Challenges and Tools in the Assessment and Management of Pacific Salmon Fisheries

by

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Abstract

I'm going to write an abstract to go here. This paragraph will be a brief introduction chapter 1: the overall topic of the research

This is the second paragraph of the dissertation abstract, which will talk broadly about chapter 2: run timing forecast models.

This is the second paragraph of the dissertation abstract, which will talk broadly about chapter 3: in-season MSE models.

This is the third paragraph of the dissertation abstract, which will talk broadly about chapter 4: multi-stock population dynamics models and the best ways to inform management trade-offs.

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Table of Contents

List of Figures

List of Tables

Chapter 1

Evaluation of Intra-Annual Harvest Control Rules via Closed-Loop Simulation

1.1 Introduction

Here's chapter 3. It's about in-season simulation models for management strategy evaluations.

1.2 Methods

I did some stuff.

1.3 Results

I found some stuff.

1.4 Discussion

Here's what it means.

#	Equation	Purpose/Description
1	$N_s = N_{tot}\pi_s$	Apportions total Chinook run size to subpopulations
2	$p'_{d,s} = \frac{e^{\frac{d-D_{50,s}}{h_s}}}{h_s\left(1+e^{\frac{d-D_{50,s}}{h_s}}\right)^2}$	Produces a time series of unstandardized entry timing values (logistic density function)
3	$p_{d,s} = \frac{p'_{d,s}}{\sum_d p'_{d,s}}$	Standardizes entry timing to sum to one for each Chinook subpopulation
4	$A_{d,1,s} = N_s p_{d,s}$	Populates first main stem reach with Chinook from each subpopulation
5	$A_{d,1,4} = \phi_d \sum_{s=1}^{3} A_{d,1,s}$	Populates first reach with chum/sockeye main stem abundance
6	$S_{d,r,s} = \psi_{r,s} \cdot (A_{d,r,s} - H_{d,r,s})$	Generates escapement in each reach on each day from each population
7	$A_{d+1,r+1,s} = A_{d,r,s} - H_{d,r,s} - S_{d,r,s}$	Transition main stem survivors to the next reach on the next day
8	$\text{logit}(p_{E,d,r}) = \beta_0 + \beta_1 full_{d,r} + \beta_2 stop_{d,r} + \beta_3\delta_{d-1,r,CH} + \beta_4\delta_{d-1,r,CS} + \beta + 5\phi_{d,r}$	Effort response model; $full$ and $stop$ are binary indicators; δ is the fraction of needed harvest obtained for Chinook (CH) and chum/sockeye (CS), and ϕ is the local species ratio
9	$E_{d,r}p_{E,d,r}F_{d,r}$	Generates realized effort in each reach on each day
10	$H_{tot,d,r} = \min\left(1 - e^{-E_{d,r}q}\sum_{s=1}^{4} A_{d,r,s}, E_{d,r}F_{d,r}CPB_{max}\right)$	Generates total salmon harvest by reach and day

Insert Figures

Appendix A

Parameterization of the Operating Model in Chapter 1

There were two main components of the operating model that needed to be parameterized based on observed information for it to adequately represent the dynamics of the real Kuskokwim River subsistence salmon fishery:

(1) *Biological*: abundance, timing, spatial characteristics of the salmon populations (three Chinook salmon substocks and one aggregate stock of chum and sockeye salmon) and

(2) *Sociological*: spatial distribution of effort and desired/needed harvest and temporal aspects of the effort dynamics.

This appendix describes how empirical information collected in the Kuskokwim River drainage was used to parameterize the operating model used in the Chapter 1 analysis.

A.1 Biological quantities

A.1.1 Chinook salmon total abundance

Drainage-wide total Chinook salmon run abundance was informed by Liller et al. (2018), which reported estimates in the years 1976 – 2017 from a maximum likelihood run reconstruction model. The model was fitted to 20 escapement indices, commercial fishery catch-per-unit-effort, and nine years of drainage-wide estimates of total abundance obtained *via* large-scale mark-recapture experiments. Based on Liller et al. (2018), drainage-wide Chinook salmon abundance has varied between 79,238 (in 2012) and 411,724 (in 1994), with a mean of 216,929 and standard deviation of 87,556. A kernel density estimator was fitted to this distribution, and the cumulative density function was obtained to allow sampling of continuous run sizes in accordance with the historical frequency of run sizes (Figure A.1). The distribution was truncated at the smallest and largest runs on record as of 2017 $\pm$ 30,000 fish.

A.1.2 Chinook salmon run timing

A.1.2.1 Aggregate timing

Run timing information for the aggregate Chinook salmon stock was available from the Bethel Test Fishery (Bue and Lipka 2016), which has produced a daily value of catch-per-unit-effort for each day between June 1 and August 24 for the years 1984 – 2018. The estimates of location (D_{50}) and inverse scale (h) of a logistic function shown in Table **??** were used to quantify the timing with which the simulated aggregate Chinook salmon stock runs through the lower river.

A.1.2.2 Substock-specific timing

The timing of the specific Chinook salmon substocks (i.e., those spawning in lower, middle, and upper river tributaries) were informed by radio telemetry studies (Stuby 2007; Smith and Liller 2017). The tag date and final tributary of each fish was available for the years 2003 – 2007 and 2015 – 2016. In the first block of years, the tagging site was located near Kalskag, which excluded any fish spawning in lower river tributaries. In the second block of years, the tag site was moved near the Johnson River, which allowed the inclusion of fish spawning in the lower river tributaries. Logistic models (**??**) were fitted to the data from each substock and year separately to obtain estimates of the D_{50} for each substock in each year data were available, and differences in D_{50} for the middle river substocks and each of the other substocks were calculated (Table A.1). For parameterizing the run timing of middle river substocks, random values drawn from the aggregate population estimates were used, and random uniform deviations for the lower river and upper river D_{50} were used in accordance with the deviations shown in Table A.1 (i.e., lower river substocks had a D_{50} value that was anywhere between 0 and 3 days later than that of the middle river, and upper river substocks had a value that was between 5 and 10 days earlier than middle river substocks.

A.1.3 Chinook salmon substock composition

Substock composition, or the fraction of the aggregate Chinook salmon run that was made up of fish from each substock, was informed by the proportions of telemetry fish that spawned in each region in the years 2015 and 2016. Only these years were used because

(1) they allowed the incorporation of information from lower river fish and

(2) the management of the fishery resulted in less selection of upper river substocks in the harvest because fishing was pushed later in the season than in the 2003 – 2007 block of years.

In each run of the operating model, a random Dirichlet vector was drawn with parameter vector equal to [lower = 20, middle = 58, upper = 22], which results in an expectation roughly equal to the average contribution in 2015 and 2016. The use of a Dirichlet distribution with these parameters generated a modest amount of variability around the expected substock composition.

A.1.4 Spatial distribution of escapement

Due to the spatial nature of the operating model, it was important to capture the behavior of fish becoming invulnerable to harvest by swimming up a spawning tributary. This aspect was informed using data from the telemetry studies: it was possible to quantify the fraction of all tagged fish that made it to a particular reach that ultimately spawned in a tributary with a confluence in that reach in each year. These fractions were averaged across years and the average was used to dictate how many fish from each substock s in reach r on day d would "peel off" from the mainstem into a tributary in that reach on that day. For the aggregate chum/sockeye stock, which does not have this kind of information, the substock structure was removed. These estimates are shown in Table A.2.

A.1.5 Species ratios

Because chum and sockeye salmon lack the abundance data available for Chinook salmon, their daily entry dynamics were modeled using observed species ratios from the Bethel Test Fishery. These data were prepared by taking the catch-per-unit-effort of chum salmon plus sockeye salmon, and dividing it by the catch-per-unit-effort of Chinook salmon on each day of each year for which data were available (assuming the subsistence fishery uses the same gill net mesh sizes as the Bethel Test Fishery, which is a largely valid assumption in recent years). This represents how many vulnerable chum/sockeye salmon were available for harvest relative to Chinook salmon. Daily values that couldn't be calculated (i.e., when zero Chinook salmon were caught) were populated with the average value for all years for which a species ratio could be calculated on that same day. These annual time series were highly variable from day to day, likely as a result of sampling variability, so a cubic spline smoother was fitted to remove this variability. The time series of smoothed ratios from all years is shown in Figure A.2.

A.2 Sociological quantities

A.2.1 Needed salmon harvest by river reach

The term “minimally needed salmon harvest” salmon harvest refers to the amount of salmon that would satisfy the very basics of the subsistence needs of fishers in the drainage – without meeting this level it is reasonable to assume the fishing population is experiencing hardship. “Maximally needed salmon harvest” represents the salmon harvest that would completely meet their needs (i.e., if they could harvest as many fish as they would like). The Alaska Board of Fisheries has produced ranges for each species, termed the “Amounts Reasonably Necessary for Subsistence”" (ANS) and represents the drainage-wide range of harvest by species needed to sustain subsistence fishers each year. These ANS ranges are 67,200 – 109,800 for Chinook salmon and 73,400 – 175,100 for chum/sockeye salmon. In this analysis, the lower bound of the ANS range was used to specify minimally needed salmon harvest by species, and the upper bound of the range was used to specify maximally needed salmon harvests. Minimal harvest needs were used to measure the attainment of management objectives and maximally needed amounts were used to drive the dynamics of the effort model.

However, these values are only available for the entire drainage – they are not partitioned to individual villages. For this analysis, a minimal and maximal value was needed for the villages located within each reach. The drainage-wide totals were thus partitioned by calculating the average fraction that villages in each reach have harvested of the drainage-wide. Hamazaki (2011) present year-, species- and village-specific salmon harvests for the period (1990 – 2009), and data through 2015 can be found in Carroll and Hamazaki (2012), Shelden et al. (2014), Shelden et al. (2015), Shelden et al. (2016a), and Shelden et al. (2016b). Only years 1990 – 2000 were included for the spatial distribution of salmon need because stakeholders indicated the restrictions in recent years make the harvest proportions non-representative and that the earlier years are more reflective of how harvest should be distributed. The partitioned values by species are shown in Table A.3.

A.2.2 Maximum daily effort by river reach

A key aspect of the sociological component to the operating model was the spatial distribution of maximum fishing effort, i.e., the greatest number of boat days that can be exerted by villages in each reach when the fishery is open. This maximum effort was altered as the simulated salmon season progressed based on the effort response submodel (Section **??**). The important characteristic to capture is the proportion of all effort that is attributable to each reach, i.e. the scale is not important as the efficiency of any one unit can be adjusted by altering the q parameter (Section **??**). To determine how effort should be apportioned to each reach, I devised a simple index of effort for each village and year based on the number of reported fishing households. The Alaska Department of Fish and Game has collected this information since 1990, and it is presented in the same studies that quantified subsistence harvest patterns: Hamazaki (2011), Carroll and Hamazaki (2012), Shelden et al. (2014), Shelden et al. (2015), Shelden et al. (2016a), and Shelden et al. (2016b). The data were reported as the number of households that "usually fish" and the number of households that "do not usually fish" as surveyed each year (as well as the number of "unknown" fishing status households). First, I apportioned any unknown households probabilistically to the other two categories by assuming the information was missing at random: if 60% of the fishing households belonged to the "usually fishes" category in a village in a year, I apportioned 60% of the unknown households to "usually fishes" and 40% to "does not usually fish". I then calculated the effort index for each village as 1 * usually fishers + 0.5 * not usually fishers, summed the values across villages within each reach and year, calculated the annual proportion belonging in each reach, and averaged these values across years.

Table A.1: Difference between D_{50} for tagged fish destined for lower or upper river tributaries and those destined for middle river tributaries. These estimates were used to inform Chinook salmon substock-specific run timing.

Year	Lower	Upper
2003		-2.0
2004		-9.5
2005		-4.9
2006		-7.8
2007		-2.5
2015	-0.7	-10.7
2016	2	-9.8

Table A.2: Spatial distribution of escapement in the operating model. The number in each cell represents the fraction of fish from a stock that make it to a reach and survive the fishery that ultimately escape and spawn in a tributary with a confluence with the main stem Kuskokwim located in that reach. These estimates were obtained from radio telemetry studies as described in Section A.1.4, and the chum/sockeye salmon estimates were obtained by removing the substock structure from the Chinook salmon data.

		Chinook Salmon			
Reach #	**Tributaries in Reach**	**Lower**	**Middle**	**Upper**	**Chum/Sockeye**
Lower River					
4	Kwethluk	65.3%	0%	0%	12.4%
5	Kasigluk, Kisaralik	80.1%	0%	0%	6%
6	Tuluksak	100%	0%	0%	1.7%
Middle River					
9	Aniak	0%	28.1%	0%	24.6%
10	Owhat	0%	0.5%	0%	0.4%
11	Holokuk, Sue Creek, Veahna	0%	3.7%	0%	3.4%
12	Oskawalik	0%	2.7%	0%	2.4%
13	Crooked Creek, George	0%	6%	0%	4.8%
15	Vreeland, Holitna	0%	77.3%	0%	64.6%
16	Stony	0%	32.8%	0%	25.8%
17	Swift, Tatlawiksuk	0%	100%	0%	55.9%
Upper River					
20	Selatna, Black	0%	0%	6%	6%
22	Takotna	0%	0%	17.5%	17.5%
24	Middle Fork	0%	0%	94%	94%
26	South Fork, East Fork	0%	0%	100%	100%

Table A.3: Key sociological quantities used in the operating model, broken down by spatial area (reach). Each reach is 35 km in main stem river length. Effort is expressed in the maximum number of boats fishing per day. The % columns represent the average fraction of the total harvest by species that was harvested by villages within each reach over the period 1990 – 2000. Harvest values have been rounded to the nearest 100 for ease of presentation, but the total column represents the sum of non-rounded quantities. Although these data were available through 2015, region stakeholders indicated that the recent years have been contaminated by harvest restrictions, and that these earlier years would be more representative.

			Chinook Salmon			**Chum/Sockeye Salmon**		
Reach #	**Villages in Reach**	**Effort**	**%**	**Min.**	**Max.**	**%**	**Min.**	**Max.**
Lower River								
1	Tuntutuliak, Eek	42	7.6%	5,100	8,300	6.2%	4,600	10,900
2	Atmautluak, Kasigluk, Nunapitchuk	74	11%	7,400	12,000	13.6%	10,000	23,900
3	Napakiak, Napaskiak, Oscarville, Bethel	415	40.5%	27,200	44,500	34.1%	25,000	59,600
4	Kwethluk, Akiachak	74	17.2%	11,600	18,900	15.2%	11,200	26,600
5	Akiak	18	4.3%	2,900	4,800	4.9%	3,600	8,600
6	Tuluksak	21	3.9%	2,600	4,300	4.4%	3,300	7,800
Middle River								
8	Lower Kalskag, Upper Kalskag	33	5.1%	3,400	5,600	4.2%	3,100	7,400
9	Aniak	46	4.2%	2,800	4,600	4.6%	3,400	8,100
10	Chuathbaluk	9	1.3%	900	1,400	2.1%	1,600	3,700
13	Crooked Creek	9	1%	600	1,100	1.5%	1,100	2,600
14	Red Devil	6	0.3%	200	400	1.1%	800	2,000
15	Sleetmute	12	1.1%	800	1,200	2.1%	1,500	3,600
16	Lime Village, Stony River	10	0.7%	500	700	4%	3,000	7,000
Upper River								
22	McGrath, Nikolai, Takotna, Telida	42	1.7%	1,100	1,800	1.9%	1,400	3,300
Total		**800**	**100%**	**67,200**	**109,800**	**100%**	**73,400**	**175,100**

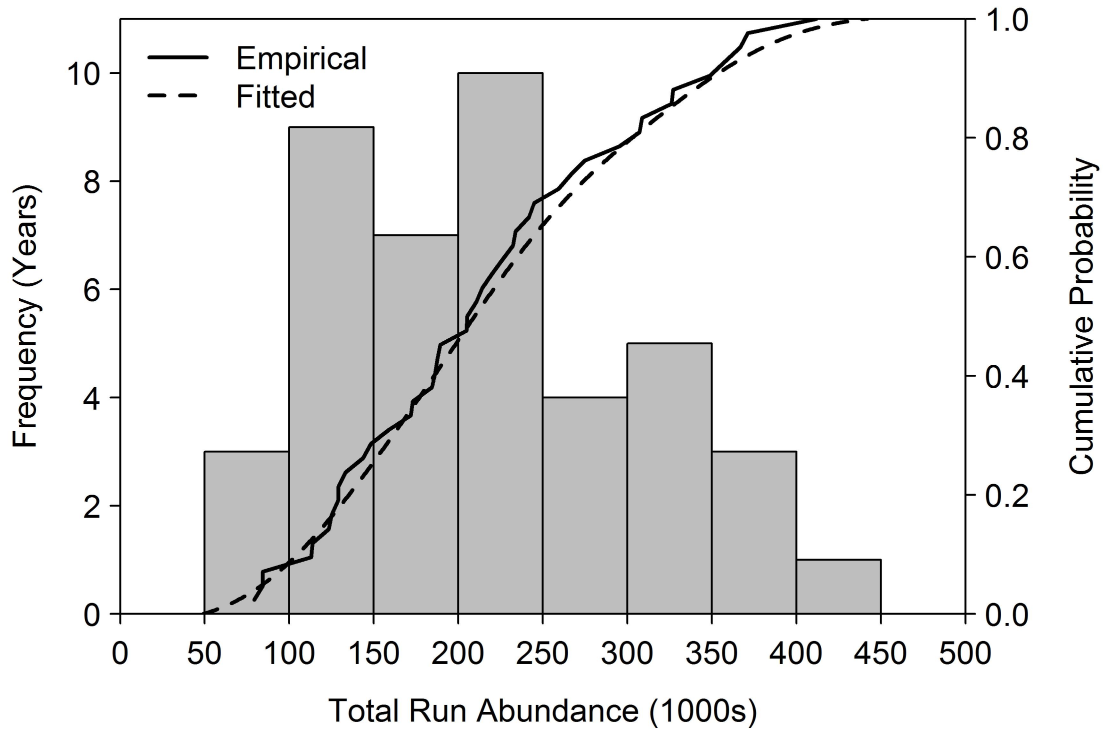

Figure A.1: Distribution of total drainage-wide run size for Kuskokwim River Chinook salmon, as presented in Liller et al. (2018). This distribution was used to generate the run size of the aggregate Chinook salmon populations entering the fishery system in a simulated year. The secondary y-axis represents the probability of a run falling below a given run size according to the historical frequency of run sizes; where the solid line shows the empirical cumulative distribution function and the dashed line shows one obtained by fitting a kernel density smoother to the empirical data. The fitted distribution was used for simulation to prevent the same 42 run size values from being replicated in the analysis.

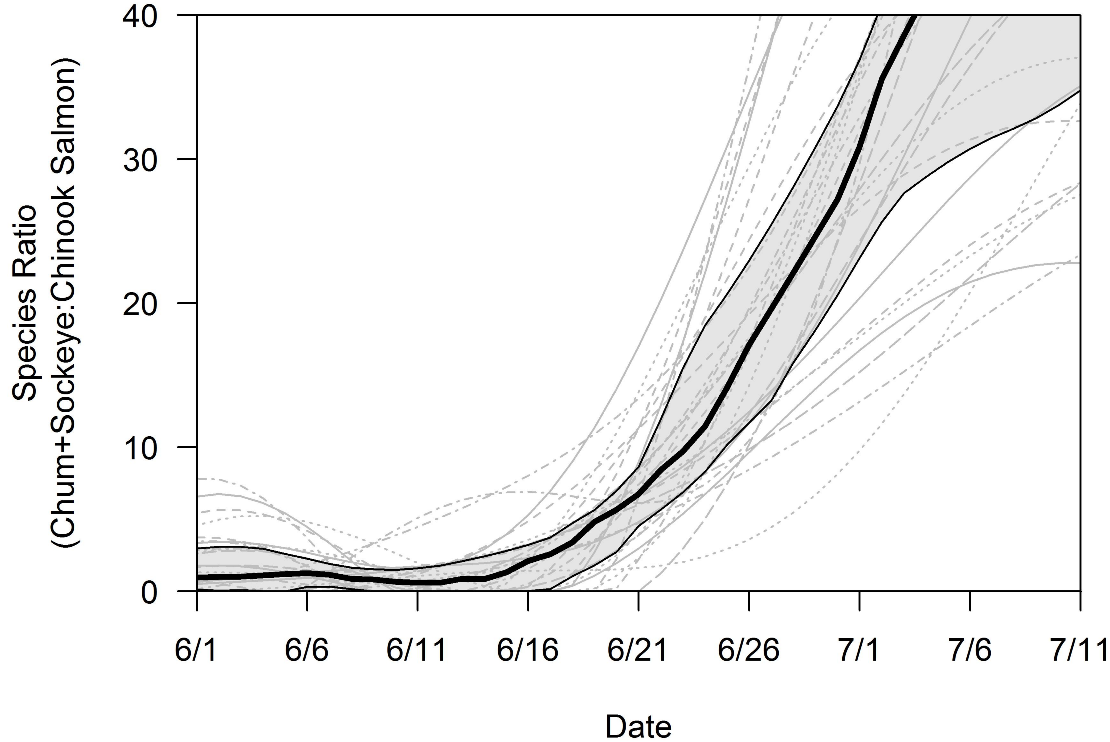

Figure A.2: Smoothed species ratios of chum+sockeye:Chinook salmon as detected by the Bethel Test Fishery. Individual grey lines represent separate years from 1984 – 2017, the grey region represents the central 50% of all smoothed ratios on each day and the thick black line represents the daily median. Only this time period is shown because at ratios larger than 20, the differences in the influence of chum/sockeye salmon on Chinook salmon harvest by the subsistence fishery are negligable.

Appendix B

Validation of the Operating Model in Chapter 1

For any closed-loop simulation model, the reliability of inferences drawn will be conditional on the ability of the model components to capture the important behavioral properties of the real system. Here, I provide a brief validation that the fishery component of the operating model does in fact provide a reasonable model of the real system when the fishery was unrestricted.

First, I thought it important that the model be able to replicate the relationship between total Chinook salmon run size and total subsistence salmon harvest. Capturing this pattern was important to ensure that the fishery would not inadvertently harvest an unrealistically large or small amount of fish in different run sizes if management mistakes were made, which would confound my conclusions. As shown in Figure B.1, this historical relationship has been quite noisy for the observed historical time series, though an increasing pattern has emerged: in general, more fish have been harvested in years with large runs than years with small runs. I found that by tuning the catchability (q) and effort response coefficients, I was able to reproduce the pattern and variability quite well.

The next behavior of interest was the spatiotemporal distribution of harvest. Because in-river salmon fisheries are sequential, fish harvested in one area are invulnerable to harvest (and escapement) in upriver areas. It also means that communities in downriver communities may finish fishing earlier in the season because they are the first to experience favorable fishing conditions (i.e., high in-river abundance and resulting catch rates; in the Kuskokwim River drying weather also plays an important role). If the timing of harvest was not captured adequately, this would be an indication that the effort response coefficients were improperly tuned and could result in unrealistic conclusions. The patterns and variability in the day of the year at which various percentiles of Chinook salmon harvest was attained by reach compared between observed data and the modeled outcomes are shown in Figure B.2. It seems that the patterns and variability in harvest timing were reasonably well-captured, particularly for downriver reaches. Reaches 14, 15, 16 and 22 seemed to have had the largest deviations between observed and modeled patterns, but given communities in these reaches harvest a negligible amount of Chinook salmon in comparison to the downriver villages (Figure B.3), I was not concerned by this finding.

The final important characteristic was the spatial distribution of end-of-season harvest. Accurately representing this component of the system would further indicate model adequacy. Figure B.3) shows a comparison of the proportion of total drainage-wide Chinook salmon subsistence harvest attributable to communities in each reach between observed and modeled outcomes. While the overall pattern was fully captured, there were moderate deviations between the model and observations in reaches 2, 3, and 4.

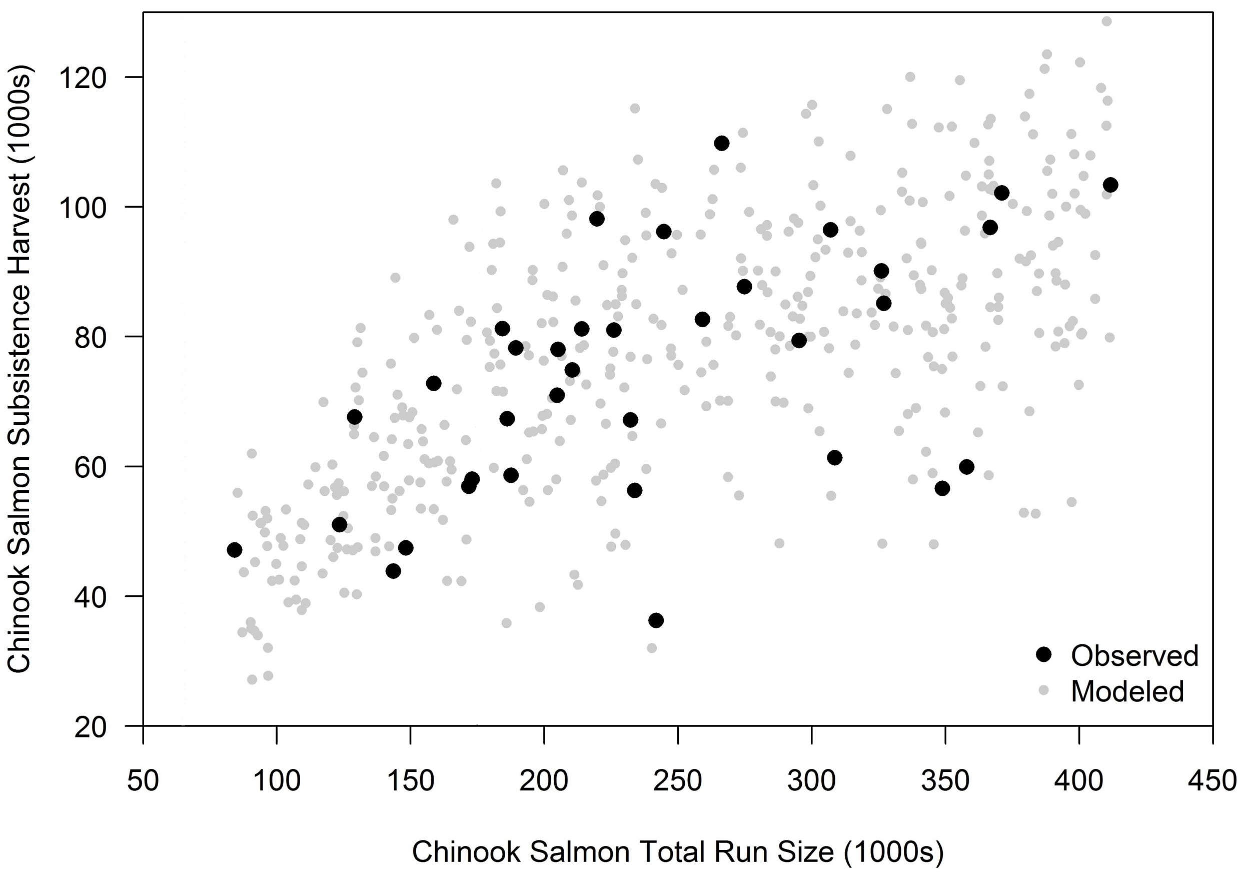

Figure B.1: Observed and modeled Chinook salmon subsistence harvest as a function of total Chinook salmon run size. Individual black dots are historical realizations in years with no harvest restrictions on the subsistence salmon fishery. Individual grey dots are modeled outcomes, each representing a hypothetical salmon run with different random subpopulation compositions, run timing, and species ratios.

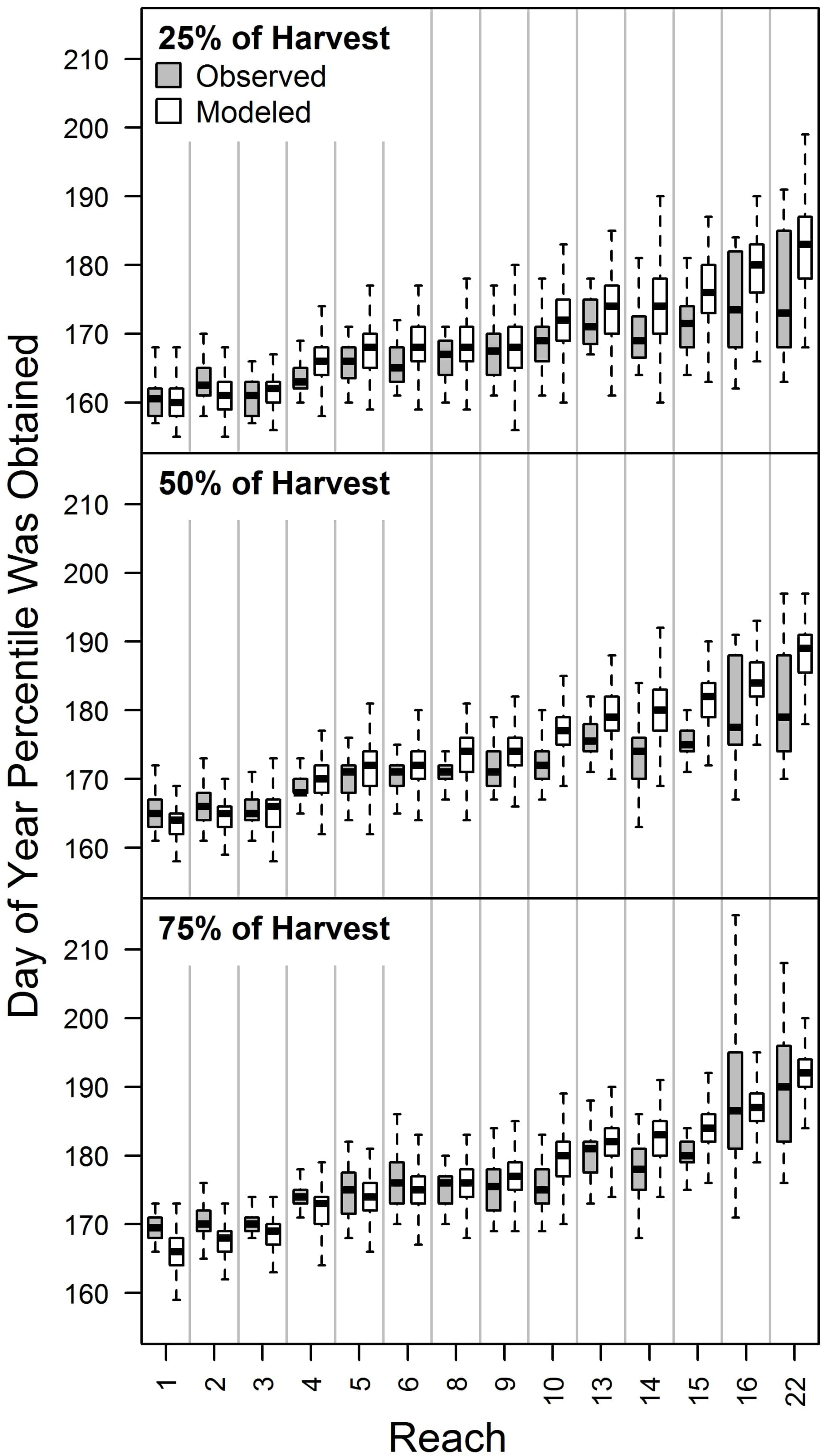

Figure B.2: Comparison of the day of the year at which various percentiles of Chinook salmon harvest was attained by reach between observed and modeled outcomes. Variability in the observed boxplots is due to inter-annual variability in run size and timing and represents between-simulation variability for the modeled outcomes. Reach numbers are ordered from downriver to upriver. Note that not all reaches contain communities that harvest salmon.

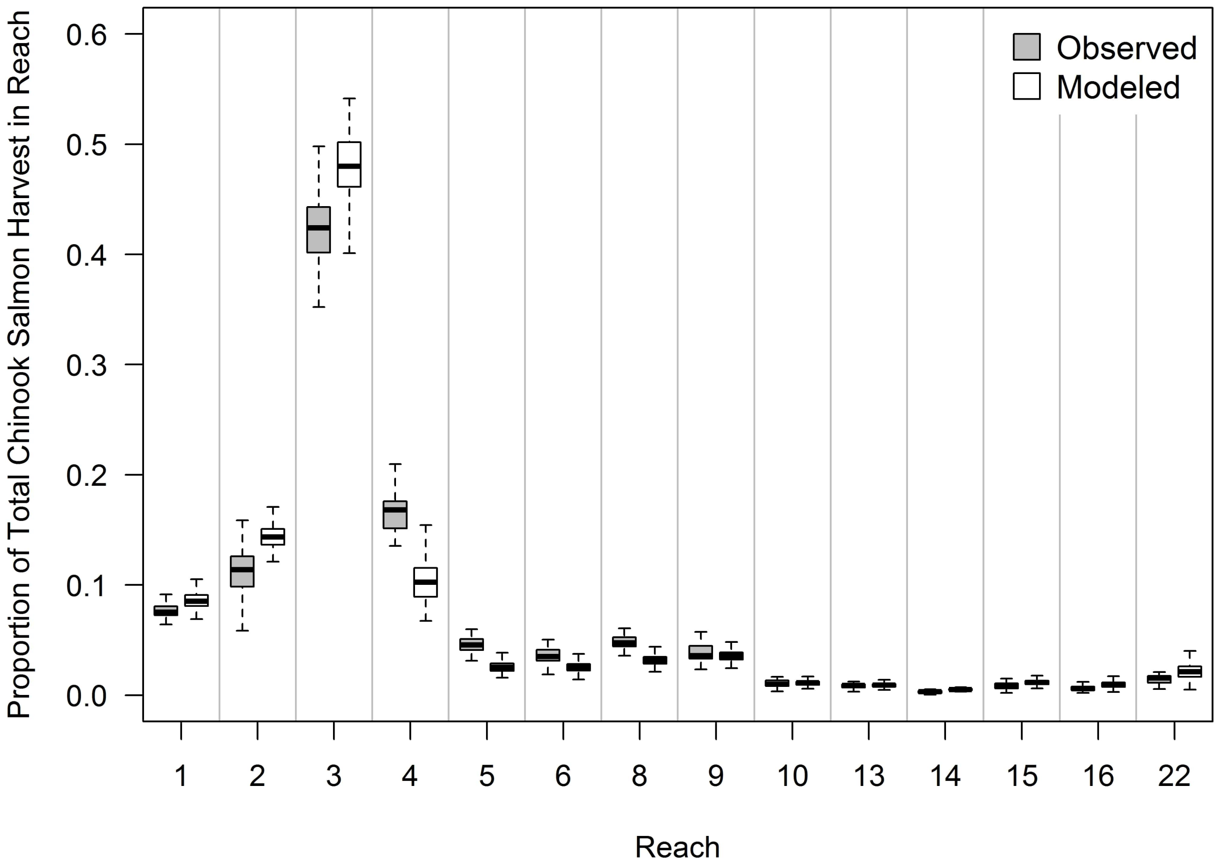

Figure B.3: Comparison of the proportion of total drainage-wide Chinook salmon subsistence harvest attributable to communities in each reach between observed and modeled outcomes. Variability in the observed boxplots is due to inter-annual variability, and represents between-simulation variability for the modeled outcomes. Reach numbers are ordered from downriver to upriver. Note that not all reaches contain communities that harvest salmon.

Bibliography

Bue, D. G. and Lipka, C. G. 2016. Characterization of the 2011 salmon run in the Kuskokwim River based on the test fishery at Bethel. Fishery Data Series 16-05, Alaska Department of Fish and Game, Anchorage, AK.

Carroll, H. C. and Hamazaki, T. 2012. Subsistence salmon harvests in the Kuskokwim Area, 2010. Fishery Data Series 12-38, Alaska Department of Fish and Game, Anchorage, AK.

Hamazaki, T. 2011. Reconstruction of subsistence salmon harvests in the Kuskokwim Area, 1990 – 2009. Fishery Manuscript Series 11-09, Alaska Department of Fish and Game, Anchorage, AK.

Liller, Z. W., Hamazaki, H., Decossas, G., Bechtol, W., Catalano, M., and Smith, N. 2018. Kuskokwim River Chinook salmon run reconstruction model revision – executive summary. Regional Information Report 3A.18-04, Alaska Department of Fish and Game, Anchorage, AK.

Shelden, C. A., Hamazaki, T., Horne-Brine, M., Chavez, R., and Frye, R. 2015. Addendum edition: Subsistence salmon harvests in the Kuskokwim Area, 2013. Fishery Data Series 15-22, Alaska Department of Fish and Game, Anchorage, AK.

Shelden, C. A., Hamazaki, T., Horne-Brine, M., Dull, I., and Frye, R. 2016a. Subsistence salmon harvests in the Kuskokwim Area, 2014. Fishery Data Series 16-49, Alaska Department of Fish and Game, Anchorage, AK.

Shelden, C. A., Hamazaki, T., Horne-Brine, M., and Roczicka, G. 2016b. Subsistence salmon harvests in the Kuskokwim Area, 2015. Fishery Data Series 16-55, Alaska Department of Fish and Game, Anchorage, AK.

Shelden, C. A., Hamazaki, T., Horne-Brine, M., Roczicka, G., Thalhauser, M. J., and Carroll, H. C. 2014. Subsistence salmon harvests in the Kuskokwim Area, 2011 and 2012. Fishery Data Series 14-20, Alaska Department of Fish and Game, Anchorage, AK.

Smith, N. J. and Liller, Z. W. 2017. Inriver abundance and migration characteristics of Kuskokwim River Chinook salmon, 2015. Fishery Data Series 17-22, Alaska Department of Fish and Game, Anchorage, AK.

Stuby, L. 2007. Inriver abundance of Chinook salmon in the Kuskokwim River, 2002 – 2006. Fishery Data Series 07-93, Alaska Department of Fish and Game, Anchorage, AK.