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Run Reconstruction, Spawner-Recruit Analysis, and Escapement Goal Recommendation for Chinook Salmon in the Copper River

by

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December 2018

Alaska Department of Fish and Game Divisions of Sport Fish and Commercial Fisheries

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Weights and measures (metric)

centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)

cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd

Time and temperature

day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s

Physics and chemistry

all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General

Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat or long
monetary symbols (U.S.)	$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	*E*
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	log_2, etc.
minute (angular)	'
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	"
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

FISHERY MANUSCRIPT SERIES NO. 18-07

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The Fishery Manuscript Series was established in 1987 by the Division of Sport Fish for the publication of technically-oriented results of several years' work undertaken on a project to address common objectives, provide an overview of work undertaken through multiple projects to address specific research or management goal(s), or new and/or highly technical methods, and became a joint divisional series in 2004 with the Division of Commercial Fisheries. Fishery Manuscripts are intended for fishery and other technical professionals. Fishery Manuscripts are available through the Alaska State Library and on the Internet: http://www.adfg.alaska.gov/sf/publications/ This publication has undergone editorial and peer review.

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF APPENDICES

Appendix **Page**

ABSTRACT

An age-structured state-space spawner–recruit model was fit to estimates of relative and absolute abundance, harvest, and age composition for Copper River Chinook salmon (*Oncorhynchus tshawytscha*) from 1980 to 2016. Bayesian statistical methods were employed to assess uncertainty in the presence of measurement error, serial correlation, and missing data. Ricker stock-recruit parameters and management reference points were estimated, including the escapement that provides for maximum sustained yield (S_{MSY}). It is recommended that a sustainable escapement goal range of 18,500 to 33,000 fish be adopted for Copper River Chinook salmon. Escapement is evaluated by subtracting estimates of inriver harvest from estimates of inriver abundance. Escapements within this range have a high probability of producing sustainable yields.

Key words: Chinook salmon, *Oncorhynchus tshawytscha*, Copper River, escapement, age composition, escapement goal, run reconstruction, spawner–recruit analysis, maximum sustained yield, measurement error, serial correlation, missing data, Bayesian statistics, JAGS

BACKGROUND

The Copper River is a glacially dominated system located in Southcentral Alaska and is the second largest river in Alaska in terms of mean annual discharge (Brabets 1997). It flows south from the Alaska, Wrangell, and Chugach mountain ranges and empties into the Gulf of Alaska, east of Prince William Sound (Figures 1 and 2). The Copper River drainage (61,440 km^2) supports spawning populations of Chinook salmon *Oncorhynchus tshawytscha*, sockeye salmon *O. nerka*, coho salmon *O. kisutch*, chum salmon *O. keta*, and pink salmon *O. gorbuscha* as well as several resident fish species. The Copper River Chinook salmon stock is composed of 6 major spawning populations (Upper Copper, Gulkana, Tazlina, Klutina, Tonsina, and Chitina). Radiotelemetry studies suggest there is negligible spawning downstream of the Chitina River (Savereide 2005; Figure 2).

Copper River Chinook salmon supports commercial, subsistence, personal use, and sport fisheries. The 10-year average annual Chinook salmon harvest from 2007–2016 was ~21,500 fish from these fisheries (Somerville 2017). Since 1999, the Copper River drainage has produced an average run of ~63,500 Chinook salmon; however, the recent 10-year average (2007–2016) is ~48,000 fish (Somerville 2017).

FISHERIES MANAGEMENT

Harvest of Copper River Chinook salmon is managed under guidelines established in 4 fishery management plans: 1) the *Copper River District Salmon Management Plan* (5 AAC 24.360); 2) the *Copper River King Salmon Management Plan* (5 AAC 24.361); 3) the *Copper River Personal Use Dip Net Salmon Management Plan* (5 AAC 77.591); and 4) the *Copper River Subsistence Salmon Fisheries Management Plan* (5 AAC 01.647). A drainagewide sustainable escapement goal of >24,000 Chinook salmon was established in 2003 based on the average of escapement estimates from 1980–1998 derived from a catch-age model (Bue et al. 2002, Savereide 2001). A mainstem mark–recapture project in place since 1999, along with commercial and inriver harvest estimates, is used to generate annual estimates of escapement and total run size.

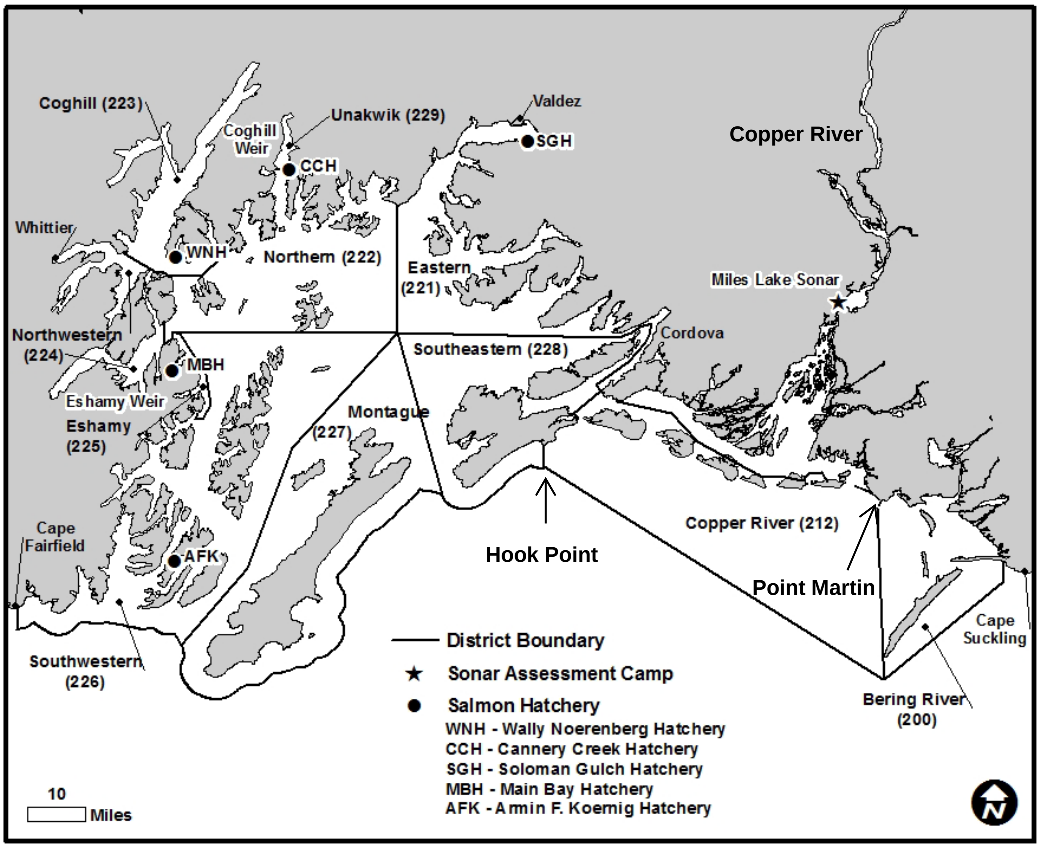

Figure 1.–Prince William Sound Management Area showing commercial fishing districts, salmon hatcheries, and Miles Lake sonar.

Figure 2.–A map of the Upper Copper River drainage demarcating the personal-use and subsistence fisheries, the major spawning tributaries (where most sport fishing occurs), and Native Village of Eyak's (NVE) mark–recapture project location.

COPPER RIVER CHINOOK SALMON FISHERIES

Commercial Fishery

The Copper River District includes all waters of the Gulf of Alaska between Hook Point and Point Martin (Figure 1). There has been a directed commercial fishery on Copper River salmon stocks since the early 1900s. In general, fishing time has been reduced over the years in response to increased efficiency of the commercial fleet and reallocations by the Alaska Board of Fisheries (BOF). The recent schedule has been two commercial fishing periods per week on Mondays and Thursdays, with the duration of each fishing period dependent upon trends in escapement, harvest, and environmental conditions. The fishery opens in mid-May and period lengths are established inseason by emergency order (EO). The fishery is a drift gillnet fishery with approximately 500 permits fished in recent years. The average 10-year commercial harvest from the Copper River District for 2007–2016 was 15,454 Chinook salmon and the 2016 harvest was 13,100 Chinook salmon (Haught et al. 2017).

Sport Fishery

Sport fisheries for salmon in the Copper River primarily target Chinook and sockeye salmon. The fisheries occur in tributaries to the Copper River with the largest harvest occurring in the Gulkana and Klutina rivers (Figure 2). The Chinook salmon fishery was traditionally the most important recreational salmon fishery in the Copper River in terms of effort and economic value, but sockeye salmon runs have increased and area sockeye salmon fisheries have gained in economic importance and angling effort, particularly in the Klutina River (Somerville 2017). Sport harvest and effort has been estimated annually since 1977 by the Statewide Harvest Survey (http://www.adfg.alaska.gov/sf/sportfishingsurvey/). The survey does not estimate fishing effort by species, but most effort in the major tributaries is likely directed at salmon. Sport harvest of Chinook salmon from the Upper Copper River drainage increased through 1996 when the harvest peaked at 9,116 Chinook salmon (Somerville and Taube 2007). Since 1996, sport harvest of Chinook salmon from the Upper Copper River drainage has declined to a low of 289 fish in 2013 (Somerville 2017). Approximately 95% of the estimated sport harvest of Chinook salmon taken from the Upper Copper River drainage comes from the Gulkana and Klutina river drainages. The average 10-year sport harvest from the Copper River for 2007–2016 was 1,767 Chinook salmon and the 2016 harvest was 327 Chinook salmon (Somerville 2017).

Subsistence Fishery

Subsistence use of Chinook salmon from the Copper River dates back over 2,000 years (Naves et al. 2015). From statehood until 1978, the dip net and fish wheel fisheries in the Copper River were classified as subsistence. In 1980, the BOF adopted the Copper River Subsistence Salmon Fisheries Management Plan. The management plan established seasons, open areas, legal gears, permit requirements, and bag limits for a subsistence salmon fishery in the Copper River. The plan also directed Alaska Department of Fish and Game (ADF&G) to manage the Copper River commercial salmon fishery to assure adequate escapement past the Miles Lake sonar to provide for subsistence harvest. In 1999, federal management of the Copper River subsistence fisheries was initiated, primarily due to the state not complying with rural preference for subsistence uses as mandated by Alaska National Interest Lands Conservation Act (ANILCA). Under federal management, residents from rurally qualified communities may attain a subsistence permit for either or both the Glennallen Subdistrict and the Chitina Subdistrict; the federal subsistence harvest in the Chitina Subdistrict is reported with state personal use harvest (see personal use fishery) because the fisheries are within the same area. Federal and state subsistence salmon fishing is restricted to 3 areas on the Copper River: 1) the Copper River District; 2) the Upper Copper River District (Glennallen and Chitina Subdistricts); and 3) the Batzulnetas area, which only harvests sockeye salmon (Figure 2). Boundary lines for the Copper River District subsistence fishery are the same as the commercial fishery. Subsistence fishing is allowed by permit from May 15 until September 30. From May 15 until 2 days before the commercial opening of the Copper River District, subsistence fishing is allowed 7 days per week. Once the commercial season has commenced, subsistence fishing is allowed only during commercial fishing periods or by EO. Drift gillnets are the only legal gear and prior to July 15 may have a maximum length of 50 fathoms with a maximum mesh size of 6 inches.

The federal fishery in the Glennallen Subdistrict opens on May 15 through September 30; the state fishery is open June 1 through September 30. Both fisheries are open for continuous subsistence salmon fishing in all waters of the mainstem Copper River upstream of the Chitina-McCarthy Bridge to the mouth of the Slana River (Figure 2). A federal or state subsistence permit is required to participate in the fishery. Under federal management, permit holders have an annual cumulative limit of 200 salmon for a household of 1 and 500 salmon for a household of 2. Federal permit holders may harvest salmon with a dip net, fish wheel, or rod and reel, or combination of these gear types through the season. Under state management, users must select only one gear type (dip net or fish wheel) when getting their permit. Permit limits are 30 salmon for a household of 1, 60 salmon for a household of 2, and 10 salmon for each additional person in a household of more than 2 people. Individuals may request additional salmon up to a maximum of 200 salmon and households may request up to 500 salmon. For participants using dip nets, only 5 of the salmon may be Chinook salmon. A subsistence fishery by permit is also allowed in a portion of Tanada Creek with spears and dip nets and near the traditional Ahtna Native fishing site of Batzulnetas with a fish wheel or dip net. The average 10-year subsistence harvest from all districts (state and federal) for 2007–2016 was 3,157 Chinook salmon and the 2016 harvest was 2,655 Chinook salmon (Somerville 2017).

Personal Use Fishery

In 1980, with the passage of ANILCA, the federal government mandated subsistence hunting and fishing preference for rural residents on federal public lands. To comply with this requirement and prevent federal involvement in fishery management, the joint Boards of Fish and Game adopted a regulation in 1982 stating only residents were eligible to participate in subsistence fishing and hunting and established 8 criteria for identifying fish stocks and game populations with customary and traditional uses. The preclusion of non-basin residents from participating in the Copper River subsistence fisheries prevented many individuals from harvesting fish for their personal use. This led the BOF to create a personal use salmon fishery in 1984 in the Copper River under the *Copper River Personal Use Salmon Management Plan*.

The Chitina Subdistrict includes the mainstem Copper River between the downstream edge of the Chitina–McCarthy Bridge and a department marker located about 200 yards upstream of Haley Creek (Figure 2). The personal use dip net salmon fishery is opened each year by EO between June 7 and June 15 and the federal subsistence fishery opens and closes on a weekly basis in alignment with the state personal use fishery. Under state management, a permit is required and the annual limit is 25 salmon for the head of a household and 10 salmon for each additional household member; only 1 Chinook salmon can be harvested per household. Under federal management, a permit is required and qualified fishers may use dip nets, fish wheels, or rod and reel, or a combination of these gear types to harvest salmon. The federal harvest limits are the same as the Glennallen Subdistrict. The average 10-year personal-use harvest (federal and state) from the Chitina Subdistrict for 2007–2016 was 1,101 Chinook salmon and the 2016 harvest was 620 Chinook salmon (Somerville 2017).

CURRENT AND HISTORIC COPPER RIVER CHINOOK SALMON ASSESSMENT

Miles Lake Sonar

This project doesn't directly assess Chinook salmon, but it does use sonar technology to enumerate the upriver migration of all salmon from mid-May (dependent on river ice) until late July into the Copper River just downstream from Miles Lake (Appendix B1, Haught et al. 2017). The 2 species of salmon migrating during this time period are Chinook and sockeye salmon. Sonar has been used since 1984 to enumerate salmon passage and the technology has improved over the years; currently one Adaptive Resolution Imaging Sonar (ARIS) 1200 and 1800 on the north bank and one ARIS 1800 on the south bank are being used to insonify the river profile from each bank. Sonar images of the entire river bottom from the north to the south shore have been obtained by the Division of Commercial Fisheries to determine where salmon are distributed throughout the river. The results showed that the vast majority of salmon migrate through the insonified area, and because of this the sonar count is considered an estimate of inriver run abundance of Chinook and sockeye salmon and not an index.

Drainagewide Escapement, Spawning Distribution, and Timing

Prior to 1999 there were no estimates of escapement, distribution, or run timing for the Copper River Chinook salmon stock. Annual aerial surveys during peak spawning over 9 significant spawning streams were conducted to provide an index of overall escapement. In 1999, ADF&G began a 6-year radiotelemetry study downstream of all the spawning tributaries and inriver fisheries to estimate inriver abundance, spawning distribution, and run timing of Chinook salmon (Wuttig and Evenson 2001, Savereide 2005). To obtain drainagewide estimates of escapement, the inriver harvest from all fisheries is subtracted from the estimate of inriver abundance. Since 2003, the Native Village of Eyak (NVE) has conducted the mark–recapture program to estimate inriver abundance using fish wheels (Piche et al. *In prep*, Appendix A1). The average 10-year escapement estimate for 2007–2016 was 25,641 Chinook salmon (Appendix A1). Distribution estimates showed that the majority of Chinook salmon spawning occurs in the Upper Copper tributaries, and the Gulkana and Chitina rivers (Wuttig and Evenson 2001, Savereide 2005). In general, upriver stocks returned earlier than downriver stocks (Wuttig and Evenson 2001, Savereide 2005).

Age-Structured Assessment Model

An age-structured assessment model was developed to estimate the abundance and escapement of Chinook salmon from 1980–1999 (Savereide 2001). Information consisted of catch-age data from all fisheries and 2 sources of auxiliary data (escapement index and spawner-recruit relationship). Results implied that an approach (time-varying) that allowed for measurement error in the pooled catch-age data from all 4 fisheries and return proportions by age to vary over time produced parameter estimates with high precision and low bias. The model integrated all available sources of data at the time, accounted for uncertainty, and provided an estimate of escapement (19,711) that produces maximum sustained yield (MSY).

Smolt Abundance and Marine Survival

The Copper River stock is 1 of the 12 stocks chosen by the ADF&G as an indicator stock for the Chinook Salmon Research Initiative (CSRI) and the lack of juvenile information has been identified as an information gap (ADF&G Chinook Salmon Research Team 2013). Furthermore, age-structured assessment models that are widely used to understand a stock's dynamics require information about processes like recruitment and mortality (natural and fishing). To better understand these processes as part of CSRI, ADF&G began a coded wire tag study in 2014 to estimate the annual abundance of Chinook salmon smolt emigrating from the Copper River and their subsequent marine survival. Chinook salmon smolt will be captured and tagged in the Copper River Delta from 2014–2019 and the subsequent returns will be sampled from 2017–2026. The first complete estimates of abundance and marine survival will not be available until the 2014 brood year is done returning in 2021.

Gulkana River Counting Tower, Distribution, Timing, and Aerial Surveys

The Gulkana River is the most important Chinook salmon sport fishery in the Copper River drainage in terms of angler days (Somerville 2017). Spawning escapement in the Gulkana River has been indexed since 1969 using aerial survey counts (Evenson and Savereide 1999, Taube 2006, Somerville *unpublished data*). Since 2002, ADF&G and the Bureau of Land Management have jointly operated a counting tower to estimate the escapement of Chinook salmon on the Gulkana River above the West Fork. Counts are conducted from late May to mid-August. The average 10-year escapement estimate for 2007–2016 was 3,089 Chinook salmon.

Results from a drainage-wide telemetry study showed that the Gulkana River counting tower assesses 50% to 85% of the entire Gulkana River Chinook salmon escapement; however, the distribution estimates within the river are relatively imprecise because of the low number of radiotagged fish used to derive those estimates (Savereide 2005). To obtain precise estimates of the proportion of the escapement that is enumerated by the counting tower ADF&G conducted a 3-year telemetry study in the Gulkana River. In all three years of the study (2013–2015), approximately 50% of the radiotagged Chinook salmon spawned above the counting tower (Schwanke and Tyers 2018). In addition, the relationship between escapement above the counting tower and drainage-wide Copper River run is relatively strong (R^2 = 54%), which implies the Gulkana River escapement estimate is a good indicator of run strength (Schwanke and Tyers 2018).

Timing and Origin using Genetic Stock Composition

The genetic stock identification study was designed to delineate major geographic and temporal stocks of Chinook salmon harvested in the Copper River drainage fisheries, determine the potential of genetic markers to distinguish among stocks within the Copper River drainage, and investigate run timing of these stocks within the Copper River (Templin et al. 2011). The results indicated that the genetic structure was adequate to delineate between 3 reporting groups within the Copper River drainage (Upper Copper, Middle Copper, and Lower Copper), as well as 4 additional reporting groups for catches in the nearshore marine waters (West Gulf, Cook Inlet, East Gulf, and Southeast Alaska/Transboundary rivers; Templin et al. 2011). This updated genetic baseline was applied to estimate the relative stock composition of Chinook salmon harvests in the Copper River District commercial fishery from 2005 to 2008. The results showed that stocks further up the drainage arrived earlier than downriver stocks and that marine fisheries targeting Chinook salmon near the mouth of the Copper River are harvesting mostly Copper River Chinook salmon (Templin et al. 2011). The results support the historical commercial management approach to provide inriver passage for all temporal components of the run. Additionally, genetic data provide the only accurate method for estimating the stock-specific harvests of wild stocks or of untagged stocks from areas outside of the Copper River.

Genetic Stock Composition of the Commercial Harvest

As part of the CSRI investigations on the Copper River, this project was designed to estimate the stock-specific harvest of Chinook salmon in the Copper River District commercial fishery by sampling the harvest using genetic samples from 2013 through 2017 (Gilk-Baumer et al. 2017). This fishery occurs in the nearshore marine waters and captures both fish destined to spawn in the Copper River and fish destined to spawn in other natal rivers throughout the Gulf of Alaska (GOA), British Columbia, and the West Coast U.S. The Chinook Salmon Research Initiative identified the Copper River as 1 of 12 indicator stocks representing diverse life history and migratory characteristics of Alaska Chinook salmon (ADF&G Chinook Salmon Research Team 2013). For the Copper River, an absence of programs to estimate stock-specific harvest in mixed-stock commercial fisheries was identified as a fundamental knowledge gap. These data are used to estimate stock productivity, provide for more accurate forecasts, and assess management actions. This project addressed this gap by applying the available baseline of genetic information representing Chinook salmon populations from within the Copper River drainage, around the GOA, and from southern populations to estimate the relative stock compositions of Chinook salmon harvests in the Copper River District commercial fishery. Three reporting groups within the Copper River were identified: Upper Copper River, Gulkana River, and Lower Copper River. Five large-scale groups were identified in the rest of the GOA and south: Northwest GOA, Northeast GOA, Coastal Southeast Alaska, British Columbia, and West Coast U.S.

COPPER RIVER CHINOOK SALMON SUSTAINABLE ESCAPEMENT GOAL (SEG)

In 2001 the BOF adopted the *Policy for Statewide Salmon Escapement Goals* (5 AAC 39.223) that formalized the procedure for establishing escapement goals. Most salmon (*Oncorhynchus* spp.) fisheries in Alaska are currently managed by monitoring the number of adult spawners (escapement) and, where possible modeling the relationship between escapements and subsequent returns (recruitment) in a density-dependent framework (Ricker 1975). Modeling salmon recruitment is often constrained by the amount and quality of data and even the best models contain high degrees of variability in recruitment rates attributable to both freshwater and oceanic conditions (Needle 2002; Peterman et al. 1998).

The current Copper River Chinook salmon lower bound SEG of 24,000 or more spawners was established in 2003 (Bue et al. 2002) to keep escapements near the historical average of 25,800 fish from 1980–2000, estimated using a catch-age model (Savereide 2001). A number of approaches to the catch-age model were used depending on the quality of data from each fishery; the approach chosen allowed the return proportions by age to vary over time and estimated that the number of spawners needed to produce maximum sustained yield (MSY), denoted as S_{MSY}, was approximately 19,700 Chinook salmon (Savereide and Quinn 2004). This SEG has been reviewed every board cycle since 2002 (Evenson et al. 2008, Fair et al. 2008, 2011, Moffitt et al. 2014). During these reviews, the escapement goal committee has considered the percentile approach (Clark et al. 2014) and habitat-based models (Liermann et al. 2010) as methodology for setting an escapement goal, but the goal has remained unchanged. During the most recent review, described in this report, a state-space model that simultaneously reconstructs runs and fits a spawner-recruit model to estimate total return, escapement, and recruitment of Copper

River Chinook salmon from 1980–2016 was completed to assess the productivity of the stock over numerous environmental regimes, management strategies, and catchability scenarios and determine the escapement level that would lead to the highest sustainable yields.

OBJECTIVES

The objectives of this analysis were to:

1. Conduct a comprehensive analysis of all relevant stock assessment data in the context of an integrated state-space model of historical run abundance and stock dynamics;
2. Provide an updated summary of abundance, harvest, and age composition statistics for this stock for the years 1980–2016; and
3. Recommend an escapement goal based on the state-space model estimates of S_{MSY}.

METHODS

DATA SOURCES

The state-space model incorporated the following input data (Appendices B1 and B2):

1. Estimates of total annual harvest and associated CVs (1980–2016) below (downstream of) and above (upstream of) Miles Lake sonar;
2. Estimates of harvest from the inriver personal-use and subsistence fisheries;
3. Miles Lake sonar counts (1984–2016),
4. Estimates of inriver abundance and associated CVs from mark-recapture (1999–2016);
5. Gulkana River aerial counts (1980–2016);
6. Gulkana River counting tower escapement estimates and associated CVs (2002–2016);
7. Genetic stock identification estimates (2005–2008); and
8. Age-composition estimates from the commercial harvest (1980–2016).

Annual Harvest

Copper River District harvests (annual harvest below the sonar) include commercial harvest from fish tickets from every fishing period throughout the fishing season including home-pack and donated fish, as well as subsistence and educational permits (Appendix A1, Haught et al. 2017). Genetic stock identification techniques were used to estimate the proportion of Copper River Chinook salmon harvested in the commercial fishery (Templin et al. 2011). Inriver harvest (annual harvest above the sonar) includes personal-use, subsistence, and sport harvests (Appendix A1, Somerville 2017). Personal-use and subsistence harvest estimates were determined from retuned harvest permits and sport harvests were estimated from the Statewide Harvest Survey.

Miles Lake Sonar

At this time the length composition of the sonar targets are not used to apportion the total run of all salmon into Chinook and sockeye salmon. The age composition of the sonar targets is not known but age composition estimates from the personal use and subsistence fisheries are similar to the commercial fishery, where the majority of the harvests are age-5 and age-6. To obtain relative measures of abundance for the state-space model, we assumed the species composition of the sonar count was the same as the species composition from the personal use and subsistence harvests. The proportion of Chinook salmon harvested in the personal use fishery is relatively consistent and has ranged from <1% to 7% since 1984; however, regulation changes in 2000 decreased the harvest limit and the range has been between <1% and 3% ever since

(Somerville 2017). The regulation changes warranted a division of the personal use harvest data into 3 management regimes (1984–1999, 2000–2008, 2009–present) to reflect the progressive decrease from 5 Chinook salmon down to 1. The proportion of Chinook salmon harvested in the subsistence fishery is also relatively consistent and has ranged from 2% to 9% since 1980 (Somerville 2017). The proportion harvested in each fishery has decreased over time in conjunction with the decrease in total run.

Measures of Abundance

Estimates of inriver abundance from ADF&G's and NVE's mark–recapture studies and the Gulkana River counting tower estimates are the measures of absolute abundance used by the model (Appendix A1, Savereide 2005, Piche et al. *In prep*). Relative measures of abundance include the following: 1) the proportion of Chinook salmon harvested in the personal-use fishery multiplied by the sonar count of all salmon; 2) the proportion of Chinook salmon harvested in the subsistence fishery multiplied by the sonar count of all salmon; and 3) the annual Gulkana River aerial index (Appendix B1).

Age-Composition

Age-composition estimates from 1980–2016 (Appendix B2) were obtained from the commercial fishery sampling program that samples a portion of Chinook salmon harvested from each fishing period throughout the season (Brenner and Moffitt 2014, Haught et al. 2017, Haught *unpublished data*). The fishery uses 6″ mesh drift gillnets that capture age-4 through age-7 Chinook salmon with relatively equal selectivity (Savereide 2004). Age composition estimates from the personal use, subsistence, and sport fisheries are similar to the commercial fishery but they are based on relatively small samples sizes and are either sporadic (sport fishery) or only collected since 1992 (personal use and subsistence, Savereide 2001). For these reasons, the age-composition estimates from the commercial harvest were assumed to be representative of the age-composition of the total run.

STATE-SPACE MODEL

The state-space model (Appendix B3) assumes a Ricker spawner–recruit relationship and time-varying productivity and maturity. It has an age-structured framework, which facilitates an accurate depiction of observation error in inriver abundance, age composition, and harvest. The model is fit to multiple sources of information on historical abundance, age composition, and harvest, which allows the model to simultaneously reconstruct historical abundance and obtain estimates of stock productivity. Uncertainty from the run reconstruction is passed through to the spawner-recruit analysis and subsequent reference points such as MSY and the escapement that provides for maximum sustained yield (S_{MSY}). The model accommodates missing data, measurement error in the data, absolute and relative abundance indices, and changes in age at maturity. By constructing an integrated model, all relevant data are considered and weighted by their precision. Sensitivity analyses are conducted to assess robustness of the results to assumptions of the run reconstruction and spawner–recruit analyses.

MODEL DETAILS

The total recruitment (R) produced from fish spawning in year y follows a Ricker (1975) formulation:

$$R_y = S_y \alpha e^{-\beta S} \quad (1)$$

where S is the number of spawners, parameter α is a measure of productivity (i.e., number of recruits per spawner in the absence of density dependence), and parameter β is a measure of density dependence. The inverse of β is the number of spawners that produce the theoretical maximum recruitment (S_{MSR}).

To account for time-varying productivity, which manifests as serially correlated model residuals, an autoregressive lognormal error term with a lag of one year (AR[1]) was included in the linearized form of the spawner–recruit relationship (Noakes et al. 1987)

$$\ln(R_y) = \ln(S_y) + \ln(\alpha) - \beta S_y + \phi \nu_{y-1} + \epsilon_{Wy} \tag{2}$$

Where ϕ is the lag-1 autoregressive coefficient, the $\{\nu_y\}$ are model residuals by year

$$\nu_y = \ln(R_y) - \ln(S_y) - \ln(\alpha) + \beta S_y \tag{3}$$

and the $\{\epsilon_y\}$ are independently and normally distributed process errors with "white noise" variance σ_W^2.

Age at maturity was modeled hierarchically: i.e., it was allowed to vary among cohorts to a specified extent. Age-at-maturity vectors $\boldsymbol{p}_y = (p_{y3}, p_{y4}, p_{y5}, p_{y6}, p_{y7})$ from year y returning at ages 3–7 were drawn from a *Dirichlet* $(\gamma_3,\gamma_4,\gamma_5,\gamma_6,\gamma_7)$ distribution. These age proportions are maturity and survival schedules for a given brood year (cohort) across calendar years. The Dirichlet parameters can also be expressed in an alternate form where

$$D = \sum_a \gamma_a \tag{4}$$

is the (inverse) dispersion of the annual age-at-maturity vectors, reflecting consistency of age at maturity among brood years. A low value of D is reflective of a large amount of variability of age-at-maturity proportions p among brood years, whereas a high value of D indicates more consistency in $\boldsymbol{p}$ over time.

The location parameters Π_a, where

$$\pi_a = \frac{\gamma_a}{D}, \tag{5}$$

are proportions that sum to one, reflecting the age-at-maturity central tendencies. To model time-varying age at maturity, the location parameters were assumed to trend according to a multivariate logistic relationship, with each $\eta 1_a$ and $\eta 2_a$ denoting logistic slope and intercept parameters associated with each age a.

$$\pi_{ya} = \frac{e^{\eta 1_a + \eta 2_a y}}{\sum_a e^{\eta 1_a + \eta 2_a y}} \tag{6}$$

The abundance (N) of age-a Chinook salmon in calendar year y is the product of the age proportion scalar p and the total return (recruitment) R from year $y-a$:

$$N_{ya} = R_{y-a} p_{y-a,a} \tag{7}$$

Total run during calendar year y is the sum of abundance at age across ages:

$$N_y = \sum_a N_{ya} \tag{8}$$

Annual harvest (H) of Copper-origin Chinook salmon below (downstream of) the Miles Lake sonar site was modeled as the product of the annual harvest rate below the site and total run,

$$H_{By} = \mu_{By} N_y \tag{9}$$

Inriver run *IR* at the sonar site was modeled as follows:

$$IR_y = N_y - H_{By} \tag{10}$$

Annual harvest above (upstream of) the sonar site was the product of the annual harvest rate above the sonar site and inriver run abundance:

$$H_{Ay} = \mu_{Ay} IR_y \tag{11}$$

Finally, spawning escapement *S* was inriver run abundance minus harvest above the sonar site:

$$S_y = IR_y - H_{Ay} \tag{12}$$

Sampling Distributions of Observed Data

Observed data included estimates of annual harvest below and above the Miles Lake sonar site (1980–2016), a mark-recapture estimate of inriver run (MR 1999–2016), four indices of inriver run relative abundance (dip net apportioned sonar or DNAS 1984–2016; subsistence apportioned sonar or SubAS 1980–2016; Gulkana aerial or GA 1980–2015; Gulkana tower or GT 2002–2016), age composition estimates from the commercial harvest, and genetic stock identification from the commercial harvest (2005–2008). Sampling distributions (likelihood functions) for the data are found below.

Estimated annual harvest ($\widehat{H}_{Ay}$) of Copper River Chinook salmon above the sonar site was modeled in the form

$$\widehat{H}_{Ay} = H_{Ay} e^{\epsilon_{HAy}}, \tag{13}$$

in which the $\{\epsilon_{HAy}\} \sim N(0, \sigma^2_{HAy})$ and

$$\sigma^2_{HAy} = \ln\left(CV^2\left(\widehat{H}_{Ay}\right) + 1\right). \tag{14}$$

The CVs for the annual harvest estimates above the sonar $\{CV(\widehat{H}_{Ay})\}$ were assumed to be 0.10; available CV estimates (2001–2016 personal use and subsistence, 1996–2016 sport) from fisheries above the sonar have ranged from 0.01–0.04 for personal use and subsistence and 0.01–0.39 for sport, with an average over all years of 0.06.

Chinook salmon harvested commercially in the Copper River District below the sonar site consisted primarily of fish originating from the Copper River; however, some Chinook salmon from other stocks were also present. Estimated total annual harvest ($\widehat{H}_{By}$) of all Chinook salmon (regardless of origin) below (downstream of) the sonar site was modeled as

$$\widehat{H}_{By} = H_{By}/p_{Cy} e^{\epsilon_{HBy}}, \tag{15}$$

in which the $\{\epsilon_{HBy}\} \sim N(0, \sigma^2_{HBy})$ and

$$\sigma^2_{HBy} = \ln\left(\left(CV\left(\widehat{H}_{By}\right)\right)^2 + 1\right). \tag{16}$$

The CVs for the annual harvest estimates $\{CV(\widehat{H}_{By})\}$ below the sonar were assumed to be 0.05. There are no CV estimates for harvests below the sonar because the harvests are all reported by fish ticket and are assumed to be a census; however, there is some error associated with this process and it was assumed to be lower than the error associated with estimates of harvest above the sonar.

The true annual proportions of Copper-origin fish p_{Cy} in the commercial harvest below the sonar H_{By} were modeled hierarchically, as beta distributed quantities

$$p_{Cy} \sim Beta(\zeta_1, \zeta_2), \tag{17}$$

with hyper-parameters ζ_1 and ζ_2. Estimates of these proportions $(\hat{p}_{Cy})$ were directly observed in years 2005–2008 using genetic stock identification (GSI) methods. The GSI data were recast as binomial counts with effective sample sizes of 1,033–1,274, obtained by back-calculating from the standard errors of GSI estimates (Templin et al. 2011).

Mark–recapture estimates were assumed to be unbiased estimates of inriver run at Baird Canyon (just upstream from the Miles Lake sonar site).

$$\widehat{MR}_y = IR_y e^{\epsilon_{MR_y}} \tag{18}$$

in which the $\left\{\epsilon_{MR_y}\right\} \sim N(0, \sigma^2_{MRy})$ and

$$\sigma^2_{MRy} = \ln\left(\left(CV(MR_y)\right)^2 + 1\right) \tag{19}$$

where the $\{CV\left(MR_y\right)\}$ are coefficients of variation associated with the MR estimates.

Four indices of abundance were available, with DNAS and SubAS treated as indices of inriver run, and GA and GT treated as indices of drainagewide escapement. Each comprised a measure of relative abundance:

$$I_{iy} = q_i X_y \epsilon_{iy} \tag{20}$$

where q_i is a factor of proportionality relating true abundance to index I_i, X_y is the generic true abundance, and $\{\epsilon_{iy}\}$ are independently and normally distributed process errors with variance σ^2_{Ii}. Parameters q_i and σ^2_{Ii} were estimated from the data. Separate factors of proportionality for DNAS were modeled for years 1984–1999 ($DNAS_1$), 2000–2008 ($DNAS_2$), and 2009–2016 ($DNAS_3$) to reflect changes in harvest regulations. The DNAS management regimes were assumed to have a single common process error variance (σ^2_{Ii}).

The model requires annual data on the age composition of the total run abundance. Because the average commercial harvest rate since 1999 was 39% and the commercial fishery harvests were a more representative sample of age classes, we used commercial harvest age composition as a surrogate for total run age composition. The model requires multinomial age counts and assumes that age counts come from a simple random sample of the total run. This assumption cannot be met for real-world fisheries data, so we rescaled the age data with an "effective sample size" of n_{Ey} = 100. Surrogate scale-age counts x_{ya} were summed to n_{Ey} rather than n_y. Scale age counts x_{ya} were modeled as multinomial distributed with order parameter n_{Ey} and proportion parameters θ_a. One study found that key results from state-space analyses of Pacific salmon data were not sensitive to choice of n_{Ey} (e.g., Fleischman and McKinley 2013).

MODEL FITTING

Markov Chain Monte Carlo (MCMC) methods, which are well-suited for modeling complex population and sampling processes, were employed. The MCMC algorithms were implemented in the Bayesian software program JAGS (Plummer 2003). This methodology allows for inclusion of the effects of measurement error, serially correlated process variation, and missing data in the analysis and provides a more realistic assessment of uncertainty than is possible with classical statistical methods. By properly specifying process variation, measurement error, and time-dependent linkage separately in the model, biases in the analysis can be reduced (Su and Peterman 2012).

Bayesian statistical methods employ the language of probability to quantify uncertainty about model parameters. Knowledge existing about the parameters outside the framework of the current analysis is the "prior" probability distribution. The output of the Bayesian analysis is called the "posterior" probability distribution, which is a synthesis of the prior information and the information contained in the data. See Fleischman et al. (2013), Staton et al. (2016), and Fleischman and Reimer (2017) for similar applications of the methods used in this report.

Prior Distributions

Noninformative priors were chosen to minimize their effect on the posterior. Initial recruitments R_{1973}–R_{1979} (those with no linked spawner abundance) were modeled as drawn from a common lognormal distribution with median μ_{logR} and variance σ^2_{logR}. Beta hyper-parameters B_1 and B_2 for Copper-origin proportions in the harvest below the sonar were given *Uniform (1,1000)* priors. Normal priors with mean zero, very large variances, and constrained to be positive, were used for $\ln(\alpha)$ and β (Millar 2002), as well as for μ_{logR}, and coefficients of proportionality q_i (log transformed). The initial model residual v_0 was given a normal prior with mean zero and variance $\sigma^2_W/(1-\phi^2)$. Annual harvest rates $\{\mu_{By}\}$ and $\{\mu_{Ay}\}$ were given beta (0.1, 0.1) prior distributions. Diffuse conjugate inverse gamma priors were used for σ^2_W and σ^2_{logR}, as well as for index uncertainty parameters $\{\sigma^2_{Ii}\}$.

Sampling from the Posterior Distribution

MCMC samples were drawn from the joint posterior probability distribution of all unknowns in the model. For results presented here, two Markov chains were saved. Of these, the first 50,000 samples were discarded, and every 500th sample from 200,000 additional samples were used to estimate the marginal posterior medians, standard deviations, and percentiles. The diagnostic tools of RJAGS (Plummer 2013) within R (R Core Team 2016), including trace plots and the Gelman-Rubin statistic (Gelman and Rubin 1992), were used to assess mixing and convergence. Credibility interval estimates were constructed from the percentiles of the posterior distribution.

REFERENCE POINTS, OPTIMAL YIELD PROFILE

Reference points were calculated for each individual MCMC sample. Spawning abundance providing maximum sustained yield S_{MSY} was approximated by (Hilborn 1985)

$$S_{MSY} \approx \frac{\ln(\alpha')}{\beta}[0.5 - 0.07\ln(\alpha')] \tag{21}$$

Sustained yield at a specified level of S was obtained by subtracting spawning escapement from recruitment:

$$Y_S = R - S = Se^{\ln(\alpha') - \beta S} - S \tag{22}$$

Other relevant quantities include harvest rate leading to maximum sustained yield, approximated by (Hilborn 1985)

$$U_{MSY} \approx \ln(\alpha')[0.5 - 0.07\ln(\alpha')] \tag{23}$$

escapement leading to maximum sustained recruitment

$$S_{MSR} = \frac{1}{\beta} \tag{24}$$

and equilibrium spawning abundance, where recruitment exactly replaces spawners:

$$S_{EQ} = \frac{\ln(\alpha')}{\beta} \tag{25}$$

The quantity

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma_R^2}{2(1-\phi^2)} \tag{26}$$

in equations 21, 22, 23, and 25 adjusts for the difference between the median and the mean of a right-skewed lognormal error distribution and the AR(1) process.

The probability that a given spawning escapement *S* would produce average yields exceeding X% of *MSY* was obtained by calculating Y_S at incremental values of *S* for each MCMC sample, and then comparing Y_S with X% of the value of *MSY* for that sample. The proportion P_Y of samples in which Y_S exceeded X% of *MSY* is an estimate of the desired probability, and the plot of P_Y versus *S* is termed an optimal yield probability profile (Fleischman et al. 2013).

The probability that yield would be reduced to less than X% of *MSY* by supplying too few spawners *S* was obtained by calculating Y_S at incremental values of *S* and tallying the number of MCMC samples for which Y_S was less than X% of *MSY* and *S* was less than S_{MSY}. A plot of the fraction of samples in which this condition occurred versus *S* is termed an overfishing profile (Bernard and Jones III 2010).

The probability that a given *S* would produce average recruitments exceeding X% of maximum sustained recruitment (MSR) was obtained by calculating *R* at incremental values of *S* for each MCMC sample, then comparing *R* with X% of the value of *MSR* for that sample. The proportion P_S of samples in which *R* exceeded X% of *MSR*, plotted versus escapement, is an optimal recruitment probability profile (Fleischman and Reimer 2017).

RESULTS

The data and model in Appendices B1, B2, and B3 produced the results described below.

Inriver Abundance, Escapement, Harvest Rates, and Age at Maturity

Indices of relative abundance exhibited similar trends through time (Figure 3). An increasing trend in abundance and escapement occurred during 1980–2006, with a decline in the most recent years (2007–2016). Uncertainty surrounding estimates of escapement and inriver abundance was greatest before 2005, when few measures of abundance were available or mark–recapture estimates were imprecise (Figure 3, Appendix A1). After 2004, estimates of inriver abundance and escapement are more precise.

Estimates of total run and recruitment are less uncertain than estimates of escapement and inriver run abundance because the harvest component of the total run is large, averaging over half of the run (Figure 4) and well-estimated (Appendix A1). Productivity and harvest rates have trended downward since the mid-1990s though harvest rates have increased somewhat since 2013 (Figures 4d and 4e, respectively). Coefficients of variation for total run, inriver run, escapement, and recruitment ranged from 4% to 57% but were relatively small (<20%) in most years (Table 1). Recruitment estimates for the latest cohorts are less precise because one or more age classes were not assessed or had not yet returned (Figure 4).

Chinook salmon runs were dominated by age-5 and age-6 fish in all years (Table 2, Figure 5 middle and lower panels), although age-4 fish have been increasing in recent years, indicating that the stock is trending toward earlier maturation (Figure 5 top panel). The relative abundance of age-5 versus age-6 fish varied greatly before 1995 (Figure 5 middle panel).

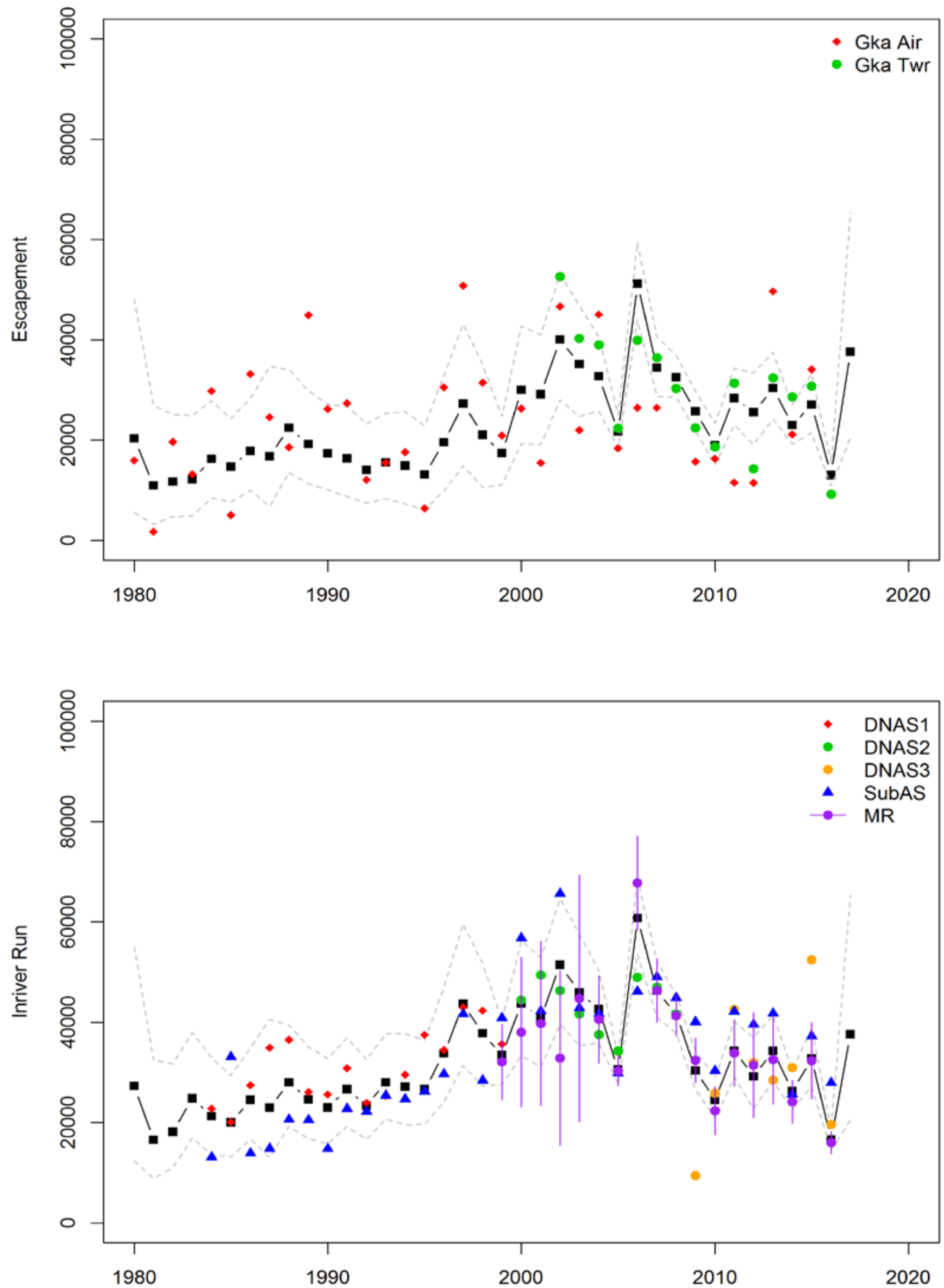

Figure 3.–Escapement (top panel) and inriver run abundance (bottom panel) of Copper River Chinook salmon as reconstructed from indices of relative abundance: Gulkana aerial index (Gka Air), escapement estimates past the Gulkana River counting tower (Gka Twr), dip net apportioned sonar ($DNAS_1$:1984–1999, $DNAS_2$: 2000–2008, and $DNAS_3$: 2009–2016), subsistence apportioned sonar (SubAS), plus a measure of absolute abundance: mark–recapture estimates of inriver abundance (MR, 95% credibility interval bounds plotted). Solid black lines show the median, and dotted lines show the 95% credibility intervals of modeled Escapement and Inriver Run.

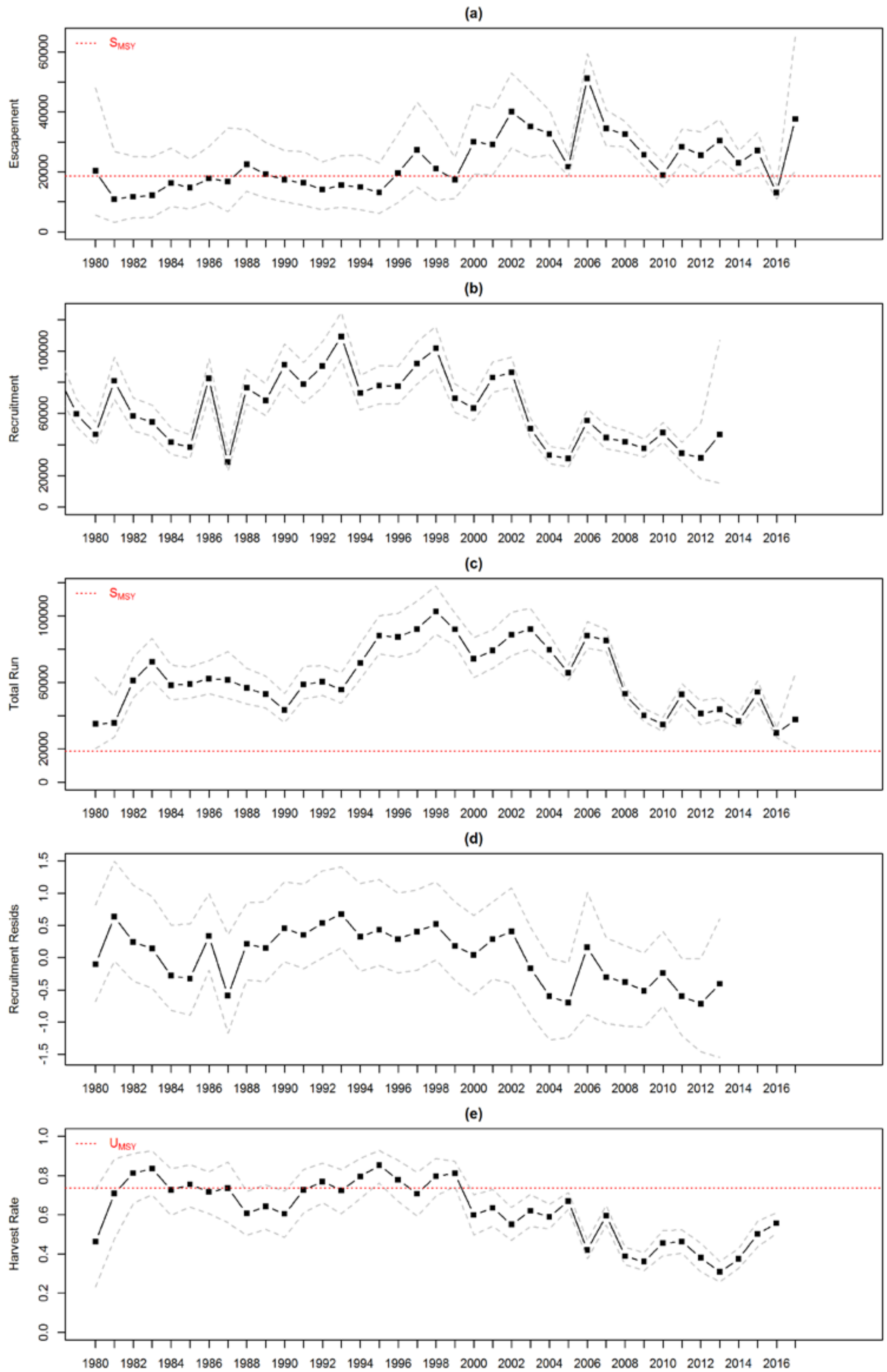

Figure 4.–Point estimates (posterior medians; solid lines) and 95% credibility intervals (dotted lines) of spawning escapement, recruitment by brood year, total run, Ricker productivity residuals, and harvest rate from a state-space model of Copper River Chinook salmon, 1980–2016.

Note: Posterior medians of S_{MSY} and U_{MSY} are plotted as short dash horizontal reference lines; the posterior median of S_{MSR} is plotted as a long dash horizontal reference line.

Table 1.–Annual median abundance estimates and CV for Copper River Chinook salmon obtained by fitting a state-space model to data from 1980 through 2016.

Year	Total Run (CV)	Inriver Run (CV)	Escapement (CV)	Recruitment (CV)
1973	-	-	-	48,335 (0.56)
1974	-	-	-	33,316 (0.38)
1975	-	-	-	27,062 (0.29)
1976	-	-	-	55,406 (0.19)
1977	-	-	-	44,117 (0.17)
1978	-	-	-	84,323 (0.08)
1979	-	-	-	59,506 (0.08)
1980	32,540 (0.33)	24,677 (0.42)	17,721 (0.57)	46,338 (0.08)
1981	34,135 (0.18)	15,108 (0.37)	94,74 (0.56)	80,204 (0.09)
1982	60,373 (0.1)	17,173 (0.29)	10,700 (0.45)	57,947 (0.09)
1983	71,853 (0.09)	23,955 (0.21)	11,241 (0.43)	54,102 (0.09)
1984	57,707 (0.09)	20,619 (0.23)	15,555 (0.3)	41,233 (0.1)
1985	58,752 (0.08)	19,597 (0.21)	14,291 (0.29)	38,054 (0.1)
1986	61,932 (0.08)	23,988 (0.19)	17,350 (0.26)	82,072 (0.07)
1987	60,309 (0.12)	21,646 (0.31)	15,436 (0.43)	28,506 (0.11)
1988	56,191 (0.1)	27,598 (0.19)	21,991 (0.23)	76,179 (0.07)
1989	52,632 (0.09)	24,092 (0.19)	18,681 (0.25)	68,076 (0.08)
1990	42,811 (0.1)	22,558 (0.19)	16,909 (0.25)	91,061 (0.07)
1991	58,384 (0.08)	26,155 (0.17)	15,868 (0.28)	78,462 (0.08)
1992	59,992 (0.08)	22,930 (0.17)	13,583 (0.29)	90,051 (0.08)
1993	55,250 (0.08)	27,638 (0.16)	15,131 (0.28)	108,865 (0.07)
1994	71,294 (0.08)	26,627 (0.17)	14,339 (0.32)	73,144 (0.08)
1995	88,112 (0.07)	26,186 (0.16)	12,630 (0.33)	77,506 (0.08)
1996	86,958 (0.08)	33,107 (0.17)	18,884 (0.3)	77,153 (0.08)
1997	91,621 (0.08)	42,946 (0.17)	26,624 (0.27)	91,731 (0.08)
1998	102,393 (0.07)	37,207 (0.16)	20,473 (0.29)	101,749 (0.07)
1999	91,936 (0.05)	33,231 (0.1)	17,230 (0.2)	69,637 (0.07)
2000	73,752 (0.08)	43,424 (0.13)	29,727 (0.2)	63,284 (0.07)
2001	78,944 (0.08)	40,508 (0.14)	28,752 (0.19)	82,915 (0.06)
2002	88,341 (0.08)	51,218 (0.12)	39,746 (0.16)	86,122 (0.06)
2003	91,854 (0.07)	45,755 (0.12)	34,907 (0.16)	50,109 (0.07)
2004	79,612 (0.05)	42,443 (0.09)	32,555 (0.12)	33,124 (0.08)
2005	65,564 (0.04)	30,508 (0.05)	21,608 (0.08)	30,828 (0.09)
2006	88,202 (0.05)	60,668 (0.06)	51,110 (0.08)	55,290 (0.07)
2007	85,200 (0.04)	46,238 (0.06)	34,437 (0.09)	44,207 (0.09)
2008	53,072 (0.04)	41,463 (0.05)	32,483 (0.07)	41,618 (0.08)
2009	40,116 (0.05)	30,317 (0.06)	25,637 (0.08)	37,565 (0.08)
2010	34,486 (0.06)	24,383 (0.08)	18,826 (0.11)	47,636 (0.07)
2011	52,643 (0.06)	34,236 (0.08)	28,272 (0.1)	34,143 (0.09)
2012	40,936 (0.09)	28,926 (0.13)	25,320 (0.14)	29,971 (0.29)
2013	43,652 (0.08)	34,126 (0.1)	30,198 (0.11)	-
2014	36,622 (0.06)	26,223 (0.08)	22,929 (0.09)	-
2015	54,190 (0.06)	32,650 (0.09)	26,930 (0.11)	-
2016	29,421 (0.05)	16,552 (0.06)	12,993 (0.09)	-

Table 2.–Total run abundance and CV by age class obtained by fitting a state-space model to data from Copper River Chinook salmon, 1980–2016.

Year	Age-4	Age-5	Age-6	Age-7
1980	562 (0.94)	8,097 (0.39)	20,617 (0.38)	2,470 (0.6)
1981	1,204 (0.69)	14,531 (0.25)	16,446 (0.29)	1,662 (0.62)
1982	2,297 (0.87)	16,183 (0.35)	39,133 (0.22)	1,412 (0.78)
1983	2,559 (0.28)	44,196 (0.1)	24,387 (0.12)	611 (0.56)
1984	1,223 (0.39)	19,114 (0.12)	35,463 (0.11)	1,846 (0.32)
1985	3,923 (0.22)	17,127 (0.12)	36,077 (0.09)	1,469 (0.36)
1986	3,301 (0.24)	32,516 (0.1)	24,460 (0.11)	1,468 (0.36)
1987	1,508 (0.37)	15,820 (0.15)	39,715 (0.13)	3,272 (0.26)
1988	1,851 (0.35)	15,980 (0.14)	34,557 (0.11)	3,561 (0.27)
1989	1,503 (0.4)	14,555 (0.15)	32,527 (0.11)	3,837 (0.27)
1990	3,008 (0.28)	12,640 (0.15)	23,197 (0.13)	3,842 (0.25)
1991	2,249 (0.33)	33,806 (0.11)	20,823 (0.13)	1,360 (0.43)
1992	2,938 (0.29)	10,491 (0.16)	43,566 (0.09)	2845 (0.28)
1993	4,070 (0.24)	34,759 (0.1)	14,858 (0.14)	1,393 (0.4)
1994	4,253 (0.26)	29,054 (0.11)	37,080 (0.1)	685 (0.56)
1995	5,537 (0.25)	47,340 (0.09)	33,950 (0.11)	962 (0.55)
1996	6,599 (0.24)	41,111 (0.11)	38,276 (0.11)	697 (0.68)
1997	8,700 (0.22)	51,595 (0.11)	30,356 (0.13)	732 (0.68)
1998	6,881 (0.24)	63,802 (0.09)	30,167 (0.13)	1,092 (0.58)
1999	8,321 (0.22)	46,532 (0.09)	35,471 (0.1)	1,100 (0.58)
2000	5,111 (0.25)	48,739 (0.1)	19,061 (0.14)	539 (0.72)
2001	9,792 (0.19)	49,073 (0.09)	19,590 (0.14)	194 (1.08)
2002	11,447 (0.18)	53,630 (0.09)	22,402 (0.13)	479 (0.75)
2003	6,710 (0.23)	57,171 (0.09)	27,396 (0.12)	170 (1.16)
2004	6,244 (0.23)	40,202 (0.09)	32,326 (0.1)	469 (0.77)
2005	5,936 (0.21)	37,347 (0.07)	21,785 (0.1)	351 (0.78)
2006	13,843 (0.17)	54,408 (0.07)	19,016 (0.14)	525 (0.78)
2007	8,119 (0.18)	54,471 (0.06)	21,972 (0.11)	371 (0.8)
2008	5,646 (0.21)	30,219 (0.08)	16,614 (0.12)	381 (0.79)
2009	7,459 (0.16)	20,293 (0.09)	11,188 (0.13)	975 (0.47)
2010	9,037 (0.18)	17,880 (0.11)	6,943 (0.19)	354 (0.83)
2011	8,576 (0.16)	38,616 (0.07)	5,234 (0.21)	32 (1.56)
2012	5,226 (0.21)	28,194 (0.11)	7,370 (0.17)	24 (1.61)
2013	8,693 (0.19)	27,438 (0.11)	7,214 (0.21)	33 (1.72)
2014	10,698 (0.12)	17,781 (0.09)	8,026 (0.14)	13 (1.77)
2015	11,737 (0.13)	30,890 (0.08)	10,674 (0.13)	709 (0.48)
2016	6,072 (0.14)	17,184 (0.07)	5,764 (0.14)	253 (0.67)

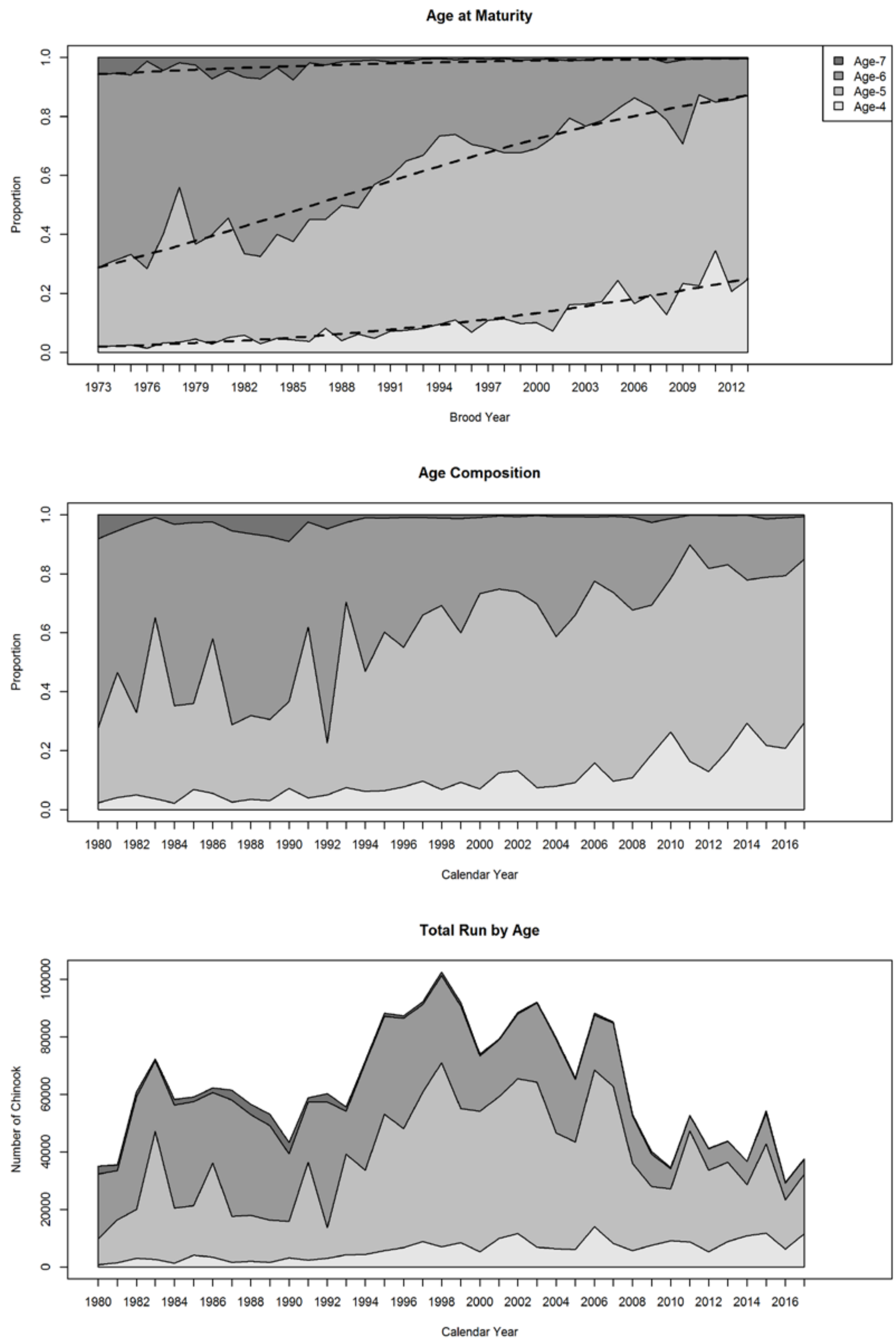

Figure 5.–Estimated age-at-maturity proportions by brood year (top), age composition proportions by calendar year (middle), and total run by age (bottom), from state-space model fitted to data from Copper River Chinook salmon.

Note: Top and middle are area graphs in which distance between lines represent age proportions.

Productivity, Yield, and Recruitment

Estimates of population parameters from the state-space model account for measurement error in escapement *S* and recruitment *R* (Figure 6). The individual paired estimates of spawners and subsequent recruitment are weighted differentially by the model based on the level of uncertainty.

None of the 1980–2012 escapements have failed to replace themselves (Figure 6). Consequently, the Ricker relationships that could plausibly explain the observed data are quite varied (Figure 6: light lines), and some deviate substantially from the median Ricker relationship (Figure 6: heavy line).

Median productivity (recruits per spawner in the absence of density effects) during 1980–2016 was high (α = 6.91; Table 3) as was the uncertainty in the parameter estimate (CV = 0.49). This is illustrated by the variation in the slopes of lefthand side of plausible spawner-recruit relationships (Figure 6). The uncertainty surrounding estimates of equilibrium abundance S_{EQ} is illustrated by the variation of values of *S* where the curves intersect the replacement line; the influence of uncertainty on β is reflected in the variability in values of *S* that lead to maximum recruitment $S_{MSR} = 1/\beta$, i.e., the peaks of all plausible spawner-recruit curves (Figure 6).

Time-varying changes in productivity after controlling for density-dependent effects are reflected in the recruitment residuals, which are deviations from recruitment expected from the median spawner-recruit relationship (Figure 4d). Productivity has been below average for all but one cohort since 2003, which coincides with the timing in decline of many other Alaska Chinook salmon stocks (ADF&G Chinook Research Team 2013).

The credibility interval around escapement leading to maximum sustained yield S_{MSY} was estimated to be 12,086 to 51,815 (posterior median 18,595, CV 0.54, Table 3). Yield is the number of fish in the expected recruitment over and above that needed to replace the spawners. The success or failure of a given number of spawners to achieve reference points across plausible spawner-recruit relationships was tallied to address this uncertainty (see Methods). The optimal yield profiles derived from this procedure illustrate the probability that a given number of spawners would achieve 70%, 80%, and 90% of MSY (Figure 7 panel 1). These probabilities increase as they approach S_{MSY} and can be used to quantify the yield performance of potential escapement goals (Figure 7: shaded areas) that take into account all of the uncertainty about the true abundance and productivity of the stock. Overfishing profiles (Figure 7: panel 2) show the probability that sustained yield would be reduced to less than 70%, 80%, or 90% of MSY by fishing too hard. For this stock, these probabilities are nearly the exact complements ($1 - p$) of the probabilities (p) in the lefthand limbs of the optimal yield profiles.

Expected sustained yield (number of fish greater than that necessary to replace the number of spawners, on average, for brood years 1980–2012) is also maximized at S_{MSY} (Figure 8). During the 5 most recent complete brood year returns (2005–2009) expected yield has decreased to approximately 50% of the 1973–2012 average (Figure 8).

Because run size is an important quantity for sport and subsistence fisheries, and because run size depends on recruitment, we constructed optimal recruitment profiles from the success or failure of a given number of spawners to achieve stated percentages of MSR across a number of plausible SR relationships. The profiles are highest near S_{MSR} (26,018, CV = 0.69, Table 3) and display the probability of achieving at least 70%, 80%, and 90% of *MSR* for specified levels of escapement (Figure 7: panel 3).

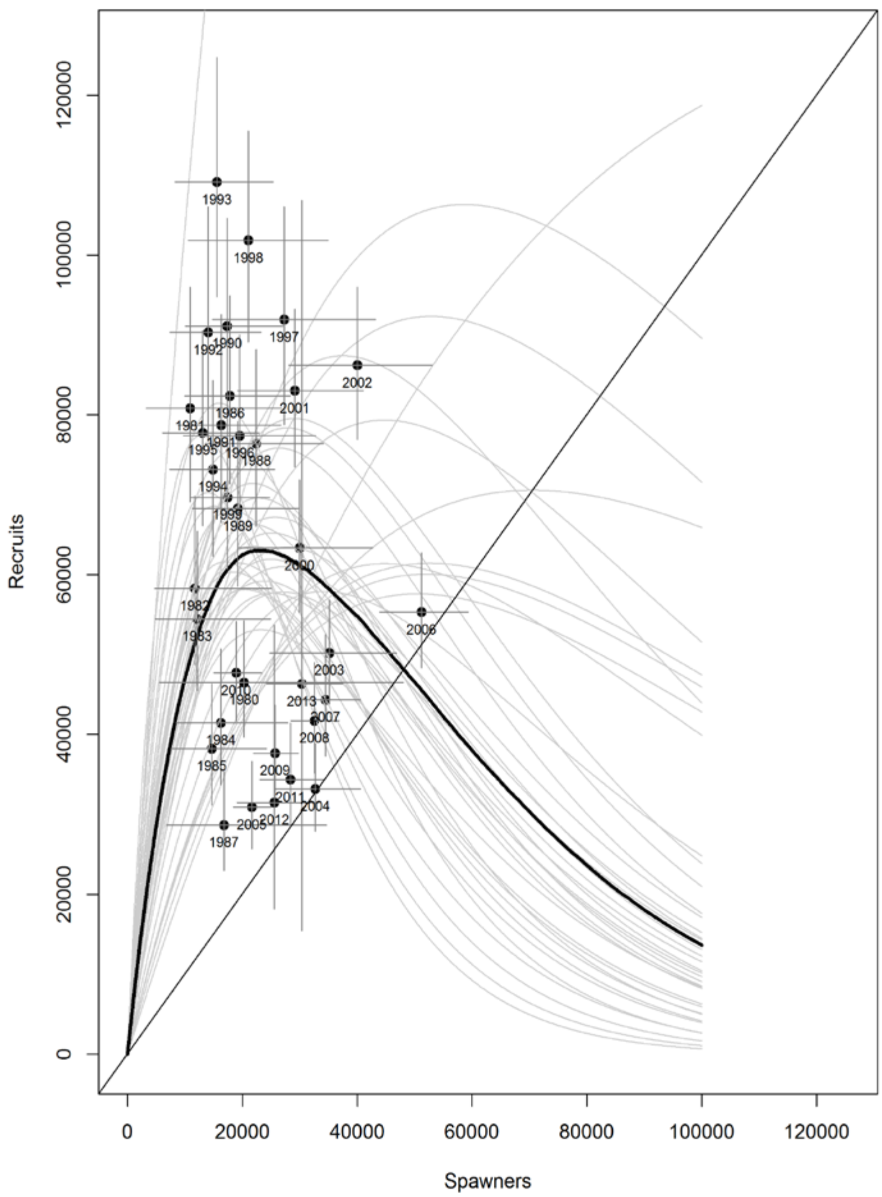

Figure 6.–Plausible spawner-recruit relationships for Copper River Chinook salmon as derived from an age-structured state-space model fitted to abundance, harvest, and age data for 1980–2016.

Note: Posterior medians of R and S are plotted as brood year labels with 95% credibility intervals plotted as light lines. The heavy line is the Ricker relationship constructed from ln(α) and β posterior medians. Ricker relationships are also plotted (light grey lines) for paired values of ln(α) and β sampled from the posterior probability distribution, representing plausible Ricker relationships that could have generated the observed data. Recruits replace spawners (R = S) on the diagonal line.

Table 3.–State-space model parameter estimates for Copper River Chinook salmon for calendar years 1980–2016.

Parameter Name	Description	Median	2.5th Percentile	97.5th Percentile	CV
α (alpha)	Measure of productivity	6.91	2.50	14.56	0.49
β (beta)	Measure of density-dependence	0.00	0.00	0.00	0.38
ϕ (phi)	Autocorrelation between recruitment residuals	0.55	0.00	0.95	0.49
S_{MSR}[a]	Number of spawners providing MSR	26,018	14,579	85,219	0.69
S_{EQ}[a]	Equilibrium spawning abundance	51,964	38,056	157,081	0.58
S_{MSY}[a]	Number of spawners providing MSY	18,595	12,086	51,815	0.55
U_{MSY}[a]	Harvest rate at MSY	0.74	0.50	0.86	0.12
q.GA	Index scale factor for Gulkana aerial counts	0.04	0.03	0.06	0.14
q.DNAS$_1$	Index scale factor for 1st dip net regime	0.97	0.86	1.00	0.04
q.DNAS$_2$	Index scale factor for 2nd dip net regime	0.41	0.32	0.51	0.12
q.DNAS$_3$	Index scale factor for 3rd dip net regime	0.18	0.14	0.22	0.12
q.SubAS	Index scale factor for subsistence fishery	0.85	0.74	0.95	0.06
q.GT	Index scale factor for Gulkana tower counts	0.12	0.10	0.14	0.08
σ^2.GA	Standard deviation of scaled relationship with Gulkana aerial counts	0.64	0.46	0.89	0.17
σ^2.DNAS	Standard deviation of scaled relationship with dip net fishery	0.32	0.24	0.44	0.16
σ^2.SubAS	Standard deviation of scaled relationship with subsistence fishery	0.30	0.20	0.43	0.19
σ^2.GT	Standard deviation of scaled relationship with Gulkana tower counts	0.26	0.16	0.43	0.26

[a] The CVs for the reference points S_{EQ}, S_{MSR}, S_{MSY}, and U_{MSY} were calculated as (97.5th percentile–2.5th percentile)/3.92/posterior median point estimate. If the posterior median is approximately normal, then the lower and upper bound of the 95% credibility interval are both ~1.96 × standard errors from the median.

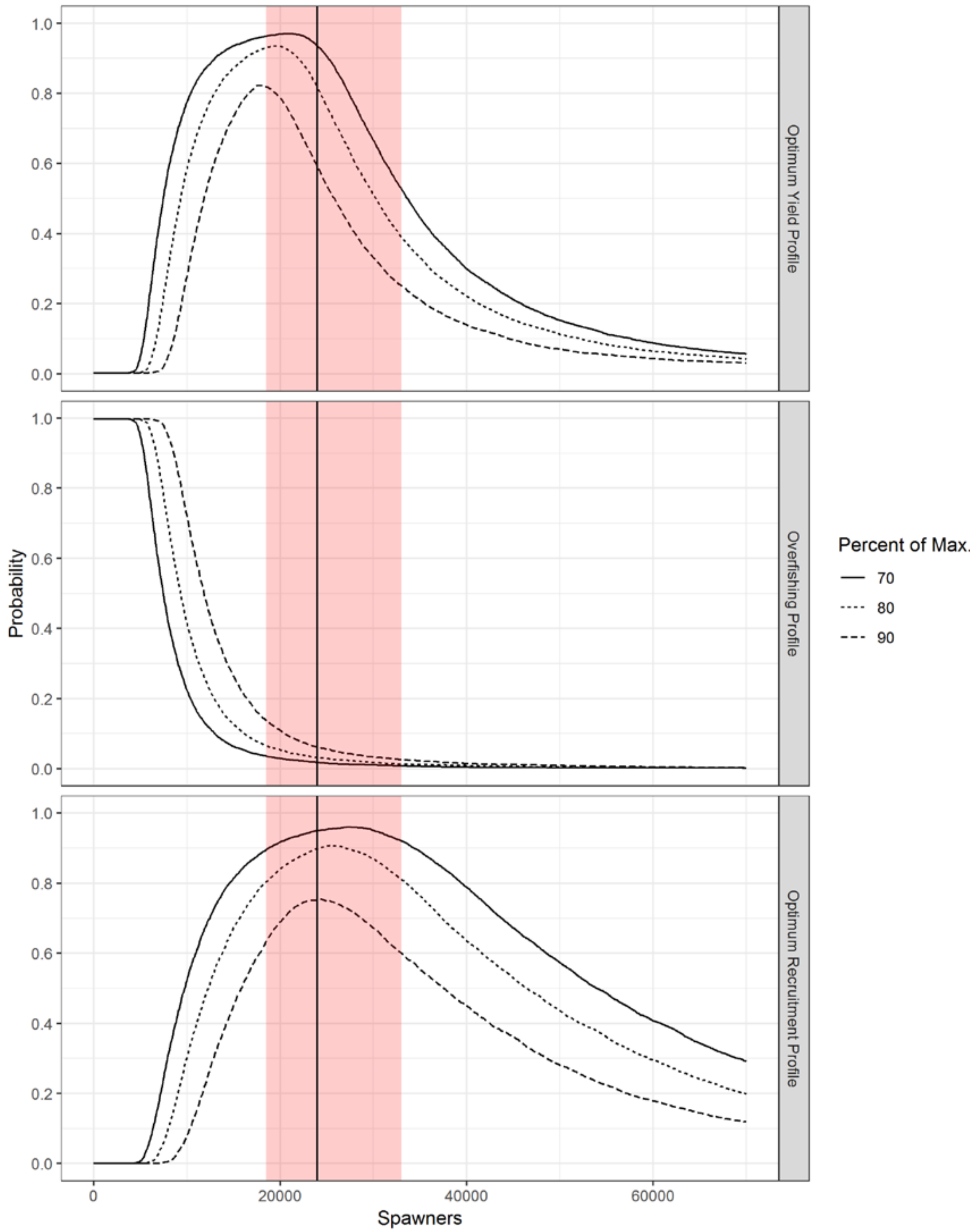

Figure 7.–Optimal yield profiles (OYPs), overfishing profiles (OFPs), and optimal recruitment profiles (ORPs) for Copper River Chinook salmon as derived from an age-structured state-space model fitted to abundance, harvest, and age data for 1980–2016.

Note: OYPs and ORPs show probability that a specified spawning abundance will result in specified fractions (70%, 80%, and 90% line) of maximum sustained yield or maximum recruitment. OFPs show probability that reducing escapement to a specified spawning abundance will result in less than specified fractions of maximum sustained yield. Shaded areas bracket the recommended goal range and the vertical black lines represent the current escapement goal.

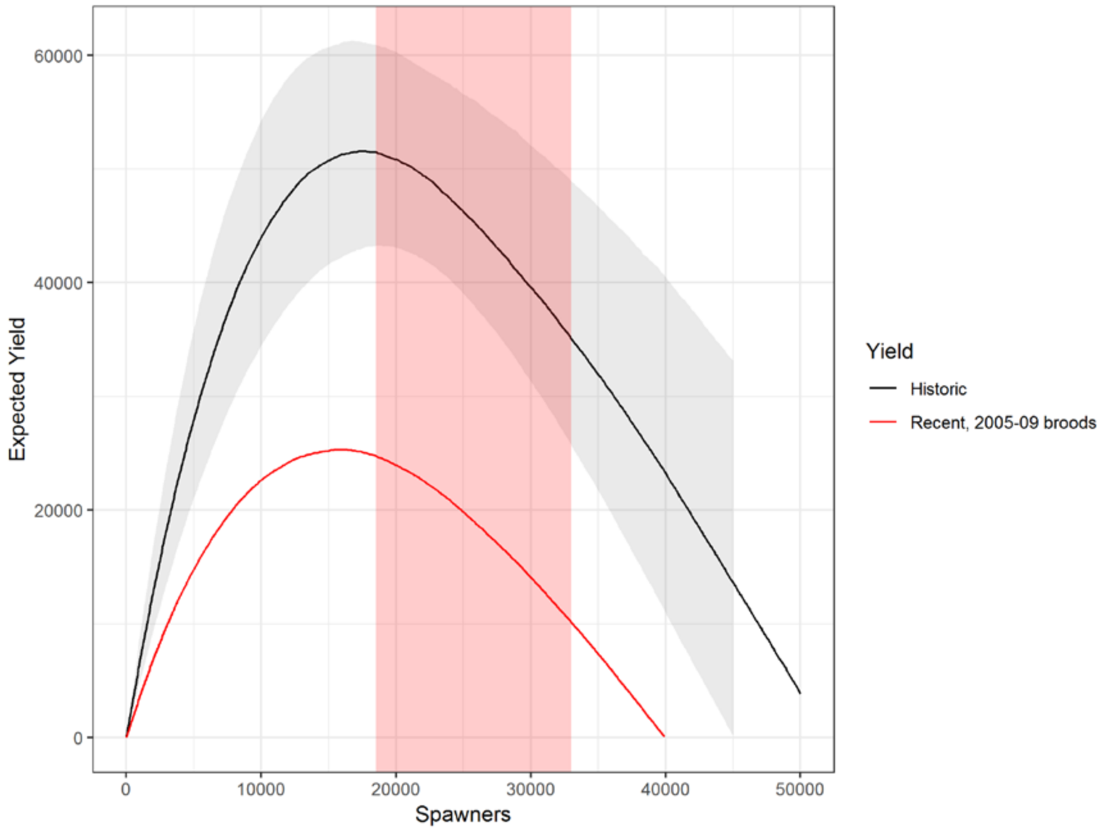

Figure 8.–Expected sustained yield (ESY) plots for Copper River Chinook salmon as derived from an age-structured state-space model fitted to abundance, harvest, and age data for 1980–2016.

Note: ESY median (solid black line) and 50% credibility interval (shaded area around the line) assume average productivity for brood years 1973–2012 (historical). Median ESY under recent, reduced productivity (brood years 2005–2009) is also shown (solid red line). The shaded vertical area brackets the recommended goal range.

DISCUSSION

SPAWNER-RECRUIT ANALYSIS

Obtaining reliable estimates of escapement and subsequent recruitment is arguably the most challenging problem a salmon stock assessment biologist endures because management of many Alaska salmon stocks is based on a fixed escapement goal that, when appropriate, attempts to maximize sustainable yields. The reference point, S_{MSY}, on which a number of these goals are based, was commonly derived under the assumption that the SR relationship is stationary over time. Clark et al. (2009) has shown that this approach can be effective but things like time-series (Walters 1985) and errors-in-variables (Kope 2006) bias, differing maturity schedules, lack of contrast in escapement (Hilborn and Walters 1992), and the fact that spawner abundance is not independent of recruitment (Fleischman et al. 2013) can lead to biased parameter estimates that affect derived reference points. Fleischman et al. (2013) developed a generalized age-structured state-space model that handles these issues by accommodating process (time-varying productivity) and observation error; the model also improved the methodology used when selecting an escapement goal because incorporating these features allows the model to better reflect the biological reality and informative content of the age-structured data.

Fitting this model to estimates of relative and absolute abundance, harvest, and age composition from Copper River Chinook salmon provided relatively precise estimates of escapement, recruitment, and total run size (Tables 1 and 2), but any inference to the true SR relationship and subsequent reference points was imprecise. The number of plausible curves derived from the posterior distribution of the α and β parameters illustrates the uncertainty in the relationship between recruits and spawners (Figure 6). Lack of spawner contrast can help explain the uncertainty in β because the stock has never experienced density-dependence at the level where they fail to replace themselves. Large observation error in some estimates of R (Figure 6) coupled with moderate serial correlation (ϕ) in model residuals can explain some of this uncertainty. The serial correlation suggests nonstationary productivity, which is reflected in the overall steep decline in productivity since the early 2000s (Figure 4d). Even though there is a lot of uncertainty about the true SR relationship and reference points, one can still evaluate what levels of S will lead to optimal yields in the long term using the optimal yield and overfishing profiles (Figure 7). These profiles illustrate the probability of achieving specified percentages of MSY while maintaining a low probability of overfishing. These optimal yield profiles provide an objective appraisal of the quality of information about optimal escapement levels contained in the data, and actual probabilities are available to help weigh risks and benefits of alternative management choices (Fleischman et al. 2013).

ESCAPEMENT GOAL RECOMMENDATION

Based on the previous information and analyses, the Alaska Department of Fish and Game recommends a sustainable escapement goal (SEG; definition in 5 AAC 39.222 [f] [36]) of 18,500–33,000 Copper River Chinook salmon.

During this review, an integrated state-space model was fit to all relevant harvest, age composition, and abundance data from 1980–2016. The method simultaneously reconstructs historical abundance and fits a spawner–recruit relationship. The model accommodates missing data, measurement error, and changes in age at maturity, and accounts for the associated uncertainty. The number of spawners that provide maximum sustained yield S_{MSY} is the biological reference point of most interest. The state-space model (S_{MSY} = 18,595), similar to the catch-age model (S_{MSY} = 19,711), estimates S_{MSY} to be lower than the current lower bound SEG.

Ideally an escapement goal would contain the estimate of S_{MSY} within the goal range to encompass the range of escapements expected to produce the largest harvestable surplus. However, results from this analysis indicate the number of recruits per spawner and age-at-maturity have decreased in recent years, and both of these attributes can affect the mechanisms that drive stock production (Figures 4 and 5). For these reasons, it may be beneficial to recommend a goal where the lower-bound starts at the full model's estimate of S_{MSY} rather than bracketing in some fashion around the full model estimate of S_{MSY}. The upper-bound should then be set at a point where the probability of achieving at least 70%, 80%, or 90% of SMSY is not too low, or in this case ~50%. The optimum yield and recruitment profiles (Figure 7) illustrate how the recommended goal is trading yield for recruitment.

The circumstances surrounding each individual stock are unique, and this is reflected in their respective escapement goals. Fleischman and Reimer (2017) compiled and published escapement goal ranges for 22 Alaska Chinook salmon stocks and standardized them by dividing the upper and lower bounds by estimated values of S_{MSY} for each stock (Appendix C1). These standardized values provide a useful way to compare the attributes of escapement goals across stocks. Among Alaska Chinook salmon stocks, lower bounds ranged from 62% to 100% (mean 77%) of S_{MSY}, and upper bounds ranged from 120% to 192% (mean 155%) of S_{MSY}. For Copper River Chinook salmon, the proposed SEG is 99.5% of S_{MSY} at the lower bound and 177% of S_{MSY} at the upper bound. The proposed Copper River Chinook salmon SEG is the highest in the state relative to S_{MSY}, among the 23 stocks (Appendix C1).

SUMMARY AND CONCLUSIONS

The state-space model has been recognized as a scientifically sound method to use when selecting an escapement goal. Escapement goals based on estimation of S_{MSY} and robust evaluation of the uncertainty surrounding plausible SR relationships (Figure 7) are more credible than goals based solely on the record of historic returns. The state-space model used for this analysis has been effectively applied to Chinook salmon stocks throughout the state (Fleischman and Reimer 2017; Fleischman and McKinley 2013; Hamazaki et al. 2012).

The recommended goal preserves the original intent of the current SEG with respect to providing sustained yield. The recommended goal attempts to accomplish this by encompassing the estimate of S_{MSY} (18,595) but also takes into account having a low probability of overfishing and high probability of maximizing recruitment (S_{MSR}). Escapements near the lower bound have a high probability (97%, 90%, and 83%) of achieving yields that are at least 70%, 80%, and 90% of MSY, respectively. The probability of maximum yield decreases as the SEG range approaches the upper bound (50%, 40%, and 25%). This decrease is offset by maintaining high probability of achieving at least 70% of maximum recruitment within the proposed escapement goal range.

The effect of the recommended goal on fishery management will depend upon total run abundance. Run-timing patterns of Copper River Chinook salmon sub-stocks is varied, but in most years a larger proportion of upriver stocks (i.e., Gulkana and E. Fork Chistochina) migrate through the various fisheries earlier than downriver sub-stocks (i.e., Klutina, Tonsina, and Chitina). During this time period the first commercial openers take place and prices for sockeye and Chinook salmon are at their highest. In addition, the personal use and subsistence fisheries open and fishers congregate throughout the drainage to get some of the "first run" salmon. Under these circumstances large runs, which are preferred by all fisheries, may take inriver fisheries under more consideration because improvements in fishery efficiency may be more important than achieving MSY. Typically, large recruitments for this stock have resulted in larger runs, and constructing optimum recruitment profiles illustrates this point (Figure 7) and supports the committee's choice to encompass both estimates of S_{MSY} and S_{MSR}.

Our knowledge of Copper River Chinook salmon stock dynamics will improve over time. This analysis relied partially upon indirect run reconstruction of past quantities because a complete time series of absolute estimates of abundance was unavailable. Stock assessment capabilities have improved greatly since 1998 and there are currently 18 estimates of escapement (1999–2016) derived from mark–recapture experiments. One configuration of the state-space model only used information from 1999–2016 and estimated S_{MSY} to be ~25,400, but the precision of this estimate was much lower than the accepted model that used all available relevant data (1980–2016). This difference is likely from the decrease in production of this stock over time. Statistical methods that accommodate varying levels of measurement error and give greater weight to more precise estimates were used during this analysis and acquiring more estimates of inriver abundance will contribute further to state-space model estimates.

The escapement goals for Copper River Chinook salmon will be periodically reviewed. All Pacific salmon escapement goals in the State of Alaska are subject to triennial review to allow for consideration of recent data, improvements in escapement assessment, and changes in stock productivity. During the next review, prior to the 2020 Prince William Sound board meeting, there will be 3 more years of direct assessment data and it will be possible to quantify the recruitment from the low escapement in 2014.

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APPENDIX A:
SUPPORTING INFORMATION FOR ESCAPEMENT GOAL RECOMMENDATION FOR COPPER RIVER CHINOOK SALMON

Appendix A1.–Estimates of Chinook salmon harvest from the Copper River District, Chitina Subdistrict, Glennallen Subdistrict, and sport fishery (1980–2016) and, when available, estimates of inriver abundance, total run, harvest rate, and escapement (1999–2016).

	Copper District						Chitina Subdistrict			Glennallen Subdistrict								
	Commercial	Subsistence	Homepack	Donated	Educational	District Total	Harvest			Harvest			Sport	Total	Inriver	Total	Harvest	Total
Year	Harvest	Harvest	Harvest	Harvest	Harvest	Harvest	State	Federal	Total	State	Federal	Total	Harvest	Harvest	Abundance	Run	Rate	Escapement
1980	8,454	19				8,473	1,767		1,767	3,035		3,035	2,101	15,376				
1981	20,178	48				20,226	1,410		1,410	2,410		2,410	1,717	25,763				
1982	47,362	60				47,422	1,900		1,900	2,764		2,764	1,802	53,888				
1983	52,500	79				52,579	4,255		4,255	5,950		5,950	2,579	65,363				
1984	38,957	68				39,025	1,760		1,760	509		509	2,787	44,081				
1985	42,214	88				42,302	1,329		1,329	1,958		1,958	1,939	47,528				
1986	40,670	86				40,756	2,367		2,367	686		686	3,663	47,472				
1987	41,001	49				41,050	2,968		2,968	813		813	2,301	47,132				
1988	30,741	59				30,800	2,994		2,994	992		992	1,562	36,348				
1989	30,863	56				30,919	2,251		2,251	787		787	2,356	36,313				
1990	21,702	60				21,762	2,708		2,708	647		647	2,302	27,419				
1991	34,787	136				34,923	4,056		4,056	1,328		1,328	4,884	45,191				
1992	39,810	142				39,952	3,405		3,405	1,449		1,449	4,412	49,218				
1993	29,727	120				29,847	2,846		2,846	1,434		1,434	8,217	42,344				
1994	47,061	164	751			47,976	3,743		3,743	1,989		1,989	6,431	60,139				
1995	65,675	154	1,688			67,517	4,707		4,707	1,892		1,892	6,709	80,825				
1996	55,646	276	2,169	0	0	58,091	3,584		3,584	1,482		1,482	9,116	72,273				
1997	51,273	200	1,243	0	0	52,716	5,447		5,447	2,583		2,583	8,346	69,092				
1998	68,827	295	1,411	0	0	70,533	6,723		6,723	1,842		1,842	8,245	87,343				
1999	62,337	353	1,115	0	14	63,819	5,913		5,913	3,278		3,278	6,742	79,752	32,090	95,909	83%	16,157
2000	31,259	689	740	6	8	32,702	3,168		3,168	4,856		4,856	5,531	46,257	38,047	70,749	65%	24,492
2001	39,524	826	935	0	16	41,301	3,113		3,113	3,553		3,553	4,904	52,871	39,778	81,079	65%	28,208
2002	38,734	549	773	4	27	40,087	2,023	33	2,056	3,653	564	4,217	5,098	51,458	32,873	72,960	71%	21,502
2003	47,721	710	1,073	3	0	49,507	1,903	18	1,921	2,538	554	3,092	5,717	60,237	44,764	94,271	64%	34,034
2004	38,191	1,106	539	5	0	39,841	2,495	7	2,502	3,346	636	3,982	3,435	49,760	40,564	80,405	62%	30,645
2005	34,624	219	760	11	92	35,706	2,043	51	2,094	2,229	389	2,618	4,093	44,511	30,333	66,039	67%	21,528
2006	30,278	779	779	3	11	31,850	2,663	18	2,681	2,769	460	3,229	3,425	41,185	67,789	99,639	41%	58,454
2007	39,095	1,145	1,019	0	70	41,329	2,694	28	2,722	3,276	663	3,939	5,113	53,103	46,349	87,678	61%	34,575
2008	11,437	470	537	4	47	12,495	1,999	23	2,022	2,381	837	3,218	3,616	21,351	41,343	53,838	40%	32,487
2009	9,457	212	876	0	50	10,595	214	9	223	2,493	543	3,036	1,355	15,209	32,401	42,996	35%	27,787
2010	9,645	276	906	0	31	10,858	700	18	718	2,099	326	2,425	2,416	16,417	22,323	33,181	49%	16,764
2011	18,500	212	1,282	0	6	20,000	1,067	13	1,080	2,319	743	3,062	1,753	25,895	33,889	53,889	48%	27,994
2012	11,764	237	853	0	6	12,860	567	5	572	2,095	415	2,510	535	16,477	31,452	44,312	37%	27,835
2013	8,826	854	564	0	55	10,299	744	18	762	2,148	374	2,522	285	13,868	32,581	42,880	32%	29,012
2014	10,207	153	768	0	36	11,164	719	14	733	1,365	420	1,785	931	14,613	24,158	35,322	41%	20,709
2015	22,506	167	1,145	0	50	23,868	1,570	15	1,585	2,212	402	2,614	1,343	29,410	32,306	56,174	52%	26,764
2016	12,348	73	727	0	86	13,234	711	15	726	2,075	396	2,471	327	16,758	16,009	29,243	57%	12,485

APPENDIX B:
DATA OBJECTS AND RJAGS CODE

Appendix B1.–State-space model input: Estimates of harvest below and above Miles Lake sonar, Miles Lake sonar abundance of all salmon, inriver abundance of Chinook salmon, Gulkana River counting tower escapement of Chinook salmon, harvest of Chinook and sockeye salmon in the personal-use and subsistence fisheries, and the Gulkana River aerial index, 1980–2016.

Year	Harvest Below Sonar[a]	Proportion of Copper Stocks in Harvest Below Sonar	Miles Lake Sonar Count	Harvest Above Sonar[b]	Inriver Abundance (CV)	Gulkana Counting Tower Escapement (CV)	Proportion in Personal Use Harvest	Proportion in Subsistence Harvest	Gulkana Aerial Index (Quality Score[c])
1980	8,473			6,903				0.09	712 (2)
1981	20,226			5,537				0.04	77 (5)
1982	47,422			6,466				0.03	879 (2)
1983	52,579			12,784				0.05	589 (4)
1984	39,025		618,732	5,056			0.035	0.02	1,331 (2)
1985	42,302		466,190	5,226			0.041	0.06	224 (1)
1986	40,756		481,628	6,716			0.055	0.02	1,484 (1)
1987	41,050		523,022	6,082			0.064	0.02	1,098 (1)
1988	30,800		528,940	5,548			0.066	0.03	831 (2)
1989	30,919		643,367	5,394			0.039	0.03	2,009 (2)
1990	21,762		624,922	5,657			0.039	0.02	1,171 (1)
1991	34,923		593,185	10,268			0.050	0.03	1,223 (3)
1992	39,952		604,898	9,266			0.038	0.03	540 (3)
1993	29,847		819,700	12,497			0.030	0.03	693 (2)
1994	47,976		738,011	12,163			0.038	0.03	786 (2)
1995	67,517		637,293	13,308			0.056	0.03	285 (2)
1996	58,091		907,267	14,182			0.036	0.03	1,364 (3)
1997	52,716		1,164,791	16,376			0.035	0.03	2,270 (2)
1998	70,533		865,896	16,810			0.047	0.03	1,407 (2)
1999	63,861		850,597	15,933	32,090 (0.12)		0.040	0.04	934 (2)
2000	32,707		636,837	13,555	38,047 (0.20)		0.029	0.08	1,174 (3)
2001	41,377		878,205	11,570	39,778 (0.21)		0.023	0.04	691 (2)
2002	40,101		830,263	11,371	32,873 (0.27)	6,390 (0.05)	0.023	0.07	2,087 (2)
2003	49,741		747,091	10,730	44,764 (0.28)	4,890 (0.06)	0.023	0.05	982 (2)
2004	39,995		684,103	9,919	40,564 (0.11)	4,734 (0.06)	0.022	0.05	2,014 (2)
2005	36,024	0.97	855,125	8,805	30,333 (0.05)	2,718 (0.06)	0.016	0.03	822 (2)
2006	32,088	0.86	959,706	9,335	67,789 (0.07)	4,846 (0.06)	0.021	0.04	1,183 (1)
2007	41,421	0.94	919,601	11,784	46,349 (0.07)	4,422 (0.06)	0.021	0.05	1,182 (2)
2008	12,537	0.92	718,344	8,856	41,343 (0.05)	3,678 (0.07)	0.024	0.05	No survey
2009	10,606		709,748	4,614	32,401 (0.07)	2,720 (0.07)	0.002	0.05	701 (1)
2010	10,858		923,811	5,552	22,323 (0.11)	2,267 (0.07)	0.005	0.03	728 (1)
2011	20,002		914,231	5,895	33,889 (0.10)	3,804 (0.07)	0.008	0.04	515 (2)
2012	12,860		1,271,354	3,541	31,452 (0.17)	1,730 (0.09)	0.004	0.03	512 (2)
2013	10,299		1,267,060	3,904	32,581 (0.14)	3,936 (0.05)	0.004	0.03	2,220 (1)
2014	11,164		1,218,418	3,318	24,158 (0.09)	3,478 (0.08)	0.005	0.02	944 (2)
2015	23,868		1,341,545	5,699	32,306 (0.12)	3,738 (0.07)	0.007	0.02	1,523 (1)
2016	13,625		801,593	3,475	16,009 (0.07)	1,122 (0.15)	0.004	0.03	No survey

[a] Harvest below sonar includes commercial, subsistence, home pack, donated, educational, and confiscated Chinook salmon in the Copper River District.

[b] Harvest above sonar includes personal-use, sport, and federal and state subsistence Chinook salmon.

[c] Quality scale of 1 through 5, where 1 equals clear skies and water and 5 equals cloudy and turbulent water.

Appendix B2.–Age-composition estimates from the Copper River District commercial fishery, 1980–2016.

Year	Age-4	Age-5	Age-6	Age-7	Sample Size
1980	0.01	0.29	0.63	0.07	219
1981	0.09	0.42	0.42	0.07	135
1982			No data collected		
1983	0.04	0.64	0.32	0.00	3,165
1984	0.02	0.34	0.60	0.03	2,387
1985	0.07	0.29	0.62	0.02	2,830
1986	0.06	0.54	0.38	0.02	2,766
1987	0.02	0.24	0.67	0.06	2,576
1988	0.04	0.26	0.64	0.07	1,752
1989	0.03	0.25	0.64	0.08	1,545
1990	0.07	0.26	0.56	0.11	1,594
1991	0.04	0.58	0.36	0.02	1,596
1992	0.05	0.14	0.76	0.06	1,996
1993	0.07	0.64	0.27	0.02	2,043
1994	0.05	0.39	0.55	0.01	1,999
1995	0.06	0.54	0.39	0.01	2,118
1996	0.07	0.47	0.45	0.01	1,729
1997	0.10	0.58	0.32	0.01	1,805
1998	0.07	0.64	0.28	0.01	1,920
1999	0.10	0.52	0.37	0.01	1,694
2000	0.06	0.70	0.24	0.01	1,830
2001	0.12	0.65	0.23	0.00	1,845
2002	0.13	0.62	0.25	0.01	2,143
2003	0.07	0.63	0.30	0.00	1,931
2004	0.07	0.50	0.42	0.01	1,865
2005	0.07	0.57	0.35	0.01	2,103
2006	0.16	0.62	0.21	0.00	1,568
2007	0.09	0.64	0.26	0.00	2,290
2008	0.11	0.58	0.31	0.00	1,365
2009	0.20	0.49	0.28	0.03	1,457
2010	0.28	0.49	0.21	0.01	725
2011	0.16	0.76	0.09	0.00	1,760
2012	0.11	0.72	0.17	0.00	1,565
2013	0.21	0.64	0.15	0.00	916
2014	0.31	0.46	0.23	0.00	1,876
2015	0.23	0.55	0.21	0.01	2,505
2016	0.21	0.58	0.20	0.01	1,775

Appendix B3.–RJAGS code for the state-space model of Copper River Chinook salmon data, 1980–2016.

```
mod=function(){
  for (y in (A+a.min):(Y+A-1)) {
    log.R[y] ~ dt(log.R.mean2[y],tau.white,500)
    R[y] <- exp(log.R[y])
    log.R.mean1[y] <- log(S[y-a.max]) + lnalpha - beta * S[y-a.max]
    log.resid[y] <- log(R[y]) - log.R.mean1[y]
    lnalpha.y[y] <- lnalpha + log.resid[y]
  }
  log.resid.vec <- log.resid[(A+a.min):(Y+A-1)]
  lnalpha.vec <- lnalpha.y[(A+a.min):(Y+A-1)]
  log.R.mean2[A+a.min] <- log.R.mean1[A+a.min] + phi * log.resid.0
  for (y in (A+a.min+1):(Y+A-1)) {
    log.R.mean2[y] <- log.R.mean1[y] + phi * log.resid[y-1]
  }
  lnalpha ~ dnorm(0,1.0E-6)%_%T(0,)
  beta ~ dnorm(0,1.0E-2)%_%T(0,)
  phi ~ dnorm(0,1.0E-4)%_%T(-1,1)
  tau.white ~ dgamma(0.001,0.001)
  log.resid.0 ~ dnorm(0,tau.red)%_%T(-3,3)
  alpha <- exp(lnalpha)
  tau.red <- tau.white * (1-phi*phi)
  sigma.white <- 1 / sqrt(tau.white)
  sigma.red <- 1 / sqrt(tau.red)
  lnalpha.c <- lnalpha + (sigma.white * sigma.white / 2 / (1-phi*phi) )
  S.max <- 1 / beta
  S.eq <- lnalpha.c * S.max
  S.msy <- S.eq * (0.5 - 0.07*lnalpha.c)
  U.msy <- lnalpha.c * (0.5 - 0.07*lnalpha.c)
```

-continued-

```
# BROOD YEAR RETURNS W/O SR LINK DRAWN FROM COMMON LOGNORMAL
DISTN
mean.log.R ~ dnorm(0,1.0E-4)%_%T(0,)
tau.R ~ dgamma(0.001,0.001)
R.0 <- exp(mean.log.R)
sigma.R0 <- 1 / sqrt(tau.R)
for (y in 1:a.max) {
  log.R[y] ~ dt(mean.log.R,tau.R,500)
  R[y] <- exp(log.R[y])
}

# GENERATE Y+A-1 MATURITY SCHEDULES, ONE PER BROOD YEAR
D.scale ~ dunif(0,1)
D.sum <- 1 / (D.scale * D.scale)

# MULTIVARIATE LOGISTIC DIRICHLET MODEL FOR TRENDING AGE AT
MATURITY
eta1[A] <- 1
eta2[A] <- 0
for (a in 1:(A-1)) {
  eta1[a] ~ dnorm(0,0.0001)
  eta2[a] ~ dnorm(0,0.0001)
}

for (y in 1:(Y+A-1)) {
  for (a in 1:A) {
    logistic.a[y,a] <- exp(eta1[a] + eta2[a] * y)
    pi.y[y,a] <- logistic.a[y,a] / sum(logistic.a[y,])
    Dirch_gamma_shape[y,a] <- D.sum * pi.y[y,a]
    g[y,a] ~ dgamma(Dirch_gamma_shape[y,a],0.1)
    p[y,a] <- g[y,a]/sum(g[y,])
```

-continued-

```
    }
  }



  # ASSIGN PRODUCT OF P AND R TO ALL CELLS IN N MATRIX
  # y SUBSCRIPT INDEXES BROOD YEAR
  # y=1 IS THE BROOD YEAR OF THE OLDEST FISH IN YEAR 1 (upper right cell)
  # y=Y IS THE BROOD YEAR OF THE YOUNGEST FISH IN YEAR Y (lower left cell,
forecast year)
  # ASSIGN PRODUCT OF P AND R TO ALL CELLS IN N MATRIX
  for (a in 1:A) {
    for (y in a:(Y + (a - 1))) {
      N.ta[y - (a - 1), (A + 1 - a)] <- p[y, (A + 1 - a)] * R[y]
    }
  }

  # OBSERVE AGE COMPOSITION
  for (t in 1:Y) {
    N[t] <- sum(N.ta[t,1:A])
    for (a in 1:A) {
      q[t,a] <- N.ta[t,a] / N[t]
    }
  }
  # MULTINOMIAL SCALE SAMPLING ON TOTAL ANNUAL RETURN N
  # INDEX t IS CALENDAR YEAR
  # OVERLAP IS MUCH LARGER THAN IN PREVIOUS VERSIONS
  for (t in 1:Y) {
    x[t, 1:A] ~ dmulti(q[t, ], n.a[t])
  }

  # INRIVER RUN OBSERVED, AS WELL AS HARVESTS BELOW AND ABOVE
ASSESSMENT SITE
```

-continued-

```
for (y in 1:Y) {
  mu.Hbelow[y] ~ dbeta(0.1,0.1)
  H.below[y] <- mu.Hbelow[y] * N[y]
  H.below.all[y] <- H.below[y] / prop.copper[y
  log.Hba[y] <- log(H.below.all[y])
  tau.log.Hba[y] <- 1 / log(cv.Hb[y]*cv.Hb[y] + 1)
  Hhat.below.all[y] ~ dlnorm(log.Hba[y],tau.log.Hba[y])

  InriverRun[y] <- max(N[y] - H.below[y], 1)
  log.IR[y] <- log(InriverRun[y])

  mu.Habove[y] ~ dbeta(0.1,0.1)
  H.above[y] <- mu.Habove[y] * InriverRun[y]
  log.Ha[y] <- log(H.above[y])
  tau.log.Ha[y] <- 1 / log(cv.Ha[y]*cv.Ha[y] + 1)
  Hhat.above[y] ~ dlnorm(log.Ha[y],tau.log.Ha[y])

  mu[y] <- (H.below[y] + H.above[y]) / N[y]
  S[y] <- max(InriverRun[y] - H.above[y], 1)
  log.S[y] <- log(S[y])
}

# HIERARCHICAL PROPORTIONS COPPER IN CHINOOK HARVEST BELOW
ASSESSMENT SITE
zeta1 ~ dunif(1,1000)
zeta2 ~ dunif(1,1000)
for (y in 1:Y) {
  prop.copper[y] ~ dbeta(zeta1,zeta2)
  count.copper[y] ~ dbin(prop.copper[y],N.copper[y])
}
```

-continued-

```
# OBSERVE MARK RECAP ESTIMATE OF INRIVER RUN
for (y in 1:Y) {
  MR[y] ~ dlnorm(log.IR[y],tau.log.mr[y])
  tau.log.mr[y] <- 1 / log(cv.mr[y]*cv.mr[y] + 1)
}

# PRIORS FOR INDEX PARAMS
q.subas ~ dnorm(0,1.0E-1)%_%T(0,1)
q.dnas1 ~ dnorm(0,1.0E-1)%_%T(0,1)
q.dnas2 ~ dnorm(0,1.0E-1)%_%T(0,1)
q.dnas3 ~ dnorm(0,1.0E-1)%_%T(0,1)
q.air ~ dnorm(0,1.0E-1)%_%T(0,1)
q.tower ~ dnorm(0,1.0E-1)%_%T(0,1)
tau.log.subas ~ dgamma(0.01,0.01)
tau.log.dnas1 ~ dgamma(0.01,0.01)
tau.log.air ~ dgamma(0.01,0.01)
tau.log.tower ~ dgamma(0.01,0.01)
sigma.subas <- 1 / sqrt(tau.log.subas)
sigma.dnas1 <- 1 / sqrt(tau.log.dnas1)
sigma.air   <- 1 / sqrt(tau.log.air)
sigma.tower <- 1 / sqrt(tau.log.tower)

# OBSERVE MILES LAKE SONAR APPORTIONED BY CHINOOK PROPORTION IN
SUBSISTENCE FISHERY AS INDEX OF INRIVER RUN
for (y in 1:Y) {
  log.qIRsubmean[y] <- log(q.subas * InriverRun[y])
  subas[y] ~ dlnorm(log.qIRsubmean[y],tau.log.subas)
}

# OBSERVE MILES LAKE SONAR APPORTIONED BY CHINOOK PROPORTION IN PU
FISHERY AS INDEX OF INRIVER RUN
# PROPORTIONALITY CONSTANT ALLOWED TO DIFFER 1980-1999 VS 2000-2016
```

-continued-

```
  for (y in 1:20) {
    log.qIRmean[y] <- log(q.dnas1 * InriverRun[y])
    dnas[y] ~ dlnorm(log.qIRmean[y],tau.log.dnas1)
  }

  for (y in 21:29) {
    # for (y in 21:Y) {
    log.qIRmean[y] <- log(q.dnas2 * InriverRun[y])
    dnas[y] ~ dlnorm(log.qIRmean[y],tau.log.dnas1)
  }

  for (y in 30:Y) {
    log.qIRmean[y] <- log(q.dnas3 * InriverRun[y])
    dnas[y] ~ dlnorm(log.qIRmean[y],tau.log.dnas1)
  }

  # OBSERVE GULKANA TOWER COUNTS AND AIR SURVEYS AS INDICES OF
ESCAPEMENT
  for (y in 1:Y) {
    log.qtSmean[y] <- log(q.tower * S[y])
    gka.tower[y] ~ dlnorm(log.qtSmean[y],tau.log.tower)
    log.qaSmean[y] <- log(q.air * S[y])
    gka.air[y] ~ dlnorm(log.qaSmean[y],tau.log.air)
  }

  # MEAN LNA FOR 5 MOST RECENT BROOD YEARS
  lnalpha.recent    <- mean(lnalpha.y[(Y+A-5):(Y+A-1)])
  lnalpha.c.recent <- lnalpha.recent + (sigma.white * sigma.white / 2 / (1-phi*phi) )
  U.msy.recent <- lnalpha.c.recent * (0.5 - 0.07*lnalpha.c.recent)
  S.eq.recent <- lnalpha.c.recent * S.max
  S.msy.recent <- S.eq.recent * (0.5 - 0.07*lnalpha.c.recent)
}
```

APPENDIX C: ESCAPEMENT GOALS RELATIVE TO ESTIMATES OF SPAWNING ABUNDANCE PROVIDING MAXIMUM SUSTAINED YIELD FOR 23 ALASKA CHINOOK SALMON STOCKS

Appendix C1.–Escapement goal lower and upper bounds for 23 Alaska Chinook salmon stocks, including the established lower bound goal for the Copper River (solid black line) and the recommended SEG range for Copper River Chinook, plotted as multiples of S_{MSY}.