for each stock.

	term	df	sumsq	meansq	statistic	p.value	CU
1	σ	8.00	409868.38	51233.55	1558.54	<0.0001	Chilko 5.2
2	Residuals	891.00	29289.66	32.87			
3	σ	8.00	461001.96	57625.24	1457.99	<0.0001	Quesnel 5.2
4	Residuals	891.00	35215.64	39.52			
5	σ	8.00	36396.28	4549.53	693.20	<0.0001	S. Thompson 4.1
6	Residuals	891.00	5847.68	6.56			

Table 10 Tukey multiple comparisons of means for simulated peak spawning grounds arrival time and Chilko 5.2 displaying the difference in means, lower and upper confidence intervals, and adjusted p-values for multiple comparisons.

	term	contrast	null.value	estimate	conf.low	conf.high	adj.p.value	CU
1	σ	0.25-0.1	0.00	15.93	13.41	18.45	<0.0001	Chilko 5.2
2	σ	0.5-0.1	0.00	-2.46	-4.98	0.06	<0.0001	
3	σ	0.75-0.1	0.00	-3.74	-6.26	-1.22	<0.0001	
4	σ	0.9-0.1	0.00	-7.96	-10.48	-5.44	<0.0001	
5	σ	1-0.1	0.00	-3.74	-6.26	-1.22	<0.0001	
6	σ	10-0.1	0.00	-47.47	-49.99	-44.95	<0.0001	
7	σ	20-0.1	0.00	-52.95	-55.47	-50.43	<0.0001	
8	σ	5-0.1	0.00	-13.80	-16.32	-11.28	<0.0001	
9	σ	0.5-0.25	0.00	-18.39	-20.91	-15.87	<0.0001	
10	σ	0.75-0.25	0.00	-19.67	-22.19	-17.15	<0.0001	
11	σ	0.9-0.25	0.00	-23.89	-26.41	-21.37	<0.0001	
12	σ	1-0.25	0.00	-19.67	-22.19	-17.15	<0.0001	
13	σ	10-0.25	0.00	-63.40	-65.92	-60.88	<0.0001	
14	σ	20-0.25	0.00	-68.88	-71.40	-66.36	<0.0001	
15	σ	5-0.25	0.00	-29.73	-32.25	-27.21	<0.0001	
16	σ	0.75-0.5	0.00	-1.28	-3.80	1.24	<0.0001	
17	σ	0.9-0.5	0.00	-5.50	-8.02	-2.98	<0.0001	
18	σ	1-0.5	0.00	-1.28	-3.80	1.24	<0.0001	
19	σ	10-0.5	0.00	-45.01	-47.53	-42.49	<0.0001	
20	σ	20-0.5	0.00	-50.49	-53.01	-47.97	<0.0001	
21	σ	5-0.5	0.00	-11.34	-13.86	-8.82	<0.0001	
22	σ	0.9-0.75	0.00	-4.22	-6.74	-1.70	<0.0001	
23	σ	1-0.75	0.00	0.00	-2.52	2.52	<0.0001	
24	σ	10-0.75	0.00	-43.73	-46.25	-41.21	<0.0001	
25	σ	20-0.75	0.00	-49.21	-51.73	-46.69	<0.0001	
26	σ	5-0.75	0.00	-10.06	-12.58	-7.54	<0.0001	
27	σ	1-0.9	0.00	4.22	1.70	6.74	<0.0001	
28	σ	10-0.9	0.00	-39.51	-42.03	-36.99	<0.0001	
29	σ	20-0.9	0.00	-44.99	-47.51	-42.47	<0.0001	
30	σ	5-0.9	0.00	-5.84	-8.36	-3.32	<0.0001	
31	σ	10-1	0.00	-43.73	-46.25	-41.21	<0.0001	
32	σ	20-1	0.00	-49.21	-51.73	-46.69	<0.0001	
33	σ	5-1	0.00	-10.06	-12.58	-7.54	<0.0001	
34	σ	20-10	0.00	-5.48	-8.00	-2.96	<0.0001	
35	σ	5-10	0.00	33.67	31.15	36.19	<0.0001	
36	σ	5-20	0.00	39.15	36.63	41.67	<0.0001	

Table 11 Tukey multiple comparisons of means for simulated peak spawning grounds arrival time and Quesnel 5.2 displaying the difference in means, lower and upper confidence intervals, and adjusted p-values for multiple comparisons.

	term	contrast	null.value	estimate	conf.low	conf.high	adj.p.value	CU
37	σ	0.25-0.1	0.00	13.98	11.22	16.74	<0.0001	Quesnel 5.2
38	σ	0.5-0.1	0.00	-1.22	-3.98	1.54	<0.0001	
39	σ	0.75-0.1	0.00	-5.81	-8.57	-3.05	<0.0001	
40	σ	0.9-0.1	0.00	-9.70	-12.46	-6.94	<0.0001	
41	σ	1-0.1	0.00	-5.81	-8.57	-3.05	<0.0001	
42	σ	10-0.1	0.00	-52.67	-55.43	-49.91	<0.0001	
43	σ	20-0.1	0.00	-56.71	-59.47	-53.95	<0.0001	
44	σ	5-0.1	0.00	-14.47	-17.23	-11.71	<0.0001	
45	σ	0.5-0.25	0.00	-15.20	-17.96	-12.44	<0.0001	
46	σ	0.75-0.25	0.00	-19.79	-22.55	-17.03	<0.0001	
47	σ	0.9-0.25	0.00	-23.68	-26.44	-20.92	<0.0001	
48	σ	1-0.25	0.00	-19.79	-22.55	-17.03	<0.0001	
49	σ	10-0.25	0.00	-66.65	-69.41	-63.89	<0.0001	
50	σ	20-0.25	0.00	-70.69	-73.45	-67.93	<0.0001	
51	σ	5-0.25	0.00	-28.45	-31.21	-25.69	<0.0001	
52	σ	0.75-0.5	0.00	-4.59	-7.35	-1.83	<0.0001	
53	σ	0.9-0.5	0.00	-8.48	-11.24	-5.72	<0.0001	
54	σ	1-0.5	0.00	-4.59	-7.35	-1.83	<0.0001	
55	σ	10-0.5	0.00	-51.45	-54.21	-48.69	<0.0001	
56	σ	20-0.5	0.00	-55.49	-58.25	-52.73	<0.0001	
57	σ	5-0.5	0.00	-13.25	-16.01	-10.49	<0.0001	
58	σ	0.9-0.75	0.00	-3.89	-6.65	-1.13	<0.0001	
59	σ	1-0.75	0.00	-0.00	-2.76	2.76	<0.0001	
60	σ	10-0.75	0.00	-46.86	-49.62	-44.10	<0.0001	
61	σ	20-0.75	0.00	-50.90	-53.66	-48.14	<0.0001	
62	σ	5-0.75	0.00	-8.66	-11.42	-5.90	<0.0001	
63	σ	1-0.9	0.00	3.89	1.13	6.65	<0.0001	
64	σ	10-0.9	0.00	-42.97	-45.73	-40.21	<0.0001	
65	σ	20-0.9	0.00	-47.01	-49.77	-44.25	<0.0001	
66	σ	5-0.9	0.00	-4.77	-7.53	-2.01	<0.0001	
67	σ	10-1	0.00	-46.86	-49.62	-44.10	<0.0001	
68	σ	20-1	0.00	-50.90	-53.66	-48.14	<0.0001	
69	σ	5-1	0.00	-8.66	-11.42	-5.90	<0.0001	
70	σ	20-10	0.00	-4.04	-6.80	-1.28	<0.0001	
71	σ	5-10	0.00	38.20	35.44	40.96	<0.0001	
72	σ	5-20	0.00	42.24	39.48	45.00	<0.0001	

Table 12 Tukey multiple comparisons of means for simulated peak spawning grounds arrival time and South Thompson 4.1 displaying the difference in means, lower and upper confidence intervals, and adjusted p-values for multiple comparisons.

term	contrast	null.value	estimate	conf.low	conf.high	adj.p.value	CU
73	σ	0.25-0.1	0.00	0.63	-0.50	1.76	<0.0001
74	σ	0.5-0.1	0.00	-0.16	-1.29	0.97	<0.0001
75	σ	0.75-0.1	0.00	-1.75	-2.88	-0.62	<0.0001
76	σ	0.9-0.1	0.00	-3.40	-4.53	-2.27	<0.0001
77	σ	1-0.1	0.00	-1.75	-2.88	-0.62	<0.0001
78	σ	10-0.1	0.00	-15.77	-16.90	-14.64	<0.0001
79	σ	20-0.1	0.00	-17.01	-18.14	-15.88	<0.0001
80	σ	5-0.1	0.00	-4.92	-6.05	-3.79	<0.0001
81	σ	0.5-0.25	0.00	-0.79	-1.92	0.34	<0.0001
82	σ	0.75-0.25	0.00	-2.38	-3.51	-1.25	<0.0001
83	σ	0.9-0.25	0.00	-4.03	-5.16	-2.90	<0.0001
84	σ	1-0.25	0.00	-2.38	-3.51	-1.25	<0.0001
85	σ	10-0.25	0.00	-16.40	-17.53	-15.27	<0.0001
86	σ	20-0.25	0.00	-17.64	-18.77	-16.51	<0.0001
87	σ	5-0.25	0.00	-5.55	-6.68	-4.42	<0.0001
88	σ	0.75-0.5	0.00	-1.59	-2.72	-0.46	<0.0001
89	σ	0.9-0.5	0.00	-3.24	-4.37	-2.11	<0.0001
90	σ	1-0.5	0.00	-1.59	-2.72	-0.46	<0.0001
91	σ	10-0.5	0.00	-15.61	-16.74	-14.48	<0.0001
92	σ	20-0.5	0.00	-16.85	-17.98	-15.72	<0.0001
93	σ	5-0.5	0.00	-4.76	-5.89	-3.63	<0.0001
94	σ	0.9-0.75	0.00	-1.65	-2.78	-0.52	<0.0001
95	σ	1-0.75	0.00	0.00	-1.13	1.13	<0.0001
96	σ	10-0.75	0.00	-14.02	-15.15	-12.89	<0.0001
97	σ	20-0.75	0.00	-15.26	-16.39	-14.13	<0.0001
98	σ	5-0.75	0.00	-3.17	-4.30	-2.04	<0.0001
99	σ	1-0.9	0.00	1.65	0.52	2.78	<0.0001
100	σ	10-0.9	0.00	-12.37	-13.50	-11.24	<0.0001
101	σ	20-0.9	0.00	-13.61	-14.74	-12.48	<0.0001
102	σ	5-0.9	0.00	-1.52	-2.65	-0.39	<0.0001
103	σ	10-1	0.00	-14.02	-15.15	-12.89	<0.0001
104	σ	20-1	0.00	-15.26	-16.39	-14.13	<0.0001
105	σ	5-1	0.00	-3.17	-4.30	-2.04	<0.0001
106	σ	20-10	0.00	-1.24	-2.37	-0.11	<0.0001
107	σ	5-10	0.00	10.85	9.72	11.98	<0.0001
108	σ	5-20	0.00	12.09	10.96	13.22	<0.0001

Table 13 Cumulative Analysis of Variance (ANCOVA) Results for examining the relationship between the proportion of simulated catch and σ while controlling for the effects of individual stocks and between σ and stock. Table displays the Degrees of Freedom (Df), Sum of Squares (Sum Sq), Mean Square (Mean Sq), F-value, and p-value (Pr(>F)) to assess the significance of the variables in the analysis.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
σ	1.00	0.00	0.00	0.00	1.00
CU	2.00	0.82	0.41	10294.98	<0.0001
σ :CU	2.00	0.00	0.00	5.82	0.02
Residuals	9.00	0.00	0.00		

Figures

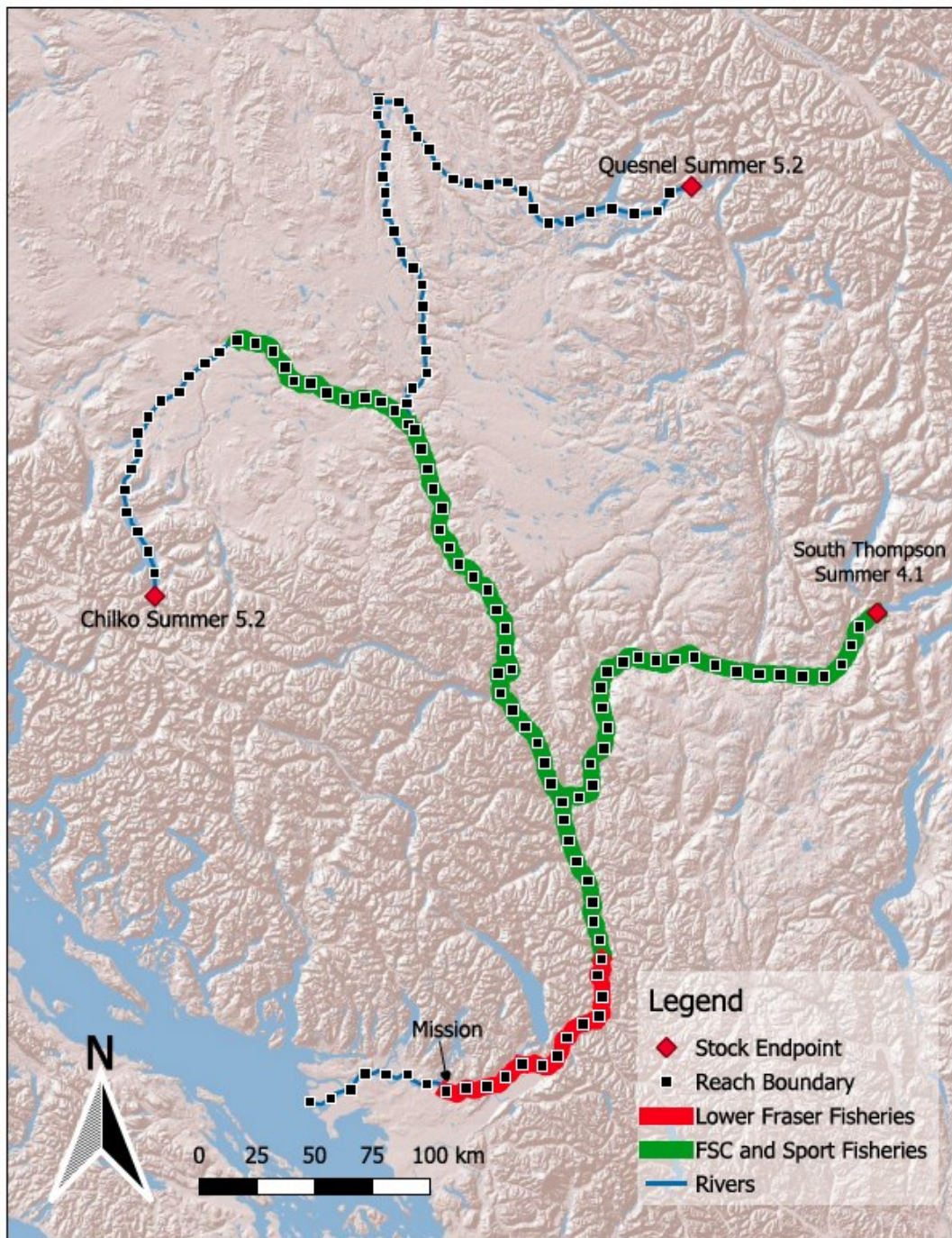


Figure 1 Fraser River map used in FRSSM simulation for the year 2012 using data from the Chinook Run Reconstruction Model. Reach boundaries are 10km apart. Lower Fraser fisheries includes main commercial and First Nations gillnet fisheries. The remaining fisheries, shown in green, were much lower effort FSC and sport fisheries.

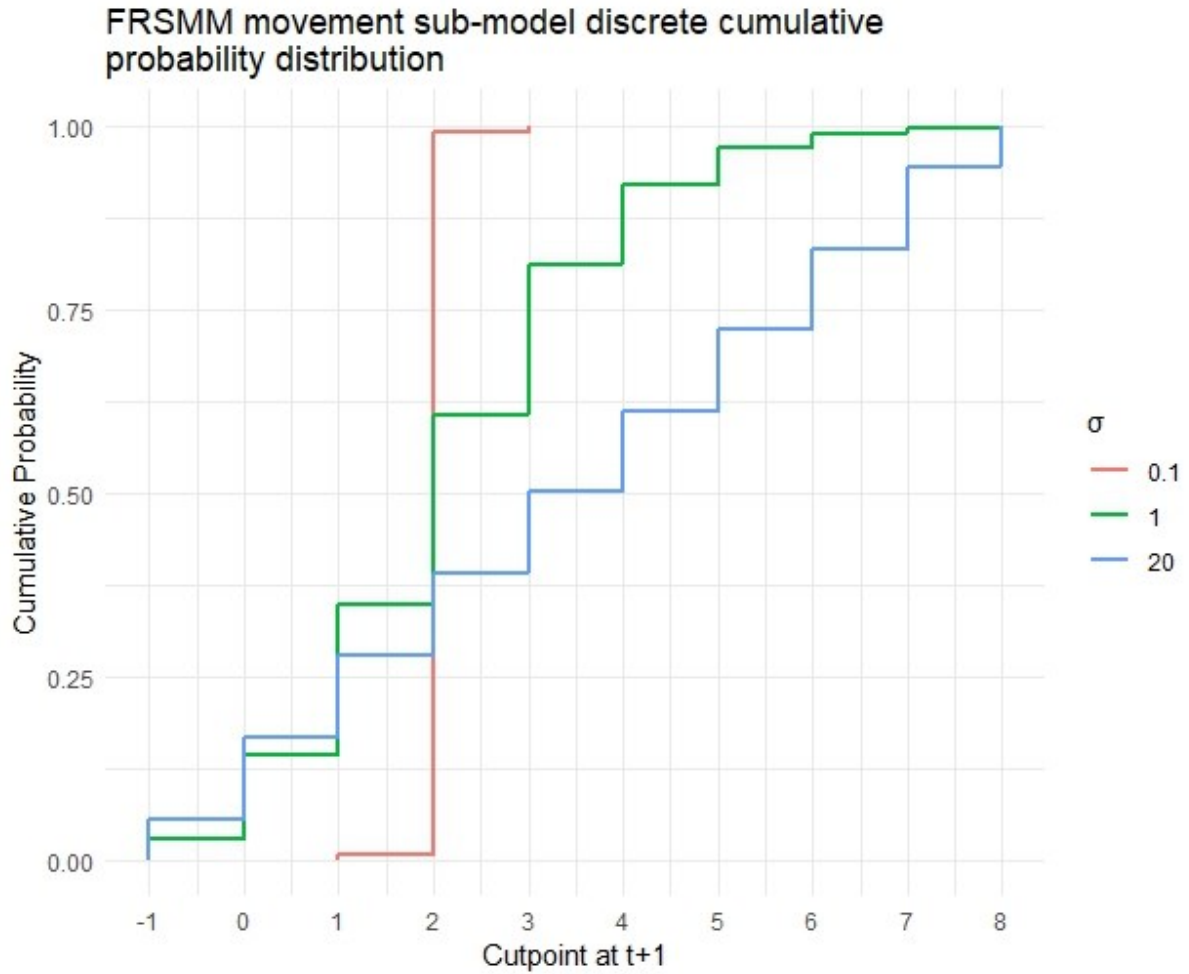


Figure 2 Discrete cumulative transition probability distributions in FRSMM movement sub-model (Equation 2) for different spread parameter values (σ) (Equation 1).

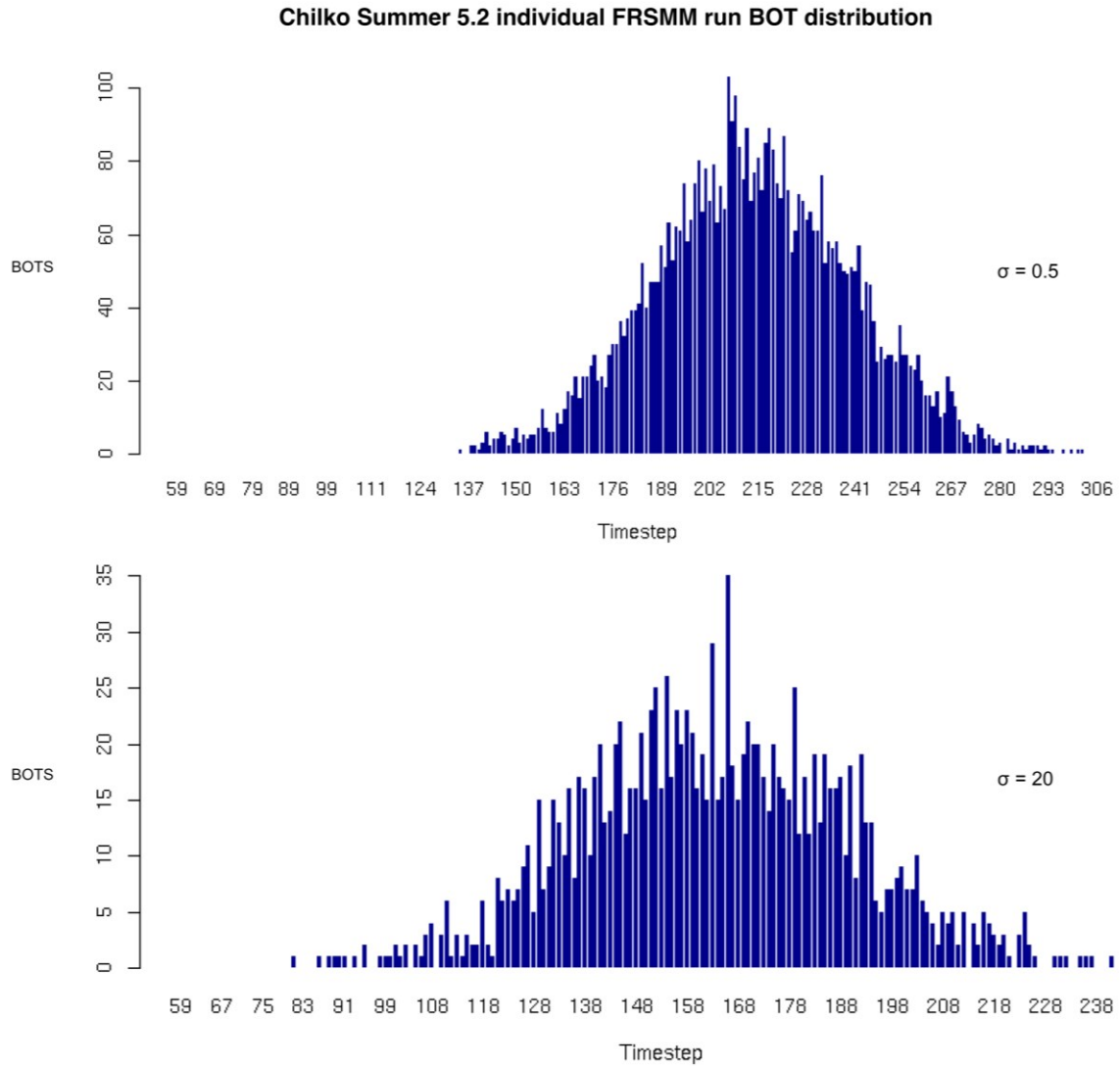


Figure 3 Individual simulation distributions of BOTS in FRSM for Chilko Sumer 5.2 chinook analyzed at their respective terminal reaches under different σ scenarios. The timestep number is on the x-axis and the number of BOTS in each timestep is on the y-axis. Note that over 100 simulations as σ increases, the average migration rate increases, as indicated by an earlier peak in timesteps, and the spread of BOTS should be more broad (Equation 1).

Quesnel Summer 5.2 individual FRSM run BOT distribution

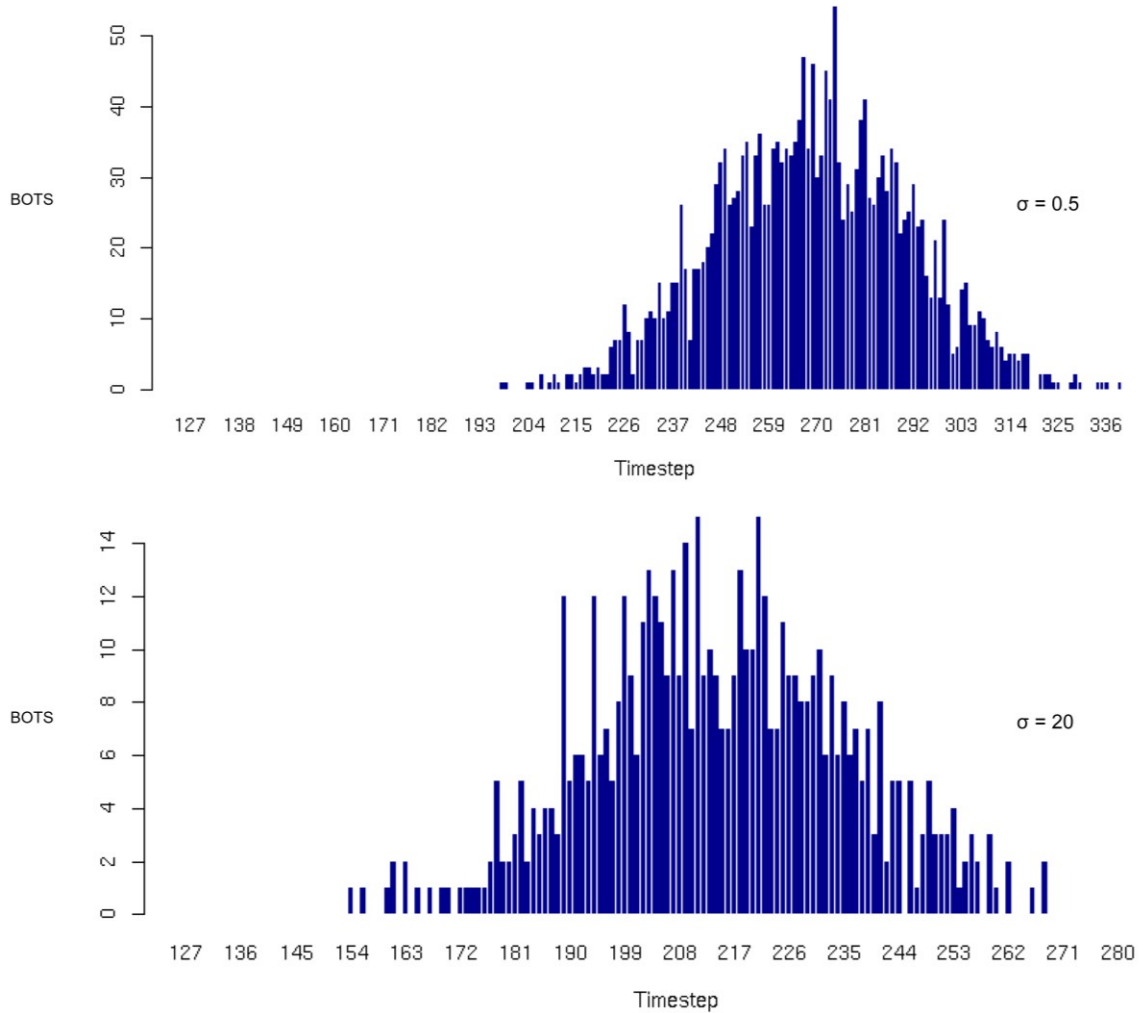


Figure 4 Individual simulation distributions of BOTS in FRSM for Quesnel Summer 5.2 chinook analyzed at their respective terminal reaches under different σ scenarios. The timestep number is on the x-axis and the number of BOTS in each timestep is on the y-axis. Note that over 100 simulations as σ increases, the average migration rate increases, as indicated by an earlier peak in timesteps, and the spread of BOTS is more broad (Equation 1).

South Thompson Summer 4.1 individual FRSM run BOT distribution

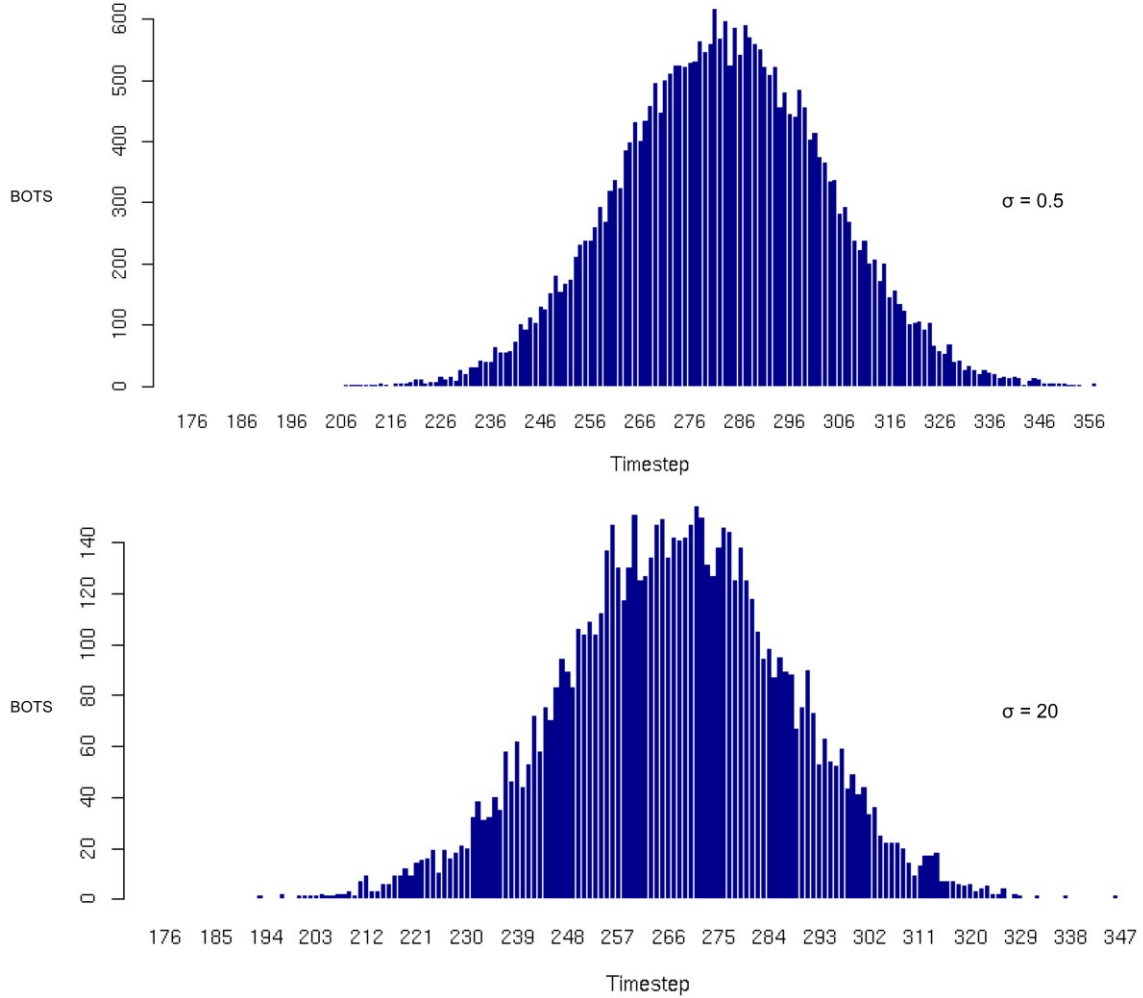


Figure 5 Individual simulation distributions of BOTS in FRSM for South Thompson Summer 4.1 chinook analyzed at their respective terminal reaches under different σ scenarios. The timestep number is on the x-axis and the number of BOTS in each timestep is on the y-axis. Note that over 100 simulations as σ increases, the average migration rate increases, as indicated by an earlier peak in timesteps, and the spread of BOTS is slightly more broad (Equation 1).

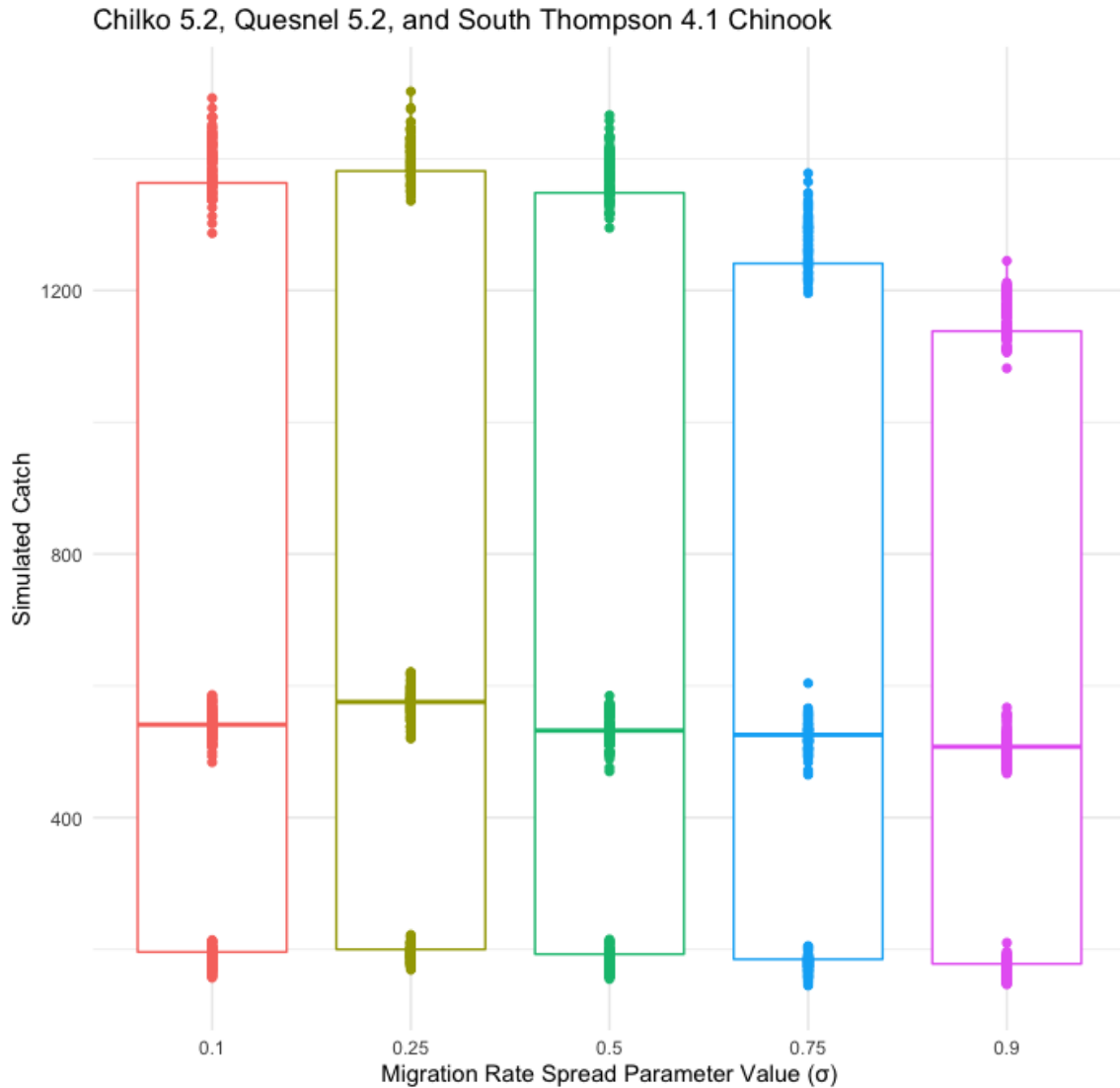


Figure 6 Box plot showing the distribution of simulated catch data for σ values of 0.1 to 0.9 for all stocks combined. The x-axis represents the different values of σ , and the y-axis represents the simulated catch. The box represents the interquartile range (IQR), with the median shown as a horizontal line within the box. The whiskers extend to the furthest observation within 1.5 times the IQR, and any points beyond the whiskers are shown as outliers.

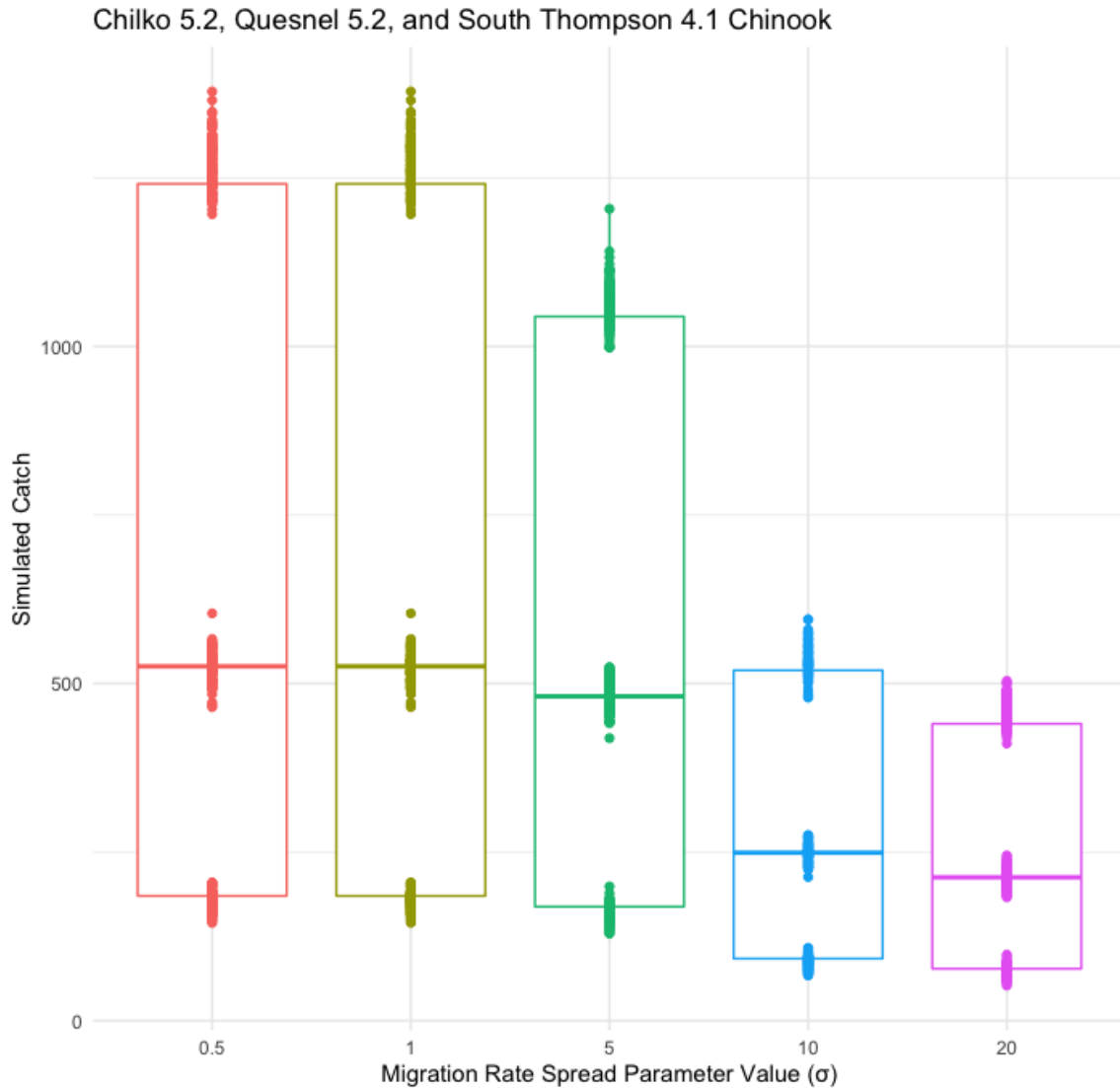


Figure 7 Box plot showing the distribution of simulated catch data for σ values of 0.5 to 20 for all stocks combined. The x-axis represents the different values of σ , and the y-axis represents the simulated catch. The box represents the interquartile range (IQR), with the median shown as a horizontal line within the box. The whiskers extend to the furthest observation within 1.5 times the IQR, and any points beyond the whiskers are shown as outliers.

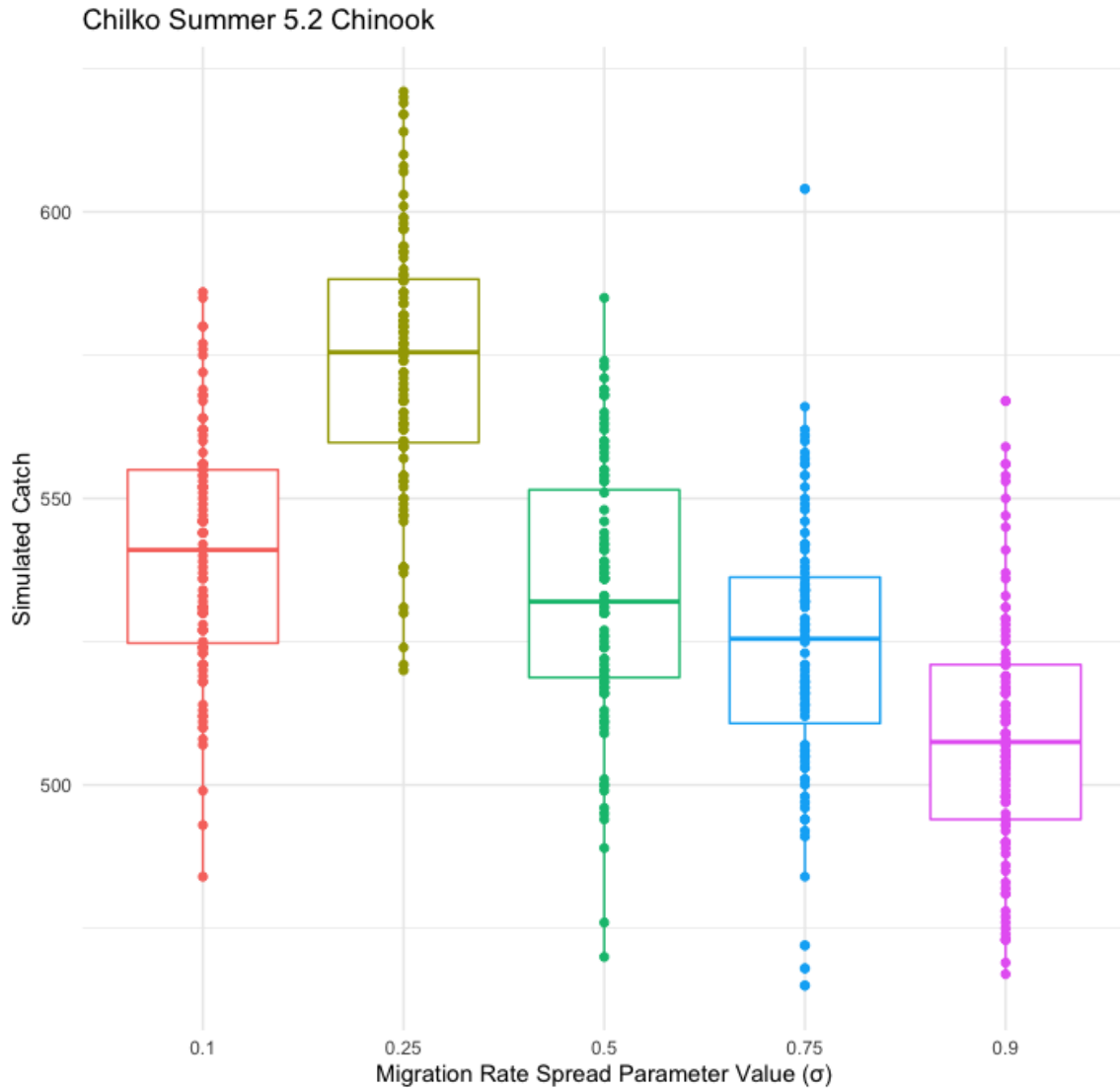


Figure 8 Box plot showing the distribution of simulated catch data for σ values of 0.1 to 0.9 for the Chilko Summer 5.2 stock. The x-axis represents the different values of σ , and the y-axis represents the simulated catch. The box represents the interquartile range (IQR), with the median shown as a horizontal line within the box. The whiskers extend to the furthest observation within 1.5 times the IQR, and any points beyond the whiskers are shown as outliers.

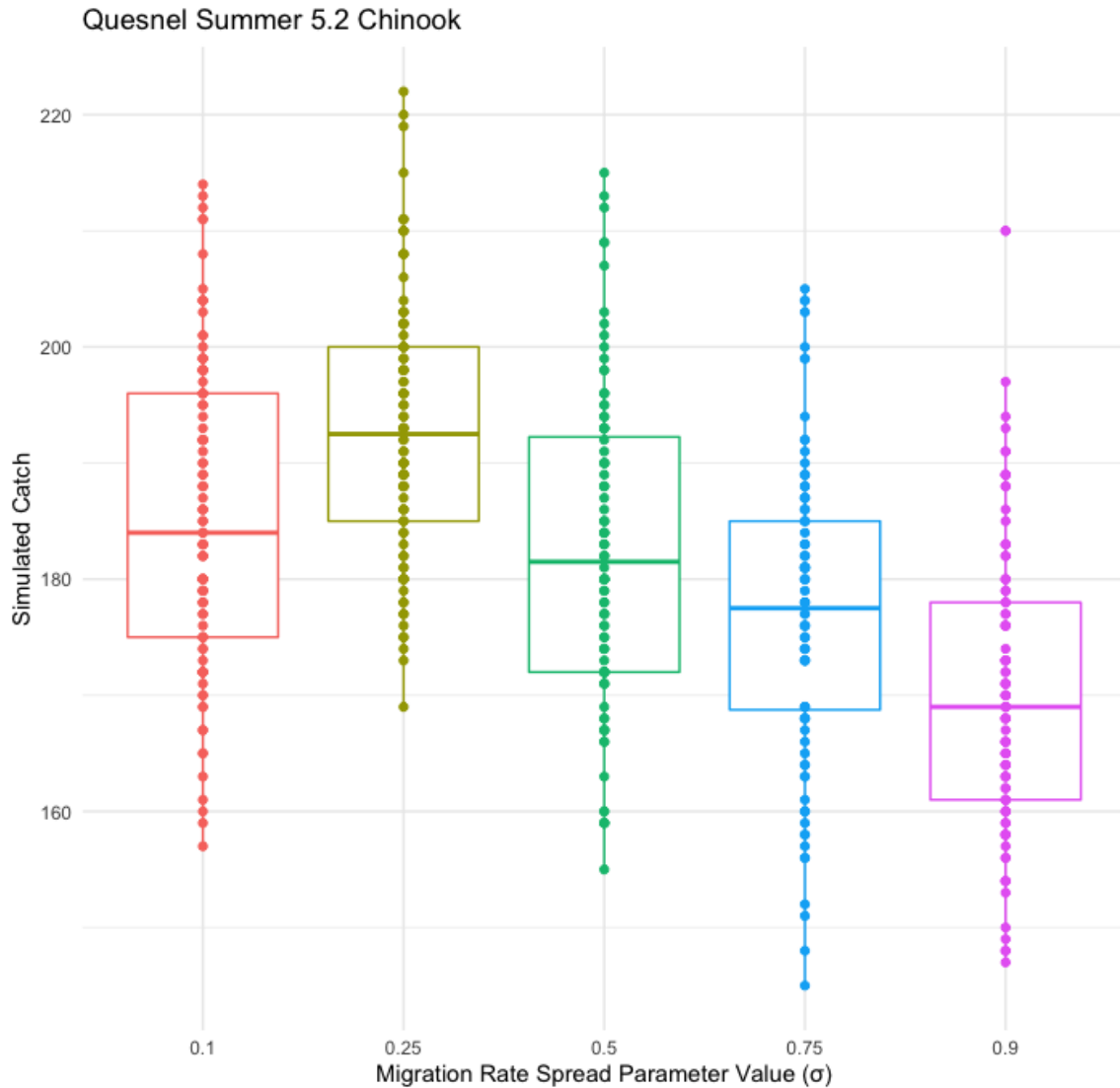


Figure 9 Box plot showing the distribution of simulated catch data for σ values of 0.1 to 0.9 for the Quesnel Summer 5.2 stock. The x-axis represents the different values of σ , and the y-axis represents the simulated catch. The box represents the interquartile range (IQR), with the median shown as a horizontal line within the box. The whiskers extend to the furthest observation within 1.5 times the IQR, and any points beyond the whiskers are shown as outliers.

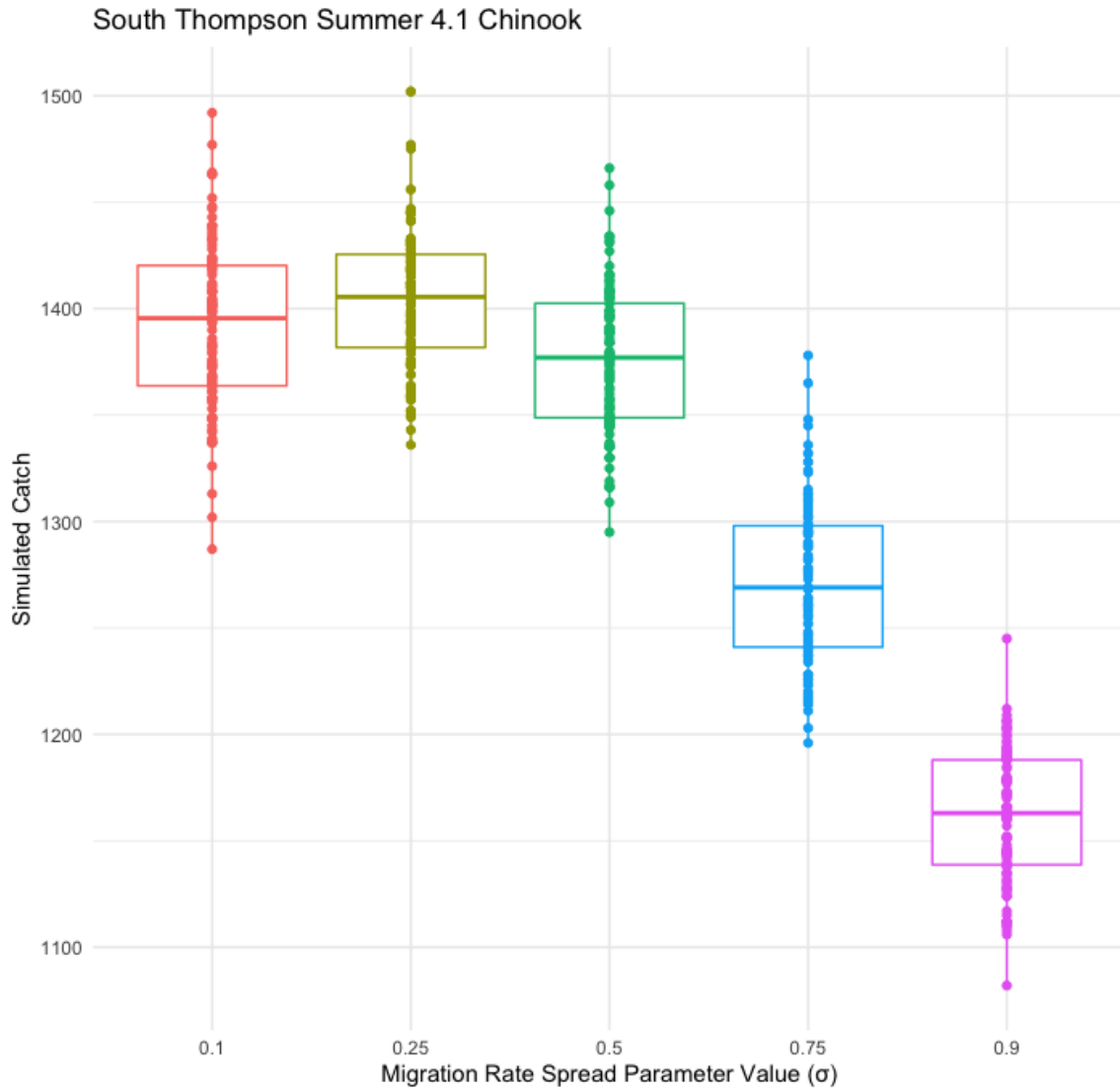


Figure 10 Box plot showing the distribution of simulated catch data for σ values of 0.1 to 0.9 for the South Thompson Summer 4.1 stock. The x-axis represents the different values of σ , and the y-axis represents the simulated catch. The box represents the interquartile range (IQR), with the median shown as a horizontal line within the box. The whiskers extend to the furthest observation within 1.5 times the IQR, and any points beyond the whiskers are shown as outliers.

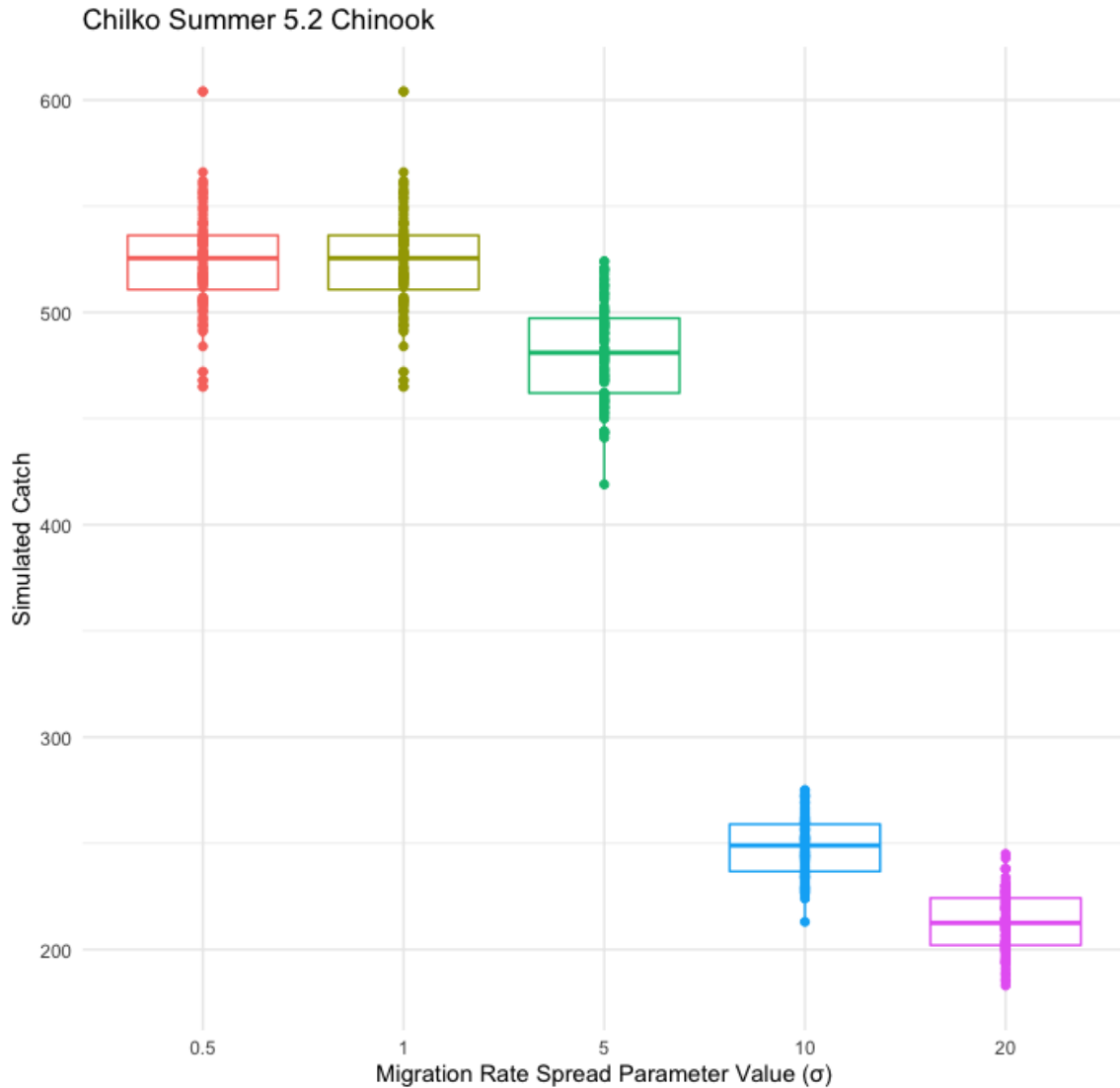


Figure 11 Box plot showing the distribution of simulated catch data for σ values of 0.5 to 20 for the Chilko Summer 5.2 stock. The x-axis represents the different values of σ , and the y-axis represents the simulated catch. The box represents the interquartile range (IQR), with the median shown as a horizontal line within the box. The whiskers extend to the furthest observation within 1.5 times the IQR, and any points beyond the whiskers are shown as outliers.

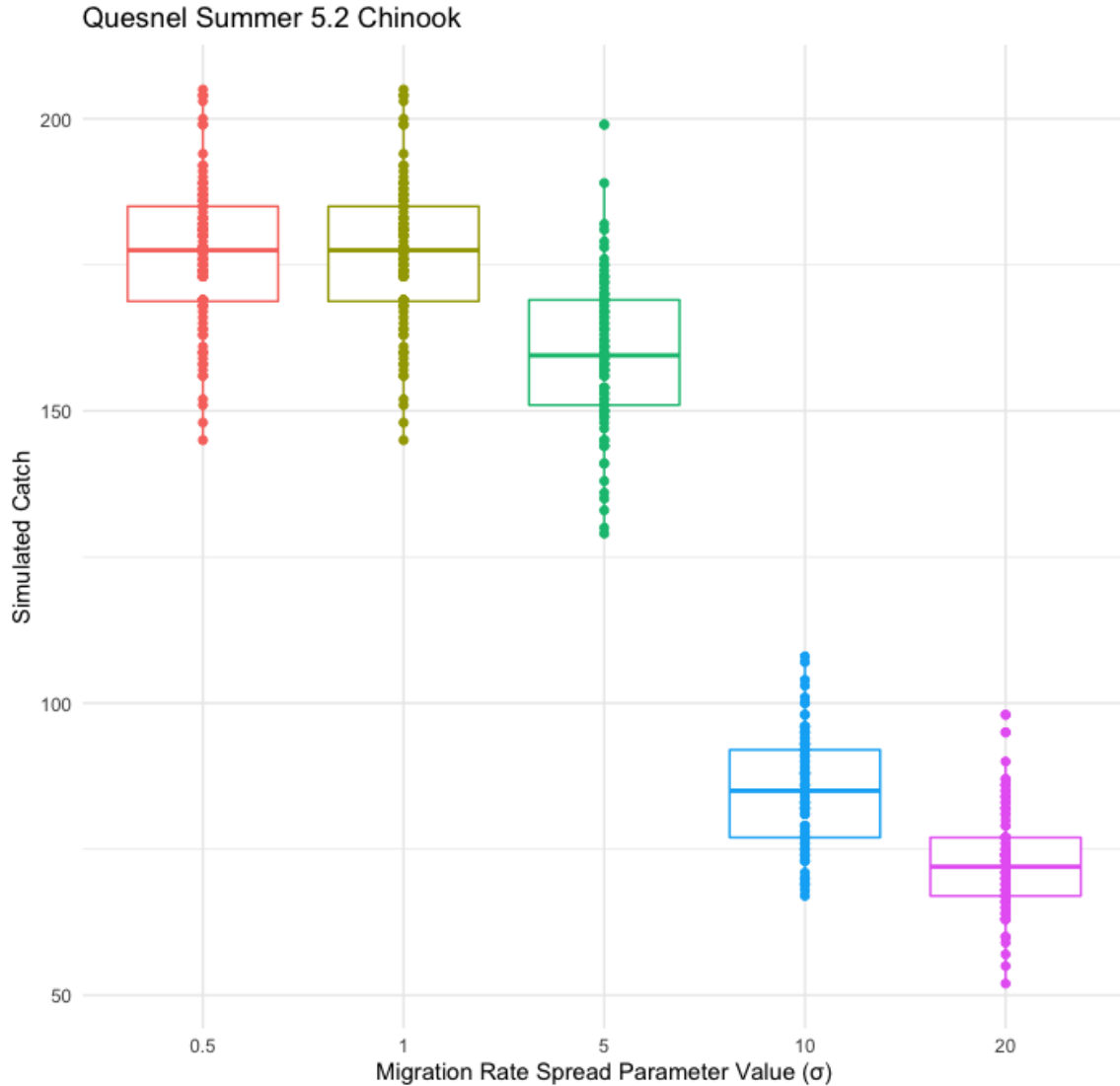


Figure 12 Box plot showing the distribution of simulated catch data for σ values of 0.5 to 20 for the Quesnel Summer 5.2 stock. The x-axis represents the different values of σ , and the y-axis represents the simulated catch. The box represents the interquartile range (IQR), with the median shown as a horizontal line within the box. The whiskers extend to the furthest observation within 1.5 times the IQR, and any points beyond the whiskers are shown as outliers.

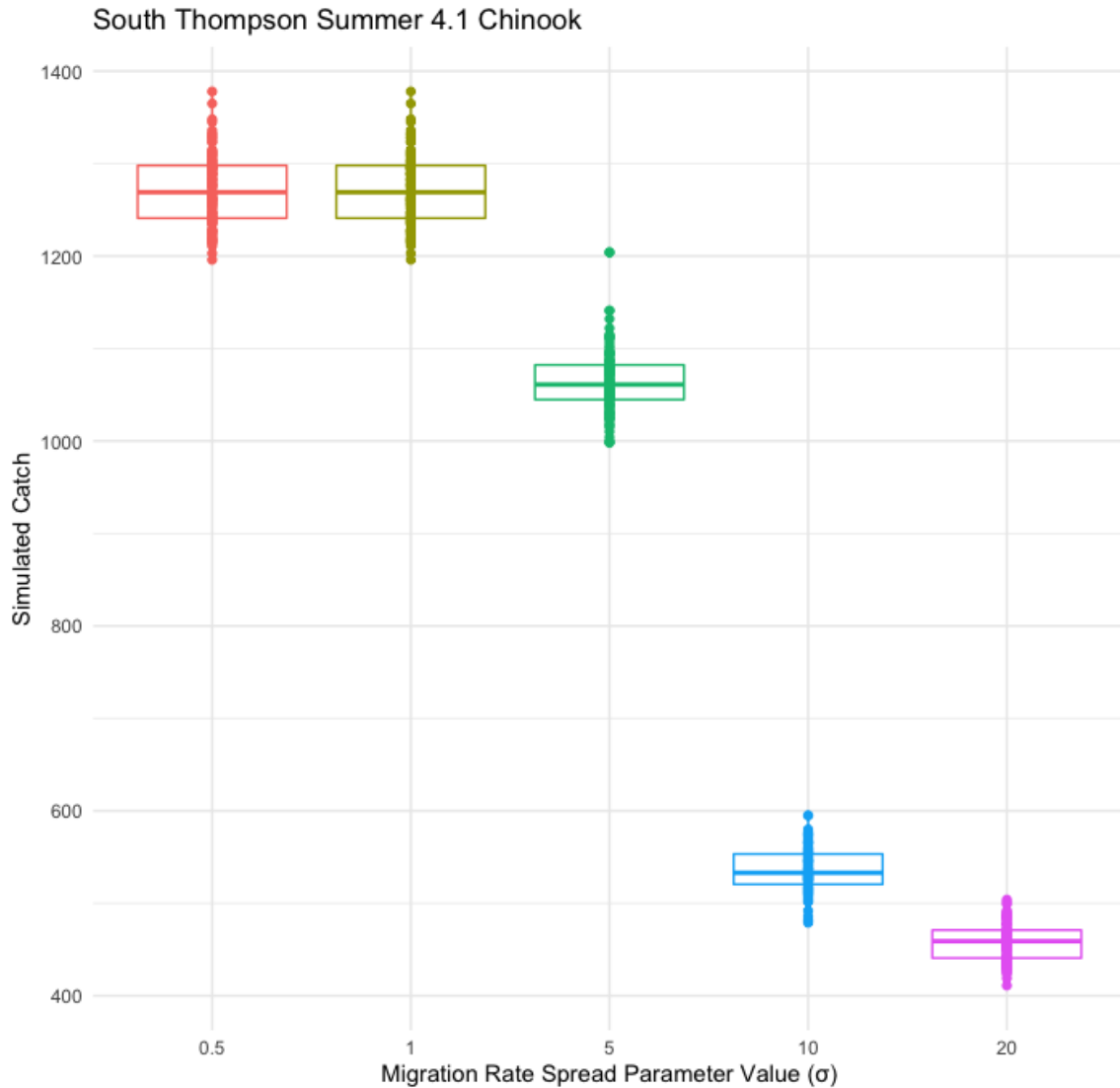


Figure 13 Box plot showing the distribution of simulated catch data for σ values of 0.5 to 20 for the South Thompson Summer 4.1 stock. The x-axis represents the different values of σ , and the y-axis represents the simulated catch. The box represents the interquartile range (IQR), with the median shown as a horizontal line within the box. The whiskers extend to the furthest observation within 1.5 times the IQR, and any points beyond the whiskers are shown as outliers.

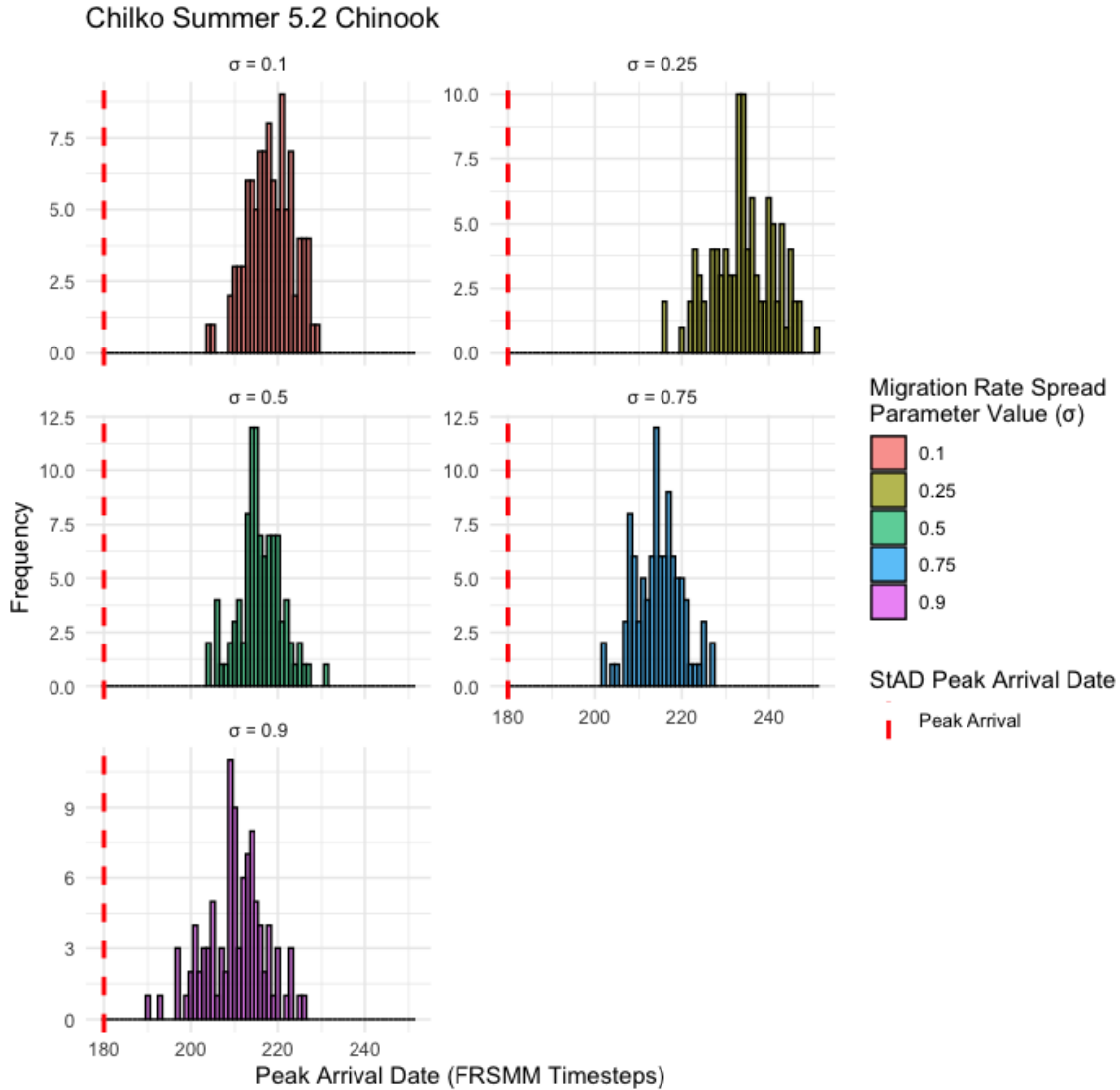


Figure 14 Histogram illustrating the distribution of simulated peak spawning ground arrival timesteps resulting from FRSMM sensitivity analysis with σ values ranging from 0.1 to 0.9 for the Chilko Summer 5.2 stock. The x-axis denotes the peak arrival timestep in FRSMM, while the y-axis represents the frequency of occurrence for each timestep. The plot is faceted by the value of σ , displaying separate histograms for each level of the migration rate spread parameter. The dashed red vertical line is the peak spawning ground arrival time from DFO Stock Assessment's (StAD) Chinook Run Reconstruction Model for the year 2012, which is FRSMM timestep 181 or Aug. 30.

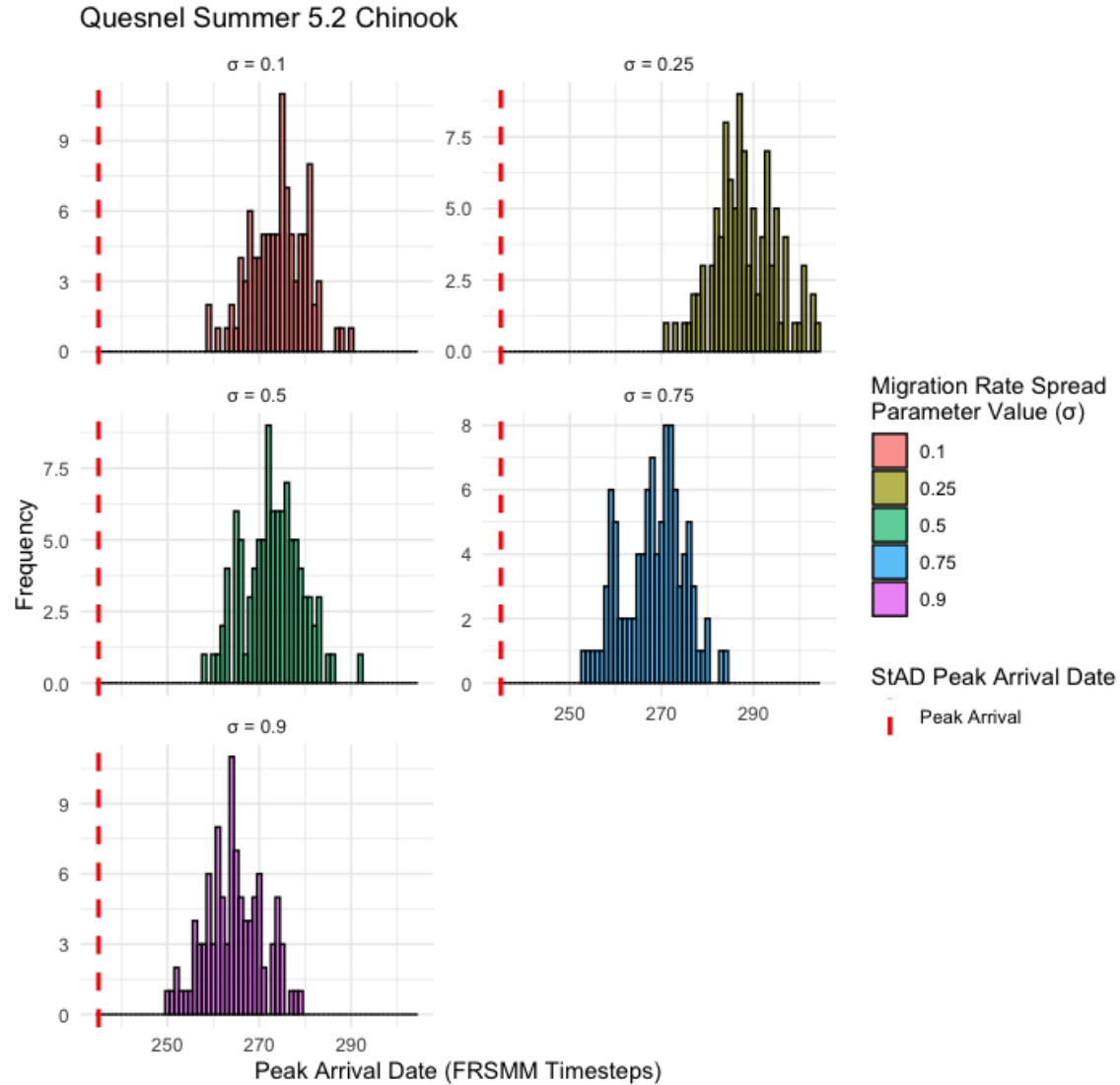


Figure 15 Histogram illustrating the distribution of simulated peak spawning ground arrival timesteps resulting from FRSMM sensitivity analysis with σ values ranging from 0.1 to 0.9 for the Quesnel Summer 5.2 stock. The x-axis denotes the peak arrival timestep in FRSMM, while the y-axis represents the frequency of occurrence for each timestep. The plot is faceted by the value of σ , displaying separate histograms for each level of the migration rate spread parameter. The dashed red vertical line is the peak spawning ground arrival time from DFO Stock Assessment's (StAD) Chinook Run Reconstruction Model for the year 2012, which is FRSMM timestep 235 or Sep. 26.

South Thompson Summer 4.1 Chinook

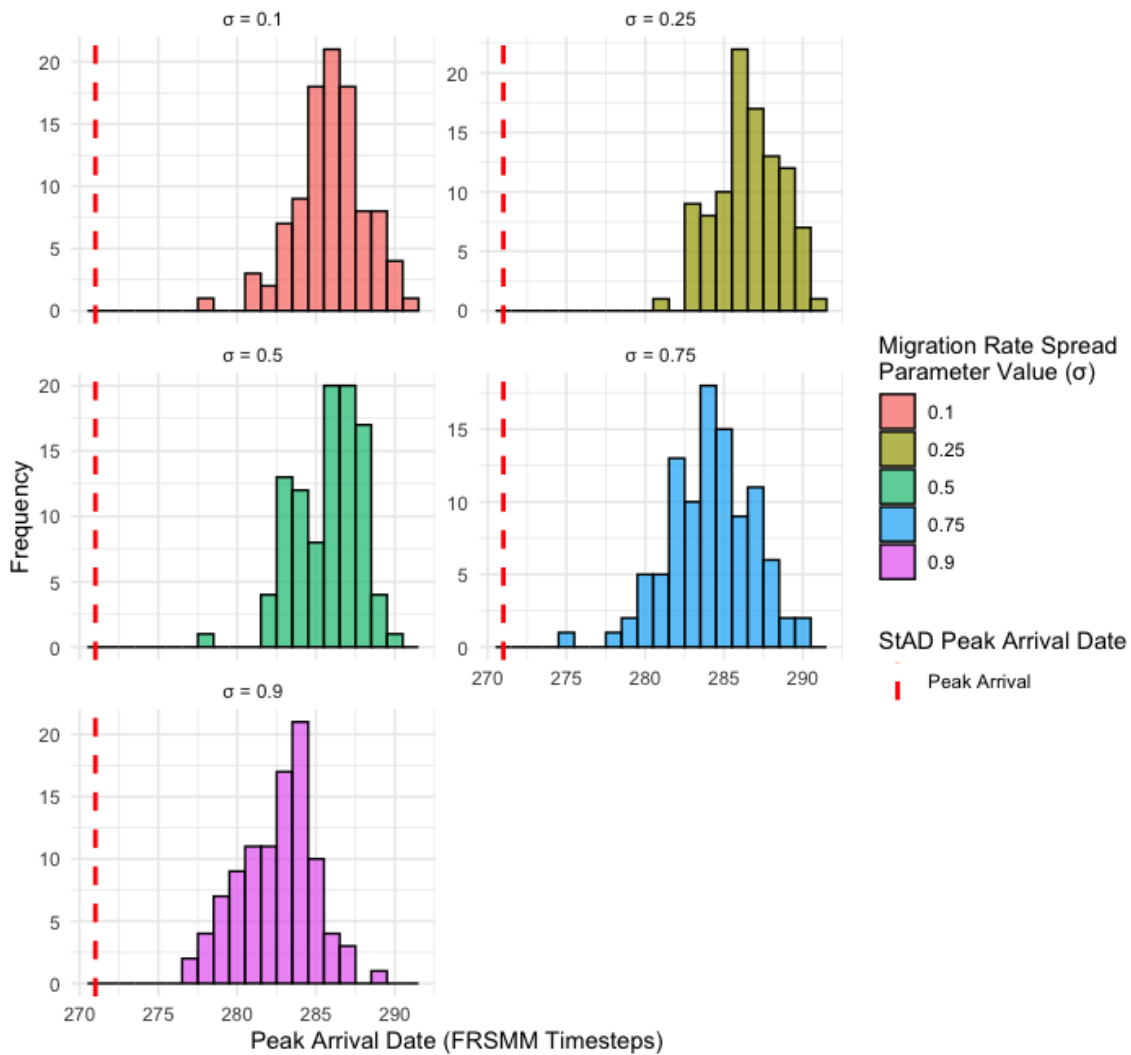


Figure 16 Histogram illustrating the distribution of simulated peak spawning ground arrival timesteps resulting from FRSMM sensitivity analysis with σ values ranging from 0.1 to 0.9 for the South Thompson Summer 4.1 stock. The x-axis denotes the peak arrival timestep in FRSMM, while the y-axis represents the frequency of occurrence for each timestep. The plot is faceted by the value of σ , displaying separate histograms for each level of the migration rate spread parameter. The dashed red vertical line is the peak spawning ground arrival time from DFO Stock Assessment's (StAD) Chinook Run Reconstruction Model for the year 2012, which is FRSMM timestep 271 or Oct. 14.

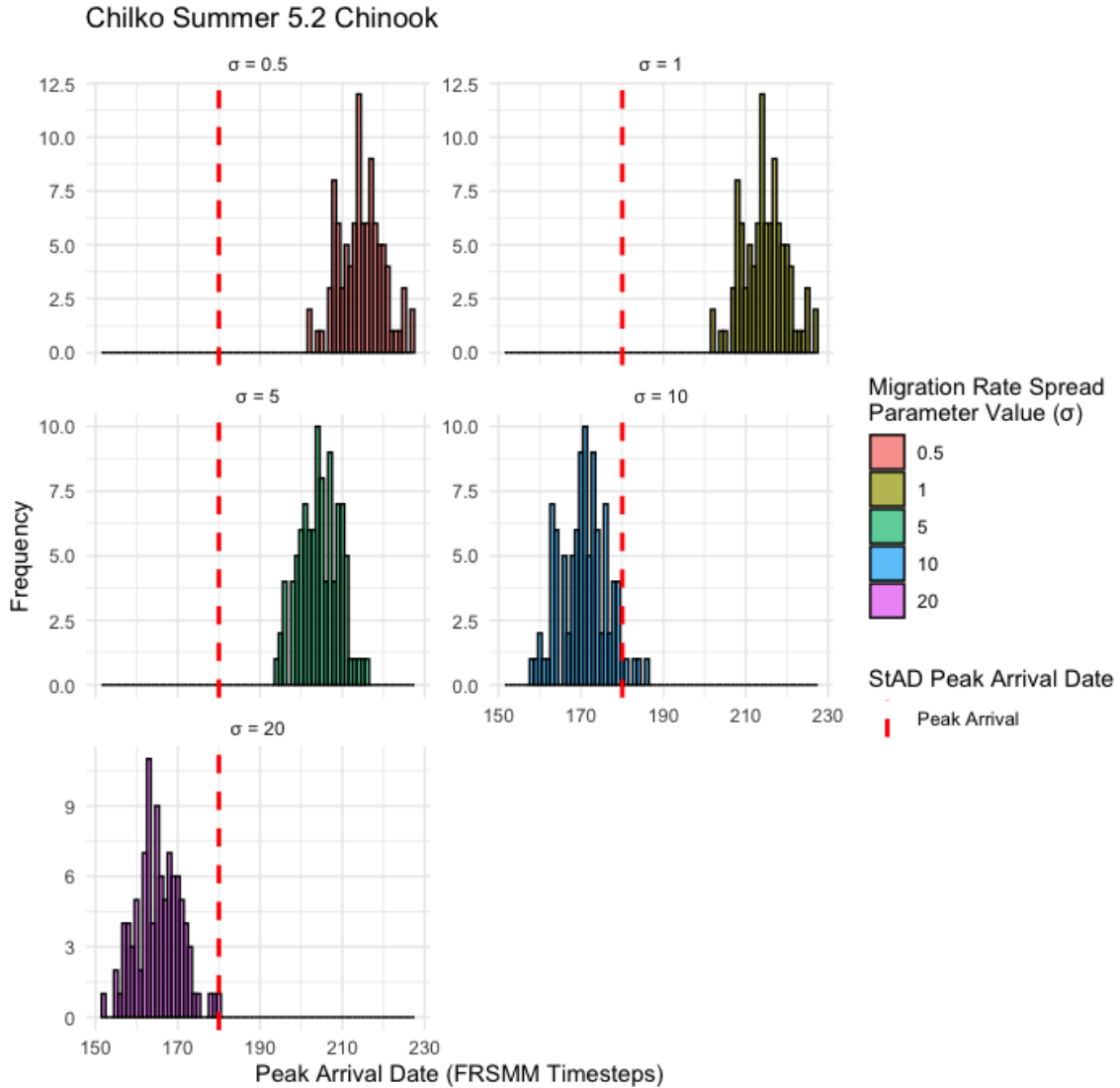


Figure 17 Histogram illustrating the distribution of simulated peak spawning ground arrival timesteps resulting from FRSMM sensitivity analysis with σ values ranging from 0.5 to 20 for the Chilko Summer 5.2 stock. The x-axis denotes the peak arrival timestep in FRSMM, while the y-axis represents the frequency of occurrence for each timestep. The plot is faceted by the value of σ , displaying separate histograms for each level of the migration rate spread parameter. The dashed red vertical line is the peak spawning ground arrival time from DFO Stock Assessment’s (StAD) Chinook Run Reconstruction Model for the year 2012, which is FRSMM timestep 181 or Aug. 30.

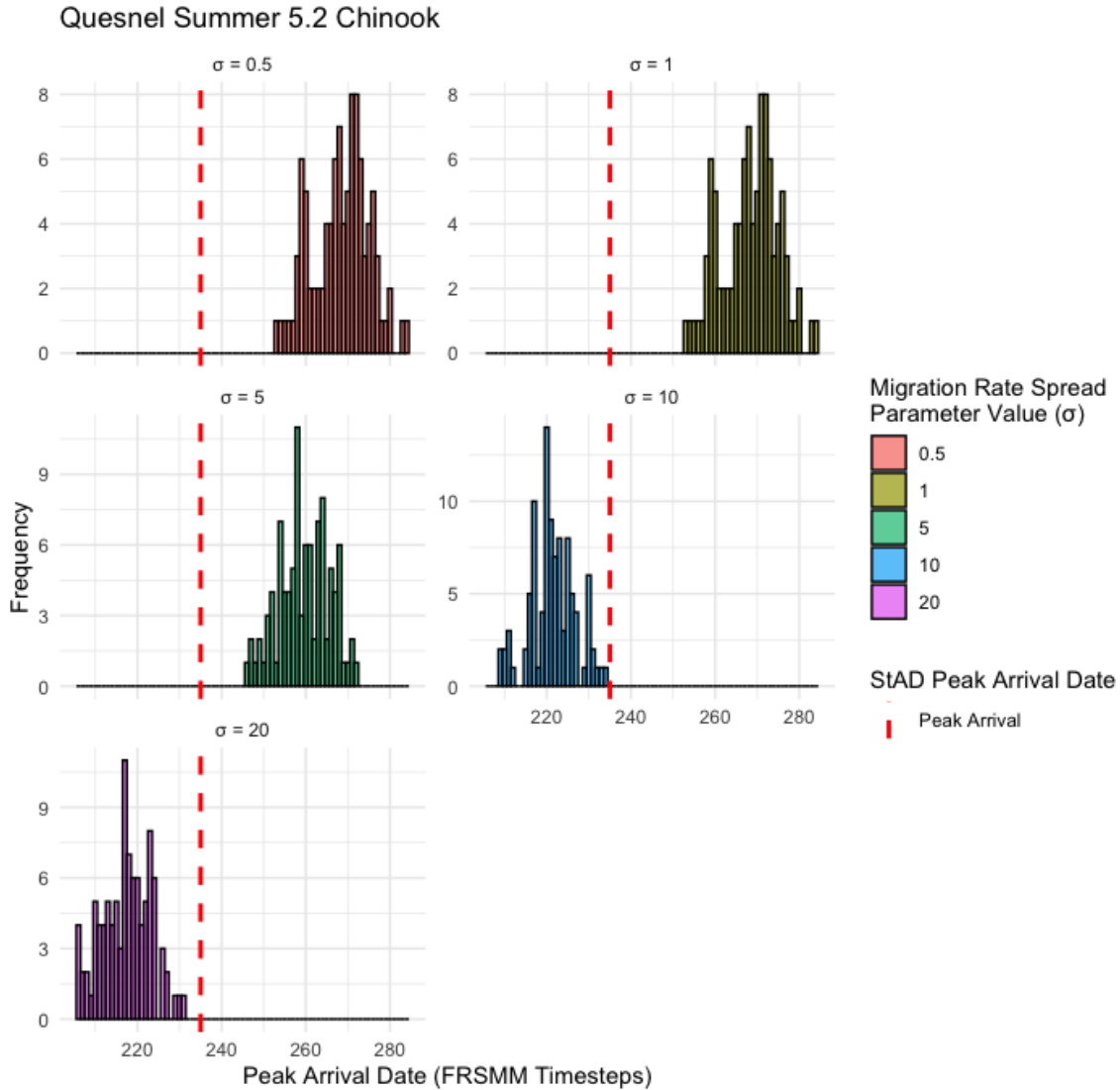


Figure 18 Histogram illustrating the distribution of simulated peak spawning ground arrival timesteps resulting from FRSMM sensitivity analysis with σ values ranging from 0.5 to 20 for the Quesnel Summer 5.2 stock. The x-axis denotes the peak arrival timestep in FRSMM, while the y-axis represents the frequency of occurrence for each timestep. The plot is faceted by the value of σ , displaying separate histograms for each level of the migration rate spread parameter. The dashed red vertical line is the peak spawning ground arrival time from DFO Stock Assessment's (StAD) Chinook Run Reconstruction Model for the year 2012, which is FRSMM timestep 235 or Sep. 26.

South Thompson Summer 4.1 Chinook

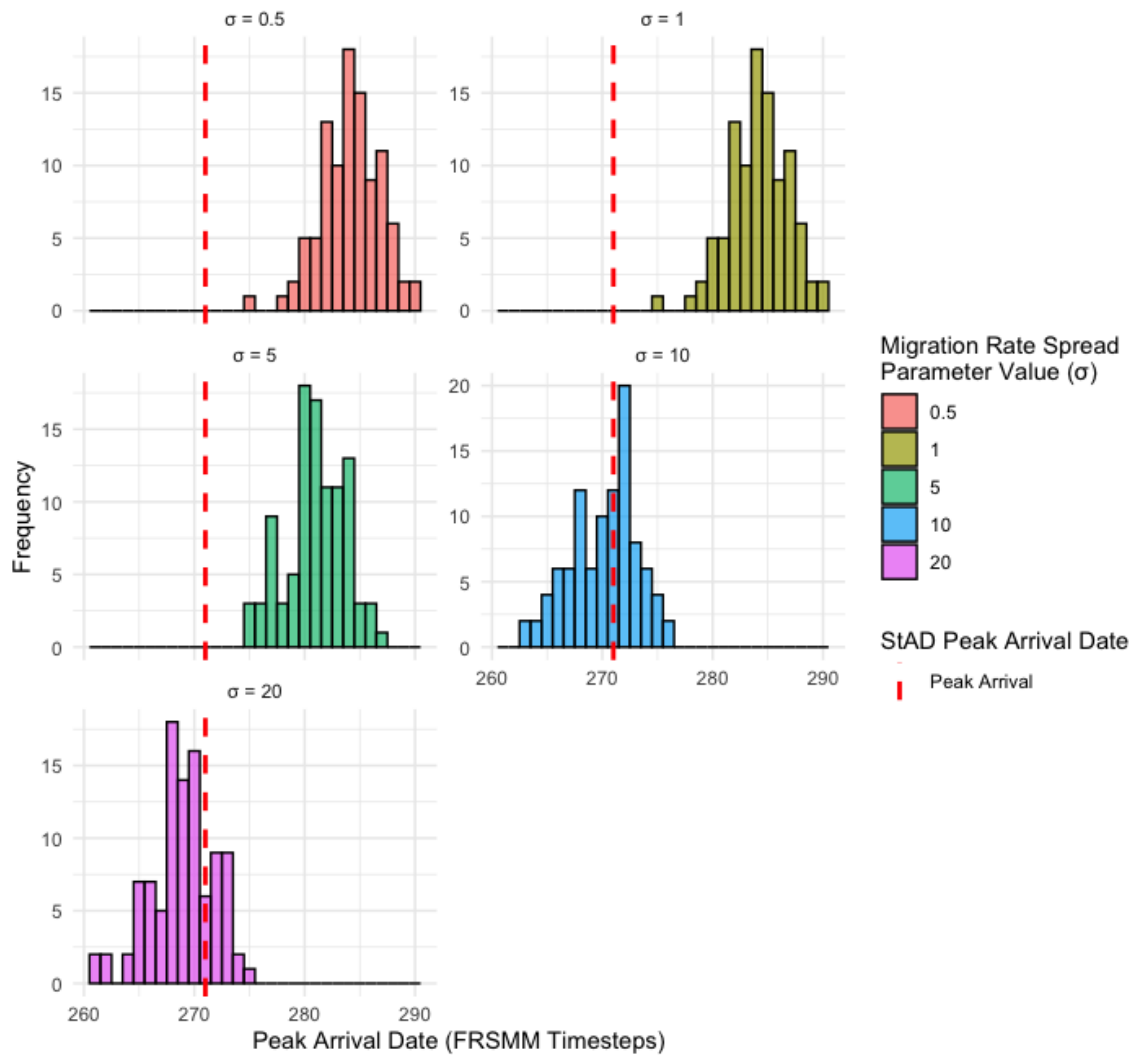


Figure 19 Histogram illustrating the distribution of simulated peak spawning ground arrival timesteps resulting from FRSMM sensitivity analysis with σ values ranging from 0.1 to 0.9 for the South Thompson Summer 4.1 stock. The x-axis denotes the peak arrival timestep in FRSMM, while the y-axis represents the frequency of occurrence for each timestep. The plot is faceted by the value of σ , displaying separate histograms for each level of the migration rate spread parameter. The dashed red vertical line is the peak spawning ground arrival time from DFO Stock Assessment’s (StAD) Chinook Run Reconstruction Model for the year 2012, which is FRSMM timestep 271 or Oct. 14.

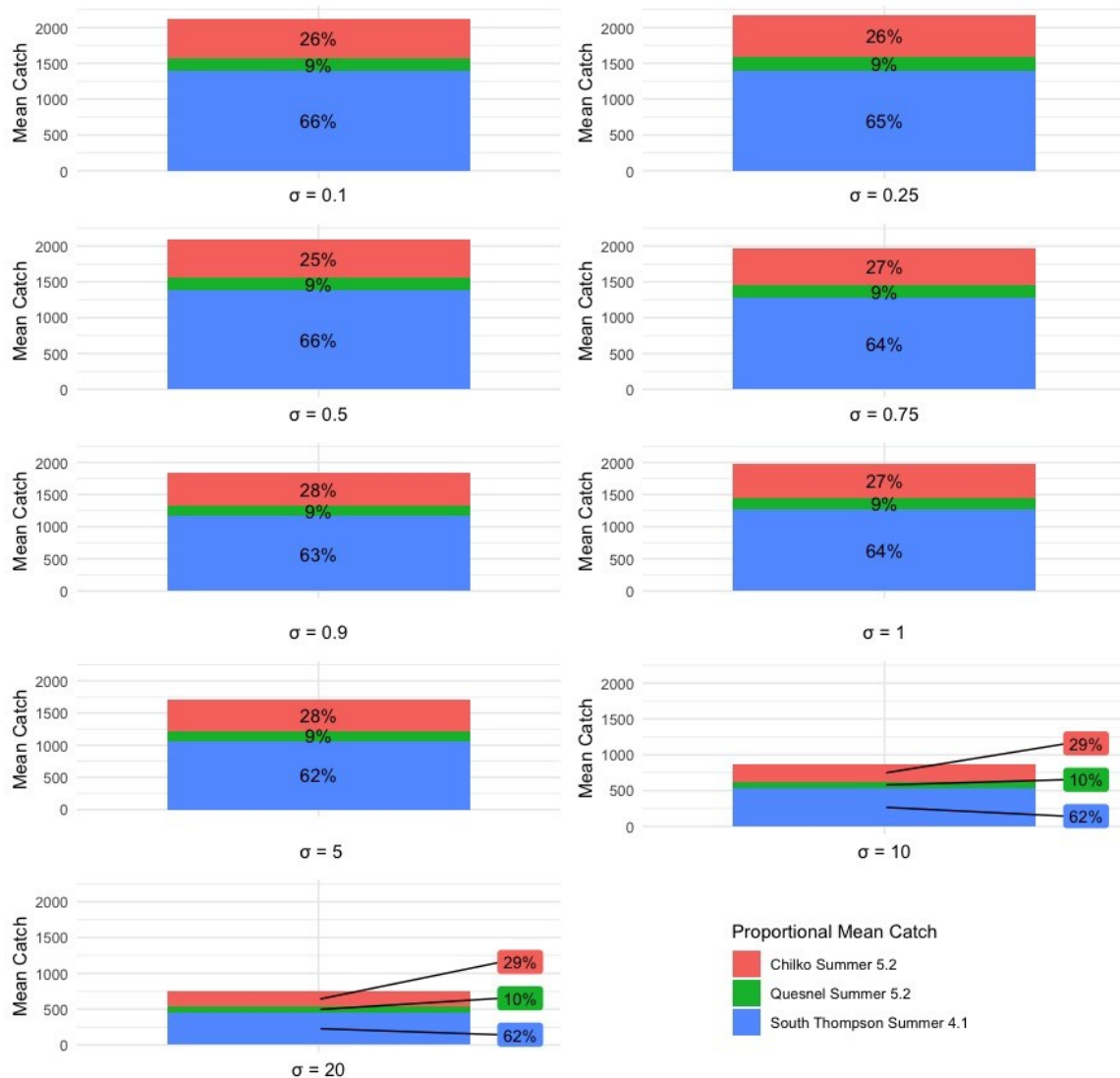


Figure 20 Bar plot showing the mean proportional catch values for each σ value used in the ANCOVA analysis and the percentage each stock constitutes in the overall mean catch. The x-axis represents the different values of σ , and the y-axis represents the proportional mean catch.

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