Spawner-Recruit Analysis and Escapement Goal Recommendation for Chinook salmon in the Kuskokwim River Drainage

by

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Symbols and Abbreviations

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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	$(F, t, \chi^2,$ 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

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ESCAPEMENT GOAL RECOMMENDATION FOR CHINOOK SALMON IN THE KUSKOKWIM RIVER DRAINAGE

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ABSTRACT

Using 1976–2011 estimates of annual run size, harvests, and age-composition from a reconstruction analysis, a spawner recruit analysis was conducted for Chinook salmon *Oncorhynchus tshawytscha* of the Kuskokwim River drainage, and the results used to select a drainagewide escapement goal. For estimation of the spawner–recruit parameters, we employed a Bayesian state-space modeling method that explicitly incorporated uncertainties associated with the size of annual run and escapement and age composition, as well as serial correlation and missing data. The analysis found that the stock is highly productive and does not show evidence of overharvest. Based on expected yield predictions from the spawner-recruit model, we recommend a drainagewide sustainable escapement goal (SEG) of 65,000–120,000 Chinook salmon. The goal will provide expected yields greater than 100,000 Chinook salmon, adequate for subsistence needs, and it has a lower bound that was chosen conservatively as an escapement equal to the lowest documented escapement from recent years that produced recruits adequate for subsistence needs. From the drainagewide escapement goal, three sustainable escapement goals were derived for the Kwethluk, George, and Kogrukluk rivers, for which Chinook salmon escapements are monitored annually with weirs, by multiplying the upper and lower bounds of the drainagewide goal by the mean proportion of tributary escapement to drainagewide escapement. Recommended tributary SEGs are 1,800–3,300 for George River, 4,800–8,800 for Kogrukluk River, and 4,100–7,500 for Kwethluk River. Discontinuation of the escapement goal for Tuluksak River was also recommended.

Key words   Chinook salmon, *Oncorhynchus tshawytscha*, Kuskokwim River, Kwethluk River, George River, Kogrukluk River, Tuluksak River, escapement goal, Ricker spawner-recruit analysis, Bayesian state-space model.

INTRODUCTION

The Kuskokwim River is the second largest river in Alaska, draining an area of about 130,000 km^2 along its 1,498 km course from interior Alaska to the Bering Sea (Figure 1) and supports a large population of Chinook salmon, *Oncorhynchus tshawytscha*. From late May to early August Chinook salmon migrate back to the mouth of the Kuskokwim River and spawn in tributaries throughout the drainage (Stuby 2007). The Kuskokwim River salmon fisheries are managed according to the *Kuskokwim River Salmon Management Rebuilding Plan* (5 AAC 07.365) adopted by the BOF in January 2001 (Burkey et al. 2000), amended in January 2004 (Bergstrom and Whitmore 2004) and again in 2007 (Linderman and Bergstrom 2006). The purpose of this plan is to provide guidelines for rebuilding and management of the fishery that will result in the sustained yield of salmon stocks large enough to meet escapement goals, provide amounts reasonably necessary for subsistence, and provide for fisheries other than subsistence. Additionally, subsistence-fishing closures are scheduled by emergency order prior to, during, and after commercial fishing periods to assure salmon harvested during open subsistence fishing periods do not reach the commercial market. Kuskokwim River Chinook salmon are harvested primarily for subsistence use. Directed Chinook salmon commercial fishing in the Kuskokwim River was discontinued in 1987 by regulation (Francisco et al. 1988). Commercial salmon fishing is restricted to 6 inch mesh; however, in District 1, ADF&G may open fishing periods during which gillnet mesh size may not exceed 8 inches. Chinook salmon continued to be harvested in chum and sockeye salmon directed commercial fisheries during late June and July under a guideline harvest range of 0–50,000 fish.

HISTORY OF THE KUSKOKWIM RIVER CHINOOK SALMON FISHERIES

Subsistence Fisheries

In the Kuskokwim River drainage, subsistence fisheries comprise 60–99% of the total Chinook salmon harvest (Figure 2). Approximately 1,000 households participate in the subsistence fishery from 26 communities found within the basin. Most harvest is taken by drift or set gillnets

of ≥ 8 inch mesh size (Molyneaux et al. 2010) during the first half of the upriver migration period (Hamazaki 2008). Annual subsistence harvest has been monitored since 1960 by ADFG Commercial Fisheries and Subsistence divisions. Annual subsistence harvest increased slightly during 1960s–1980s from average of 33,000 to 50,000, increased further during the 1990s to 90,000–100,000, and slightly declined to 84,000 during the 2000s (Figure 2). The increase since the 1990s is probably due to increased survey coverage and improvement in harvest estimation methodology (Hamazaki 2011). The Alaska Board of Fisheries (BOF) determined the annual "amount necessary for subsistence" (ANS) to be 64,500–83,000 for Kuskokwim River Chinook salmon (5 AAC 01.286(b)).

Commercial Fisheries

Commercial salmon fishing for export has occurred in the Kuskokwim River since about 1935 (Pennoyer et al. 1965). Establishment of directed commercial fisheries occurred during the 1970s. The majority of commercial harvest occurs in District W-1, which spans the lower 200 river kilometers (rkm) of the Kuskokwim River (Figure 1). More limited harvest has occurred in District W-2, which encompasses in the middle Kuskokwim River from rkm 262 near Kalskag to rkm 322 near Chuathbaluk, but the most recent Chinook harvest from District W-2 was only 3 fish in 1998 (Whitmore et al. 2008). Historically, there was a District W-3 that extended upstream of Chuathbaluk, but it was discontinued in 1966. Gear types used in the commercial fishery changed throughout history. From 1960s to 1984 commercial gillnet mesh size was unrestricted (primarily ≥ 8 inch) prior to June 25 and was restricted thereafter to ≤ 6 inch mesh to target species other than Chinook salmon. In 1985 commercial gillnet mesh size was restricted to ≤ 6 inch mesh. In 1987 the directed Chinook salmon commercial fishery (i.e., opening prior to June 25 with unrestricted mesh size) was discontinued. Since 1987, the only commercial Chinook salmon catch is incidental, from chum, sockeye, and coho fisheries. Commercial Chinook salmon harvest averaged 23,000 per year during the 1960s, and ranged from 30,000 to 40,000 from 1970 to mid-1990s. Since 1995, commercial harvest declined with an average harvest of 6,000 (Figure 2; Brazil et al. 2011). The decline was largely due to the lack of market and processing capacity. The price of Chinook salmon has been about equal to that of sockeye salmon. During 2000s, the price was about $0.5 per pound (Brazil et al. 2011).

Decline of Chinook Salmon 2010–2012

From 1976 to 2011 annual runs of the Kuskokwim River Chinook salmon showed a cyclical pattern of peaks and valleys occurring on a roughly 10 year cycle (Figure 2; Bue et al. 2012). Severe declines in the annual run were reported in the mid-1980s and late 1990s to early 2000s, which led a number of management actions (Brazil et al. 2011). The decline in the mid-1980s led to discontinuation of the directed Chinook salmon commercial fishery in 1987. The decline in 2000 led to the Alaska Board of Fisheries designating Kuskokwim River Chinook salmon as a "stock of concern," with harvest restrictions for all users, including the institution of weekly closures of the subsistence fishery (Burkey et al. 2000; Hamazaki 2008; Estensen et al. 2009).

In 2010, the US Fish and Wildlife Service took special action, Emergency Order No. 3-KS-01-10, for conservation of Chinook salmon in Federal waters of the Tuluksak and Kwethluk rivers and was in effect from July 10, 2010 until July 31, 2010. Under this action, subsistence fishing using gillnets was restricted to less than 4 inches mesh and shorter than 60 feet length. Furthermore, subsistence fishing for Chinook salmon was closed for all gear types including hook and line. Failure of achieving escapement goals in 2008–2010 in lower Kuskokwim River

tributaries, combined with a forecast for a low run similar to 2010, prompted a preseason determination of required action at the tributary levels in 2011. In 2011 subsistence fishing in lower Kuskokwim River tributary waters was closed from June 1 through July 25 (Emergency Order No. 3-S-WR-01-11). Additionally, subsistence fishing within the Federal Conservation Unit (from the mouth of the Kuskokwim River upstream to the confluence of the Aniak and Kuskokwim Rivers, including all tributary rivers in between) was closed to gillnets with mesh greater than 4 inches from June 30 until July 2 (Federal Management special actions contained in 3-KS-01-11 and 3-KS-02-11). The resulting escapements in 2011 did not achieve escapement goals at the lower river tributaries. This failure to achieve escapement goals in the lower Kuskokwim River tributaries prompted similar preseason actions in 2012 (EO No. 3-S-WR-01-12), and further mainstem restrictions resulting in a total of 14 days of subsistence closure (gillnets limited to ≤ 4 inch), and 23 days of additional gear size limited to ≤ 6 inch mesh gillnets throughout most of the river.

Escapement Goal Review

Salmon in Alaska are managed to achieve escapement goals consistent with the *Policy for the Management of Sustainable Salmon Fisheries* (5 AAC 39.222, 2000) and the *Policy for Statewide Salmon Escapement Goals* (5 AAC 39.223, 2001). Currently there are 11 established Chinook salmon escapement goals on the Kuskokwim River: 7 assessed with aerial surveys and 4 assessed with weirs, established or revised in 2005 and 2007 (Volk et al. 2009). All goals are sustainable escapement goals (SEGs) derived using the percentile method (Bue and Hasbrouck *Unpublished[1]*; Bue et al. 2002). Since 2007 knowledge about Kuskokwim River Chinook salmon run, escapement, and productivity have been greatly improved through studies funded by Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative (AYKSSI 07-304, 45082 and 45554). During 2002–2006, mark–recapture studies were conducted annually to estimate the number of Chinook salmon migrating upstream of 155 river mile (near Kalskag). These inriver abundance estimates, along with weir counts in tributaries of the lower river, were used to generate the estimates of run size and escapement (Schaberg et al. 2012). Further, by combining all available historical escapements, harvests, and age compositions throughout the Kuskokwim River drainage, Bue et al. (2012) estimated drainagewide annual run, escapement, and age composition of the Kuskokwim River Chinook salmon from 1976 to 2011. From these estimates, brood year recruitment (number of adult progenies from a brood year escapement) was reconstructed. The reconstructed spawner-recruit data showed an inverse relationship between escapement and recruit (Figure 3). Years of high escapement resulted in low or below replacement recruitment (i.e., recruitment (R) is less than escapement (S), or R/S < 1.0) in 1977, 1978, 1980, 1981, 1994-1997, and 2004–2005 (Figure 3). In contrast, years of low escapement resulted in high recruitment, especially in 1986, 1989, and 2000.

These advances made it possible to fit a spawner-recruit model to estimate productivity and capacity of Kuskokwim River Chinook salmon, thereby providing basis for setting a drainagewide escapement goal. In 2008 the AYKSSI convened an expert panel to evaluate methods to establish a drainagewide escapement goal for the Kuskokwim River Chinook salmon stock (AYKSSI 2011). The expert panel developed a Bayesian state-space modeling approach to

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[1] Bue, B. G., and J. J. Hasbrouck. *Unpublished*. Escapement goal review of salmon stocks of Upper Cook Inlet. Alaska Department of Fish and Game, Report to the Alaska Board of Fisheries, November 2001 (and February 2002), Anchorage.

estimate spawner-recruit parameters, and also evaluated how the choice of a management strategy (e.g. setting levels of minimum escapement goal according to various policy choices) would affect average subsistence catch, probability of meeting minimum ANS, or probability of a stock of concern designation (AYKSSI 2011). Based on these advances, the Alaska Department of Fish and Game recommends establishing a Kuskokwim River drainagewide Chinook salmon escapement goal and revising select tributary escapement goals to achieve consistency with the drainagewide goal.

OBJECTIVES

The objectives of this report are to: 1) describe the productivity and capacity of the Kuskokwim River Chinook salmon stock, as quantified from stock-recruit analyses, 2) recommend a drainagewide escapement goal based on this information, and 3) revise escapement goals for selected tributaries.

METHODS

DATA SOURCE

Historical (1976–2011) estimates of Kuskokwim River Chinook salmon annual run size, its coefficient of variation (CV), and age-composition were obtained from Bue et al. (2012) (Table 1; Appendix A1). Bue et al. (2012) estimated the historical run size using a methodology developed by Shotwell and Adkison (2004) that combined all available historical escapement, harvest, and run size data under a Maximum Likelihood framework. However because available data were limited and accuracy and precision of the data are unknown, we doubled the reported CVs of annual run size. This assumes greater uncertainty of annual run size than estimated by the run reconstruction model.

Bue et al. (2012) estimated age composition of the total run by compiling data from escapement projects and from commercial and subsistence fisheries; making carefully considered assumptions and substitutions where necessary; and weighting each component by relative abundance. Because they did not provide a measure of uncertainty for the age composition estimates, we assumed an effective sample size of 25 for 1976–1999 and 100 for 2000–2011. Effective sample size is an index of uncertainty, with lower size indicating greater uncertainty.

Kuskokwim River Chinook salmon runs comprise 6 age classes (age 3 to age 8); however, the proportions of age 3 (0.2 and 1.1) and age 8 (1.6 and 2.5) are very small (Bue et al. 2012). Those 2 age classes were dropped from the run age composition, and adjusted age composition (age 4 to age 7) was recalculated and used for the spawner-recruit model.

Harvest of Kuskokwim River Chinook salmon consists of commercial, subsistence, sport, and test fisheries (Appendix A1). Harvests of sport and test fisheries were combined with subsistence harvest.

In this report we follow the convention of using the term "run" to describe the number of adults migrating back to their natal stream in a given calendar year and either being harvested or escaping to spawn. The term "recruitment" refers to fish from a single spawning event migrating back over multiple calendar years.

SPAWNER-RECRUIT ANALYSIS

For the purpose of setting an escapement goal, a Bayesian state-space spawner-recruit model (Rivot et al. 2004; Su and Peterman 2012) was employed to fit abundance, harvest, and age composition data. The model provides information about the productivity and capacity of the Kuskokwim River Chinook salmon stock. The state-space model considers process variation in stock productivity, recruit, and age-at-maturation separately from observation error in run size, harvest, and age composition. Explicit consideration of age structure allows for more realistic depiction of missing data and more complete use of recent data. The possibility of time-varying productivity is accounted for and estimated. Because historical run size and age-composition of the Kuskokwim Chinook salmon were estimated from incomplete data sources (Bue et al. 2012), the Bayesian space-state model is appropriate for this application.

Bayesian State-Space Model

In constructing a Bayesian state-space model (BSS), we separate two components of uncertainties: observation error and process variation. Observation error reflects the uncertainty of imperfect measurement of observations (e.g., annual run, escapement, age composition), whereas process variation describes natural fluctuation in the actual quantities.

Process Sub-model

The process variation (similar to "process error" in frequentist statistics) component of the state-space model specifies productivity and age at maturity by cohort, identified by the brood year of the spawning event. Salmon produced from a single cohort migrate back to their natal stream over multiple calendar years. The observation error component operates in calendar year steps, in the form of annual harvest surveys, weir counts, and age composition sampling. Observed annual quantities from these programs make it possible to reconstruct the runs from individual spawning events, by brood year, from components staggered across multiple calendar years. In the following modeling section, root parameters (those requiring prior distributions) are typed in **bold**, and notation of all years is based on calendar year.

Assume that log of recruitment (R) of Chinook salmon from the t-th brood year run, or the number of adults returning from spawners of t-th year, $\ln(R_t)$, is an independent random variable from normal distribution with mean μ_t and variance $\boldsymbol{\sigma_R}^2$:

$$\ln(R_t) \overset{iid}{\sim} N(\mu_t, \sigma_R^2) . \tag{1}$$

Here, μ_t is a Ricker (1954) stock-recruit function with autoregressive lognormal errors (Noakes et al. 1987):

$$\mu_t = \ln(S_t) + \ln(\alpha) - \beta S_t + \phi \omega_{t-1} . \tag{2}$$

In equation 2, $\boldsymbol{\ln(\alpha)}$ and $\boldsymbol{\beta}$ are the productivity and density dependent parameters of the Ricker stock-recruit relationship, S_t is the number of spawners in the t-th year, φ is the autoregressive lag 1 (AR1) coefficient, and ω_{t-1} is a difference between model and observation of previous year ($\ln(R_{t-1}) - \mu_{t-1}$), starting from unknown parameter $\boldsymbol{\omega_0}$. For year t,

$$\omega_t = \ln(R_t) - \mu_t = \ln(R_t) - \ln(S_t) - \ln(\alpha) + \beta S_t . \tag{3}$$

For Chinook salmon, t-th brood year recruitment (R_t) consists of multiple ages {a: 1, 2,.., a,.. ,n_a) classes,

$$R_t = R_{t,1} + R_{t,2} +,..., R_{t,a} + ...R_{t,n_{aa}} \quad \text{or} \quad R_t = \sum R_{t,a} .$$ (4)

Further, let $p_{t,a}$ be the proportion of the a-th class for R_t recruitment; then,

$$R_{t,a} = p_{t,a} \cdot R_t \quad \text{and} \quad R_t = \sum p_{t,a} \cdot R_t$$ (5)

The proportion of the a-th age class, $p_{t,a}$ is considered a maturity schedule and is assumed to be drawn from a Dirichlet distribution, implemented by generating independent random variables from the gamma distribution, $g_{ta} \sim \Gamma(\gamma_a, 1)$ and dividing by their sum,

$$p_{t,a} = \frac{g_{t,a}}{\sum g_{t,a}} \quad g_{t,a} \sim \Gamma(\gamma_a, 1)$$ (6)

As a part of model diagnosis, proportions of recruit at age (π_a) and dispersion parameter (D) of the Dirichlet distribution were calculated as:

$$\pi_a = \frac{\gamma_a}{D} \quad \text{and} \quad D = \sum \gamma_a .$$ (7)

The parameter D can be interpreted as an index for the variability of the age proportion vectors across cohorts, with smaller D leading to more variability and vice versa.

Those multiple age classes of t-th brood year recruit in $t+a$-th year. Alternatively, the a-th age Chinook salmon returning in t-th year is a recruit from spawner of $t-a$ th year.

The number of age-a Chinook salmon returning to spawn in year t ($N_{t,a}$) is

$$N_{t,a} = R_{t-a,a} = p_{t-a,a} \cdot R_{t-a} .$$ (8)

Then, total number of Chinook salmon retuning in calendar year t is the sum of the number of run-at-age across all ages:

$$N_t = \sum N_{t,a} = \sum_a p_{t-a,a} \cdot R_{t-a}$$ (9)

And the proportion of a-th age class in calendar year t ($q_{t,a}$) is calculated as

$$q_{t,a} = \frac{N_{t,a}}{\sum_a N_{t,a}}$$ (10)

During the season, Chinook salmon are harvested first by the commercial fishery (H_{ct}), with harvest rate u_{ct}, applied to the number of fish at the mouth of the river (N_t),

$$H_{ct} = u_{ct} \cdot N_t .$$ (11)

The subsistence fishery (H_{st}) is assumed to occur after the commercial fishery, with harvest rate u_{st} applied to remainder of fish ($N_t - H_{ct}$):

$$H_{st} = u_{st} \cdot (N_t - H_{ct}) .$$ (12)

6

Since the end of directed Chinook salmon commercial fisheries in 1987, commercial harvest of Chinook salmon occurs incidentally during chum and sockeye directed fisheries later in the season after the majority of subsistence fishery harvest has occurred. However, this does not affect estimates of H_{ct} and H_{st} that were fitted to observed harvests (equations 16 and 17).

Assuming no other inriver mortality (e.g., mortality during migration to spawning grounds), the number of Chinook salmon reaching spawning grounds (i.e., escapement, S_t) in calendar year t is the difference between the run size and the harvest by commercial and subsistence fisheries:

$$S_t = N_t - H_{ct} - H_{st}.$$

(13)

Observation Sub-model

The observed number of Chinook salmon run in t-th calendar year ($N_{(ob)t}$) was modeled to be log-normally distributed (LN) with mean $\ln(N_t)$ and variance σ^2_{Nt},

$$N_{(ob)t} \sim LN(\ln(N_t), \sigma^2_{Nt}),$$

(14)

where σ^2_{Nt} was derived from the observed CV as,

$$\sigma^2_{Nt} = \ln(CV^2_{Nt} + 1).$$

(15)

In a similar manner, observed commercial ($H_{(ob)c,t}$) and subsistence fisheries ($H_{(ob)s,t}$) of t-th year was modeled to be log-normally distributed with mean $\ln(H)$ and variance derived from the observed CV:

$$H_{(ob)c,t} \sim LN(\ln(H_{ct}), \sigma^2_{ct}), \qquad \sigma^2_{c,t} = \ln(CV^2_{ct} + 1)$$

(16)

$$H_{(ob)s,t} \sim LN(\ln(H_{st}), \sigma^2_{st}), \qquad \sigma^2_{s,t} = \ln(CV^2_{st} + 1)$$

(17)

The proportion of *a-th* age Chinook salmon in calendar year t ($q_{(ob)t,a}$) is a composite from various sources with unknown variances. Variance of age composition was quantified by multiplying the proportion ($q_{(ob),t,a}$) by the annual "effective sample sizes" $n_{ef,\,t}$. Let

$$x_{t,a} = q_{(ob)t,a} \cdot n_{ef,t}.$$

(18)

The age counts $x_{t,a}$ were assumed to be have a multinomial distribution,

$$X_t \sim mult(n_{ef,t}, \theta_t)$$

(19)

where $X_t = \{x_{t,1}, x_{t,2}, \dots, x_{t,a}\}$, $\Sigma x_{t,a} = n_{ef,t}$,

$\theta_t = \{q_{t,1}, q_{,t,2}, \dots, q_{t,a}\}$ $\Sigma q_{t,a} = 1$ from equation (10).

Prior Distributions

Bayesian analyses require that prior probability distributions be specified for all unknown parameters in the model. For this analysis, all prior distributions were designed to be non-informative.

For variance of $\ln(R_t)$, $\sigma_R{}^2$,

$\sigma_R{}^2 \sim 1/\Gamma(0.001, 0.001)$.

For the Ricker model parameters: $\ln(\alpha)$, β, φ, ω_0,

$\ln(\alpha) \sim N(0, 10^6)$, $(\ln(\alpha) > 0)$;

$\beta \sim N(0, 10^6)$, $(\beta > 0)$;

$\varphi \sim Uni(-1, 1)$; and

$\omega_0 \sim N(0, \sigma_R{}^2/(1- \varphi^2))$, $(-5 \leq \omega_0 \leq 5)$.

For proportions of recruit ages, γ_{ab} ,

$\gamma_a \sim \Gamma(0.005,0.005)$.

For harvest rates, u_{ct} and u_{st},

$u_{ct} \sim Beta(0.1,0.1)$, and

$u_{st} \sim Beta(0.1,0.1)$.

Biological Reference Points for Management

To determine biological reference points important for management, we estimated the following parameters: equilibrium escapement producing recruitment equal to escapement (S_{eq}); escapement providing maximum sustainable yield (S_{msy}); and escapement providing maximum recruitment (S_{max}). S_{msy} was calculated using Hilborn's (1985) approximation, incorporating corrections for lognormal process variation and AR(1) serial correlation (CTC 1999). We started with,

$$S_{eq} = \ln(\alpha')/\beta, \text{ where} \tag{20}$$

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

Then we calculated S_{msy} and S_{max} as,

$$S_{msy} = \ln(\alpha')(0.5-0.07\ln(\alpha'))/\beta \tag{21}$$

$$S_{max} = 1/\beta. \tag{22}$$

Model Fitting

Markov-chain Monte Carlo (MCMC) methods (WinBUGS v1.4; Spiegelhalter et al. 1999) were used to generate the joint posterior probability distribution of all unknowns in the model. Two Markov chains were initiated. A total of 2.5 million MCMC updates were generated, with a 125,000-sample burn-in period that was discarded. Each chain was thinned by taking every 500th sample. This resulted in 4,750 posterior samples for each chain. Bayesian credible intervals (95%) were obtained from the percentiles (2.5 and 97.5) of the marginal posterior distribution. The slowest mixing parameter (with highest autocorrelation) was D. History plots and kernel density plots for convergence diagnostic are provided in Appendix C.

From each posterior sample, expected sustained yield at a specified level of *S* was obtained by subtracting spawning escapement from the expected recruit, per the Ricker model:

$$Y_S = Se^{\ln(\alpha') - \beta S} - S . \tag{23}$$

For each MCMC sample of $\ln(\alpha')$ and β, Y_s was calculated for incremental values of escapement (*S*). By plotting percentiles of Y_s versus *S*, uncertainty about expected yield can be graphically depicted. Note that this does not depict a range of predicted annual yields, but instead, depicts uncertainty about the true average yields at different levels of *S*.

The probability that a given spawning escapement *S* would produce average yields exceeding 90% of *MSY* was obtained by calculating Y_S at incremental values of *S* (0 to 200,000 by 2,000) for each MCMC sample, then comparing Y_S with 90% of the value of *MSY* for that sample. The proportion P_Y of samples in which Y_S exceeded 90% of *MSY* is an estimate of the desired probability, and the plot of P_Y versus *S* is termed an optimal yield probability profile.

The probability that a given spawning escapement *S* would produce average recruit exceeding 90% of maximum recruit *MR* was obtained by calculating *R* at incremental values of *S* (0 to 200,000 by 2,000) for each MCMC sample, then comparing *R* with 90% of the value of *MR* for that sample. The proportion P_R of samples in which *R* exceeded 90% of *MR* is an estimate of the desired probability, and the plot of P_R versus *S* is termed a maximum recruitment probability profile.

Sensitivity to Model Assumptions

In the base analysis, we made an arbitrary decision about uncertainty of annual runs and age composition (Table 1). Here we examined the effects this arbitrary decision by running the same model with different assumptions of uncertainties. For alternative analysis BSSA-1, we provide the results using the original CVs from Bue et al. (2012; not doubled). For alternative analysis BSSA-2, we set effective sample size (*efn*) to 100 for all years. Finally, alternative analysis BSSA-3 was a combination of BSSA-1 and BSSA-2 (i.e., CVs from Bue et al. (2012; not doubled), and all *efn* = 100).

We also calculated estimates of spawner-recruit parameters using more traditional analysis methods (TSR). The linearized form of the Ricker relationship with multiplicative process error (Hilborn and Walters 1992) was used:

$$\ln\left(\frac{R}{S}\right) = \ln \alpha - \beta S + \varepsilon \quad \text{where } \varepsilon \sim N\left(0, \sigma_\varepsilon^2\right). \tag{24}$$

Linear regression of $\ln(R/S)$ on *S* was conducted to estimate the parameters $\ln\alpha$ (*y*-intercept), β (slope), and σ_ε^2 (residual error). Statistical uncertainty about the parameters and reference points was assessed with a bootstrap technique: resampling the residuals of the linear regression with replacement, calculating all parameter estimates and reference points for each bootstrap replicate, and using percentiles of the bootstrap values to obtain interval estimates. Productivity was corrected for lognormal process error (Hilborn 1985).

The differences between the baseline model and 4 alternative models can be summarized as follows. The TSR analysis assumes that the data were accurate and without error. The baseline analysis assumes the data were accurate but have high uncertainties. Finally, the 3 BSSA analyses assume the data were accurate and have some uncertainty but less than in the baseline model.

TRIBUTARY ESCAPEMENT GOAL DETERMINATION

After the Kuskokwim River drainagewide goal (EG_{drn}) was determined, tributary escapement goals (EG_{trib}) were adjusted to synchronize with the drainagewide goal. The tributary escapement goals (EG_{trib}) were determined by multiplying the upper and lower bounds of EG_{drn} by the average proportion of tributary contribution to drainagewide escapement ($\bar{p}_{trib}$),

$$EG_{trib} = \bar{p}_{trib} \cdot EG_{drn}. \tag{25}$$

The average proportion ($\bar{p}_{trib}$) of escapement at each tributary was estimated as,

$$\bar{p}_{trib} = \frac{\sum \hat{p}_{trib,t}}{n} \quad \text{where} \quad \hat{p}_{trib,t} = N_{trib,t} / N_{drn,t}, \tag{26}$$

where,

$\hat{p}_{trib,t}$ = the annual proportion of escapement observed at tributary in year (t),

$N_{trib,t}$ = escapement of a tributary ($trib$) in year (t), and

$N_{drn,t}$ = escapement to Kuskokwim River in year (t).

The above formula assumes that relative proportion of each tributary to drainagewide escapement fluctuates around a central tendency. This was also a fundamental assumption for the Kuskokwim River Chinook salmon run reconstruction (Bue et al. 2012).

RESULTS

In the Bayesian state-space model, all uncertain quantities are dynamic and considered in the context of all other quantities. The MCMC values of model parameters are those that plausibly could have resulted in the observed data. Because annual values of total run, N, are uncertain parameters like any others, information about them is updated in the course of the analysis. Thus, the posterior medians and percentiles of annual run and escapement differ from Bue et al. (2012) (Figure 4), which served as input data. In statistical terminology, the original values of Bue et al. (2012) "shrank" toward the fitted values of the SR model.

The posterior median point estimate of the Ricker spawner-recruit relationship in both linearized (Figure 5) and typical (Figure 6) forms illustrate shrinkage of spawner and recruit points toward the fitted values. All results from the state-space model take into account measurement error in both S and R as depicted by the error bars, essentially weighting the individual data pairs depending on how precisely they were estimated. Productivity residuals were spread around 0 across years, which indicates a good model fit (Figure 7). Median residuals were negative (i.e., lower recruit than model expectation) during the 1977–1987 and 1994–1997 periods, whereas large positive residuals were observed in 1989 and 2000.

The (baseline, BSS) estimate of ln(α) was 2.07 (95% CI 1.91–2.48), corresponding to $\alpha = 7.9$ (95% CI: 4.6–11.9; Table 2). The estimate of the density dependent parameter β was 1.13×10^{-6} (95% CI: 0.77×10^{-6}–1.45×10^{-6}), and σ_R^2 was 0.19 (95% CI: 0.10–0.30). The estimated AR(1) parameter φ was 0.34 (95% CI: -0.59–0.92), which suggests weak serial correlation in residuals. Median brood year recruit age proportions were 0.194 for age 4 (pi[1]), 0.382 for age 5 (pi[2]), 0.390 for age 6 (pi[3]), and 0.033 for age 7 (pi[4]), which indicates, consistent with observation, that the majority of adults complete their spawning migration at age 5 and 6. The age proportion variation parameter D was 137, which suggests stable recruit age composition.

Median S_{msy}, S_{max}, and S_{eq} were 65,440 (95% CI: 54,800–82,500), 88,515 (95% CI: 69,000–129,300), and 185,000 (95%CI: 161,650–223,600), respectively. Median yield at S_{msy}, the maximum sustainable yield (MSY) was approximately 186,000 (95% CI: 118,000–269,000); yield at S_{max}, the level expected to produce maximum recruitment (R_{max}), was approximately 170,000 (95% CI: 116,000–253,000).

From those two reference parameters, two escapement goal ranges were calculated: 1) a range achieving at least 90% of MSY more than 90% of time, and 2) a range achieving at least 90% of R_{max} more than 90% of time. Based on probability profile analyses, S_{msy} range was determined to be 48,400–84,400 fish, and S_{max} range was determined to be 68,000–113,600 (Figures 8 and 9). With either of these goals, the 95% lower bound of expected yield is about 100,000 Chinook salmon, or in other words, there is less than a 2.5% probability that the expected yields would be less than 100,000 Chinook salmon (Figure 9).

ESCAPEMENT GOAL RECOMMENDATION

DRAINAGEWIDE ESCAPEMENT GOAL RANGE

We recommend a **drainagewide Kuskokwim River Chinook salmon escapement goal range of 65,000–120,000.**

Rationale

In setting a Kuskokwim drainagewide escapement goal, the two standard reference parameters were calculated as described above: 1) spawning population size that maximizes sustained yield (MSY) on average, S_{msy}; and 2) spawning population size that maximizes recruitment (R_{max}) on average, S_{max}. The main difference between the two objective parameters resides in the nature of fisheries. An S_{msy} based escapement goal is deemed more appropriate where fishery is dominated by commercial fisheries that have excess fishing power sufficient to harvest all available yields. On the other hand, an S_{max} based escapement goal is deemed more appropriate where the fishery is dominated by subsistence and sport fisheries that harvest a fixed amount of fish regardless of run size and are attempting to minimize the effort needed to harvest.

In finalizing escapement goal recommendations, the following factors were considered.

1) The predominant Chinook salmon fishery of the Kuskokwim River is a subsistence fishery; therefore, expected yields must be adequate for subsistence needs (i.e., yield at least 100,000 fish) and the goal should be set to minimize the chance of restricting the fishery.

2) There is also a limited commercial fishery with maximum harvest level of 50,000 fish (typically harvested incidentally in chum and sockeye directed fisheries), and a small sport fishery that typically harvests less than 2,500 fish.

3) The lower bound of the escapement goal should not be lower than the lowest historical estimated escapement that has provided recruit sufficient for meeting subsistence harvest needs.

Based on the first two considerations, a goal with a lower bound that has a high probability of achieving MSY and an upper bound that has a high probability of achieving maximum recruitment would have the highest probability of meeting subsistence harvest needs, minimizing subsistence fishery restrictions, and providing a harvestable surplus for the other fisheries. Rounding the lower bound estimate of S_{msy} (48,000–84,400) and the upper bound estimate of S_{max} (68,000–113,600), the range would be 48,000–120,000 Chinook salmon. For the third consideration, the lowest estimated escapements with recruit information occurred in 1986 (58,556 fish) and 2000 (65,180 fish; Figure 3). Of the two, the estimated escapement in 2000 was deemed more reliable in terms of accuracy and is more recent, therefore better reflecting present environmental and fishery conditions. Based on the above considerations, the recommended Kuskokwim River Chinook salmon escapement goal range was determined as 65,000–120,000 fish. Escapements in this range have a 95% of chance producing yields greater than 100,000 Chinook salmon, except when escapements are consistently at 120,000 (Figure 9). The goal recommended here is a sustainable escapement goal (SEG), given that the range provides sustained yields that do not have the greatest potential to produce MSY.

TRIBUTARY ESCAPEMENT GOAL RANGES

We recommend revising or discontinuing tributary sustainable escapement goals as follows.

- **Kwethluk River: revise existing SEG (6,000–11,000) to an SEG of 4,100 –7,500;**

- **Tuluksak River: discontinue existing SEG (1,000–2,100);**

- **George River: revise existing SEG (3,100–7,900) to an SEG of 1,800–3,300;**

- **Kogrukluk River: revise existing SEG (5,300–14,000) to an SEG of 4,800–8,800.**

Rationale

With the recommendation for a drainagewide escapement goal, the escapement goal review team discussed at length strategies for retaining, revising, or discontinuing the existing escapement goals for tributary systems. Currently, there are 11 SEGs for Chinook salmon in tributaries of the Kuskokwim River. Of these, 4 are assessed with weirs and 7 are assessed with aerial surveys. Generally speaking, the majority of the Kuskokwim River subsistence fishery harvests occur at the lower mainstem. While there is no stock identification technique available to identify stock of origin in the harvest, it is unlikely that the harvests target one stock more heavily than other stocks. With few exceptions (e.g., Kwethluk River), there is very limited terminal fishing that targets specific spawning stocks. While upriver stocks tend to migrate earlier than downriver stocks, there is a considerable overlap among stocks (Stuby 2007). Therefore, harvests and any management actions in the mainstem river would more likely to affect escapement of sub-stocks equally. During the Chinook salmon run season, management will be primarily based on Bethel test-fishery and escapement past weirs. Hence, we decided that the weir-based goals should be revised such that their relative contribution to the total

escapement was consistent with the drainagewide goal. Setting weir tributary escapement goals independent of the drainagewide goal could result in increased occasions of meeting drainagewide goal but failing to meet tributary goals or vice versa.

Currently, there are 6 tributary systems with weir enumeration projects, and 4 of those systems have existing SEGs. In determining whether to establish (or retain) an escapement goal for any of these stocks, we considered the length and continuity of the data set, location of the tributary in the drainage (e.g., upper, middle, or lower portion of the drainage), whether there were goals in nearby systems that adequately indexed that portion of the drainage, and the relative size of the escapement in that system compared to the total drainage escapement. Of the 6 systems, the average contribution to the total drainagewide escapement was highest for Kogrukluk (7.3%), followed by Kwethluk (6.2%), George (2.7%), Tatlawiksuk (1.1%), Tuluksak (0.7%), and Takotna (0.3%; Figure 1, Table 3). The Tatlawiksuk and Takotna rivers are in the upper portion of the drainage and goals to index that portion of the drainage are desirable; however, the length of the data sets and relative size of their escapements were deemed insufficient to establish a goal.

We recommend that the existing escapement goal for the Tuluksak River be discontinued. The river has been extensively altered by mining activity and supports only a very small and variable escapement of Chinook salmon. While the Tuluksak River escapements correlate with drainagewide escapement (Bue et al. 2012), the biological importance of this escapement goal is uncertain. As an index of escapement for lower Kuskokwim River king salmon stocks, the nearby Kwethluk and Kisaralik rivers are more appropriate because they support much larger escapements. It should also be noted that discontinuation of the escapement goal does not mean there will be no management consideration. The Tuluksak River escapement will continue to be monitored and appropriate management action will be taken when warranted.

For aerial survey goals, we recommend retaining all current goals. Aerial surveys have been conducted over a much longer time frame and thus encompass a broader range of escapements and production cycles. Aerial surveys are not used for inseason management, but are used as indicators of escapement at postseason review.

DISCUSSION

In conducting spawner-recruit analyses, it is imperative to have long-term data that are both accurate and informative. Inaccurate historical run, escapement, and age-composition data could lead to biased estimates of spawner-recruit relationship. Availability of accurate and long-term data does not necessarily imply that the data are informative to discern a stock's productivity and carrying capacity. Better statistical inference can be made when productivity data have contrast (i.e. largest spawning escapement divided by smallest escapement) greater than 4 (CTC 1999) and when harvest rates are moderate. Simultaneously, accuracy of spawner-recruit model estimates are influenced not only by accuracy of data but also by accuracy of estimation methods. The Bayesian state-space model approach generally provides more robust and accurate estimates than traditional approach (Su and Peterman 2012). In the following sections, we discuss those issues as they apply to Kuskokwim River Chinook salmon.

ACCURACY OF RECONSTRUCTION OF HISTORICAL RUN

The greatest uncertainty of this analysis is the accuracy of historical runs reconstructed by Bue et al. (2012). Since this run reconstruction methodology and resulting estimates were extensively reviewed by the AYKSSI expert panel, we were confident of the appropriateness of using these data for the spawner-recruit analyses.

While true run size is unknown, the fluctuation of the reconstructed Kuskokwim runs was consistent with historical accounts. For instance, the Chinook salmon run during 1981 was described as "above average" (Jonrowe et al. 1982), and another report described the Chinook salmon run during 1985–1986 as "poorer than average" with a declining trend observed since 1982 (Francisco et al. 1987). The 1995 run was described as a "strong run" (Burkey et al. 1997). On the other hand, the Chinook salmon run during 1994 was not reported as high as the model indicated, although escapement goals were met for both years (Francisco et al. 1995). This suggests that reconstructed historical run sizes and escapements during the entire 1976–1999 period are reasonably accurate with respect to trends in run size.

The reconstructed Kuskokwim Chinook salmon run and escapement data was informative in terms of assessing productivity. Spawner-recruit estimates spanned of 32 years (1976–2007), and escapement estimates ranged from 58,556 to 287,178 with contrast of 4.9, satisfying the recommendation of CTC (1999). Harvest rates ranged from 25% to 62%, averaging 42%, with some escapements exceeding the estimated carrying capacity (Figure 1).

INFLUENCE OF OBSERVATIONAL UNCERTAINTIES AND MODEL SENSITIVITY ANALYSES

It is widely known that accuracy of statistical estimation of spawner-recruit model parameters are affected by various factors, such as observational (measurement) uncertainties, time series auto correlations, aging uncertainties, and non-random environmental variability (Caputi 1988; Hilborn and Walters 1992; CTC 1999; Kehler et al. 2002; Zabel and Levin 2002; Kope 2006). However, not all uncertainties lead equally to significant biases of management reference points, and direction and extent of bias differs among characteristics of fishery data (Kehler et al. 2002; Kope 2006; Su and Peterman 2012).

For low productivity (e.g., $\alpha < 4$) or highly exploited stocks were observed escapements range lower than true S_{msy}, the bias tends to move toward overestimation of productivity (α) and underestimation of S_{msy}. On the other hand, for high productivity (e.g., $\alpha > 4$) and less exploited stocks in which observed escapements range greater than S_{max}, the bias tends to move toward underestimation of productivity and overestimation of S_{msy} (Kope 2006; Su and Peterman 2012). These biases were more likely to be pronounced when a traditional spawner-recruit model fitting approach was used than when a Bayesian state-space modeling approach was used (Su and Peterman 2012). Among various source of uncertainties Kope (2006) reported that observational uncertainty had the strongest influence. Sensitivity analyses were designed to address potential effects of this source of uncertainty, as described below.

In our sensitivity analysis, the base model (BSS) and four alternative models (TSR, BSSA-1, BSSA-2, BSSA-3) represent 5 different treatments of observation uncertainty. BSS model assumes full observation uncertainty, whereas TSR assumes no observation uncertainty. BSSA-1 assumes less observation uncertainty for historical run, BSSA-2 assumes less observation uncertainty for age composition, and BSSA-3 assumes less observation uncertainty

for both historical run and age composition. Thus, among the 5 models, estimates of management reference points derived from the TSR are the most influenced by observation errors and likely the most biased, whereas those of BSS are the least influenced by observation errors and likely the least biased.

Kuskokwim Chinook salmon is a highly productive and lightly exploited stock (Table 2, Figure 2), and thus, result of sensitivity analyses showed that the direction of bias was toward underestimation of productivity and overestimation of S_{msy} (Table 2; Figure 10). Among the 5 models, using traditional SR methods (TSR), estimates of $\ln(\alpha)$ and β were lower than the BSS estimates (Table 2). The TSR estimate of the Ricker relationship shifted right toward higher escapements, and estimates of S_{msy}, S_{max}, and S_{eq} were higher and their confidence interval were narrower than those from the BSS model (Figure 10). The magnitude of uncertainties of BSSA-1, BSSA-2, and BSSA-3 yielded very similar results to those from the BSS model (Table 2; Figure 10). Similarity of estimates between BSS and BSSA-2 (Figure 10) shows that uncertainties of age composition have little impacts on estimation of spawner-recruit relationship (Kope 2006).

Another interesting observation was that estimate of D, an index of annual variation of recruit age composition or maturity schedule, was higher with BSS than other 3 alternative models (Table 2). Higher D indicates less annual variation, so that the baseline model estimates less annual maturity variation than alternative 3 models. Annual variation in maturity schedule is influenced by both variation of annual run size and run age composition. When estimates of annual run or age composition are more precise (simulated in these alternative models by smaller CV or high effective sample size), the model puts more weight on the observed variability and thus assumes high variability in maturity schedule (i.e., smaller D). On the other hand, when estimates of annual run and age composition are less precise (higher CV and lower effective sample size), the model attributes more observed variability due to observation error and thus attributes less variability in maturity schedule (i.e., larger D).

Finally, similarity of spawner-recruit model parameters and S_{msy} estimates among BSS and 4 alternative models (Table 2; Figure 10) suggests clearly that impacts of observational uncertainties are small relative to the information content of these data. Moreover, the direction of bias is toward higher S_{msy}, or toward conservation of Kuskokwim Chinook salmon stock. The recommended goal would not change in any important way as a result of using one of the alternate data configurations, or the TSR model, instead of the BSS baseline model and data. For the TSR analysis, which generated the highest estimate of S_{msy}, and had the largest differences with the BSS results, the range of escapement with $\geq 90\%$ probability of producing at least 90% of MSY is approximately 52,000 to 99,000. This range overlaps almost completely with that from the BSS (48,400 to 84,400). Because the lower bound of the goal was chosen conservatively, based on the smallest measured escapement providing enough yield to meet subsistence harvest needs, the goal itself is almost entirely insensitive to moderate observational uncertainties in the analysis.

OTHER CONSIDERATIONS: ENVIRONMENTAL CHANGES AND QUALITY OF ESCAPEMENT

While the Kuskokwim Chinook salmon spawner-recruit data fit well to the Ricker-spawner recruit model, it is possible the observed overcompensatory patterns are circumstantial, not caused by a density-dependent relationship (CTC 1999), but by environmental factors (e.g.,

Mueter et al. 2002; Helle et al. 2007). For instance, a large escapement followed by unfavorable environmental conditions or a small escapement followed by favorable environmental conditions could produce a pattern similar to the Ricker-based density-dependent relationship. However, for the Kuskokwim Chinook salmon data, events of "high escapement resulted in below replacement recruit" and "low escapement resulted in large recruit" occurred consistently throughout years (Figure 2). It is unlikely that all these observed patterns were produced by coincidental environmental changes.

In recent years, quality of escapement (i.e., age-sex composition of spawners) has been of great public concern. As with most escapement goal analyses of Pacific salmon, the state-space model described and the spawner-recruit model assumes that the age and sex composition of spawners are relatively constant. When composition of spawners changes greatly from average (e.g., 100% of spawners were males), the number of recruits could greatly differ from that predicted by the model.

In the Kuskokwim River, most Chinook salmon are harvested by large ($\geq$ 8 inch) mesh, which selectively targets large and older fish, and possibly more females, resulting in more smaller and younger fish and fewer females on spawning grounds. Those size selective fisheries can affect productivity and genetic composition of Chinook salmon stocks (e.g. Bromaghin et al. 2011).

For practical considerations, Kuskokwim River Chinook salmon lack sufficient historical escapement data to discern demographic trends of spawners, except in data from the Kogrukluk River weir (1976–2011). Average proportion of female in the escapements at Kogrukluk River was 32.5%, ranging from 13.3% (1979) to 53.2% (1999), and no discernible trend was observed. It should also be noted that this spawner-recruit analysis was conducted based on data from historical and current selective fishery conditions, so that the effects of selective fishery have already been incorporated into spawner-recruit model and estimation of reference points. Characteristics of the fishery have not changed since 1987. Kuskokwim River Chinook salmon stocks are harvested primarily by subsistence fisheries at low to moderate harvest rates. Furthermore, we are not aware of any proposed fishery changes that would greatly and permanently alter demographic composition of spawners beyond observed historical variations. Those facts suggest that, with respect to age-sex composition, estimates derived from this spawner-recruit analysis are applicable for setting escapement goals for current fisheries.

Moreover, methods for determining demographic specific escapement goals have not been established. Thus far, we were not able to find any peer reviewed studies that explicitly incorporated demographics of spawners into a spawner-recruit model and set an escapement goal. Clearly, further studies are needed before we are able to incorporate this issue into setting an escapement goal.

We believe that the present spawner-recruit analyses using Bayesian state-space modeling approach is scientifically defensible. It implicitly incorporates environmental variation and possible demographic trends over the time period. It is the most appropriate approach, given currently available data, methodologies, and scientific understanding, to determine escapement goal of the Kuskokwim River Chinook salmon stock.

DRAINAGEWIDE ESCAPEMENT GOAL SUMMARY

In determining the recommended drainage-wide escapement goal, consideration was given not only to sustainability of Kuskokwim Chinook salmon stock and sustainability of fisheries, but

also to trade-offs for setting an escapement goal (AYKSSI 2011; Dorner et al. 2009; Collie et al. 2012). For instance, to increase sustainability of a Chinook salmon stock, it may be desirable to increase the escapement goal. However, a higher escapement goal requires reduction of fishing harvest which may result in increased frequency of restriction or fishery closure (AYKSSI 2011). The proposed drainagewide escapement goal range of 65,000–120,000 is sustainable because it maintains viability of stock by setting the lower bound of the goal within the S_{msy} range, and provides expected yields of greater than 100,000 fish for subsistence harvests. As the majority of Chinook salmon is harvested by subsistence fisheries, the capacity of the commercial fishery is limited, and historical average run size is about 247,000, it is likely that escapement goal range will be achieved in most years. The proposed lower bound of the escapement goal (65,000) will become a target objective only during the years of low runs when restrictions of subsistence fisheries could be warranted (e.g., years 2010–2012). Increasing the lower bound would result in even more severe restrictions in subsistence fisheries. The proposed escapement goal would provide a balance between achieving higher escapements and avoiding unnecessary closures.

TRIBUTARY ESCAPEMENT GOALS SUMMARY

For setting tributary goals, we applied the average contribution of each tributary to total run from all available years. Using average proportions is appropriate because there seems to be no discernible trend in contribution proportions, except for Kogrukluk River showing an increasing trend during 2000–2011 (Figure 11). It is unknown whether those fluctuations are due to natural variation or to fisheries. The proposed escapement goal ranges are generally lower than the current percentile goal ranges (Table 3). This is expected because the percentile goal bounds were determined using data from 2000 to 2007, a short time period of high runs and escapements with low exploitation levels (Figures 2, 4). As more escapement data are collected those bias would be corrected. In fact, if the escapement goals were updated through 2012 using the percentile method, their lower bounds would be similar to the lower bounds of the proposed goals (Table 3).

Molyneaux and Branian (2006) estimated S_{msy} based on watershed size (Parken et al. 2006), which were within or lower than the recommended escapement goal ranges, except for the George River (Table 3). In the George River, even during the high run years of 2004–2006 observed escapement was in the range of 4,400–5,200 Chinook salmon (Schaberg et al. 2012), which indicates that watershed based estimate is biased high. These comparisons help to confirm the validity of applying the spawner-recruit model based estimates to individual tributaries, which is expected because habitat factors are already implicitly incorporated in the Ricker-based spawner-recruit model.

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TABLES AND FIGURES

Table 1.–Data sources and assumptions.

Data	Source	Assumptions
Annual run and CV	Bue et al. 2012	Reported CV multiplied by 2
		Effective sample size
Annual run age composition	Bue et al. 2012	25: 1976-1999 100: 2000-2011
Commercial fishery harvest	Bue et al. 2012	CV assumed 0.02
Subsistence fishery harvest 1976-1989	Brazil et al. 2011	CV assumed 0.10
Subsistence fishery harvest 1989-2011 and CV	Hamazaki 2011 Carroll and Hamazaki 2012a,b	Reported CV
Test fish, sport fish harvest	Brazil et al. 2011	Combined with subsistence harvest

Table 2.–Bayesian state-space spawner-recruit model results, alternative models; Kuskokwim River Chinook salmon.

	Baseline (BSS)	Traditional (TSR)	CV original (BSS-A1)	Efn 100 (BSS-A2)	CV original Efn 100 (BSS-A3)
$\ln(\alpha)$	2.07 (1.91, 2.48)	1.98 (1.74, 2.21)	2.12 (1.64, 2.52)	2.03 (1.51, 2.42)	2.07 (1.69, 2.36)
α	7.91 (4.58, 11.90)	7.21 (5.60, 9.28)	8.33 (5.15, 12.43)	7.58 (4.51, 11.28)	7.90 (5.37, 10.54)
$\beta\ (10^{-5})$	1.13 (0.77, 1.45)	0.97 (0.82, 1.11)	1.11 (0.86, 1.34)	1.09 (0.72, 1.42)	1.06 (0.83, 1.25)
φ	0.304 (-0.59, 0.92)	NA	0.57 (-0.21, 0.96)	0.02 (-0.75, 0.73)	0.11 (-0.47, 0.68)
σ_R^{2}	0.19 (0.10, 0.30)	0.27 (0.21, 0.34)	0.18 (0.08, 0.29)	0.23 (0.13, 0.34)	0.24 (0.17, 0.35)
D	137 (63, 370)	NA	87 (56, 130)	90 (49, 128)	85 (47, 133)
pi[1]	0.194 (0.170, 0.219)	NA	0.192 (0.167, 0.219)	0.180 (0.159, 0.201)	0.180 (0.160, 0.201)
pi[2]	0.382 (0.352, 0.412)	NA	0.385 (0.353, 0.417)	0.379 (0.353, 0.406)	0.383 (0.357, 0.409)
pi[3]	0.390 (0.360, 0.422)	NA	0.388 (0.356, 0.419)	0.406 (0.378, 0.435)	0.401 (0.375, 0.428)
pi[4]	0.033 (0.024, 0.045)	NA	0.035 (0.025, 0.047)	0.036 (0.028, 0.047)	0.036 (0.027, 0.046)

Note: Numbers in parenthesis indicate upper and lower 95% credible bounds. NA = not applicable (did not include in the model).

Table 3.–Summary of tributary escapement proportions, existing and recommended escapement goal ranges, habitat S_{msy} from Molyeanux and Brannian (2006); and updated ranges by percentile method.

System	Percent of Total Escapement	Existing Goal Range	Recommended	Habitat[a] S_{msy}	Updated Percentile Method[1]
Kuskokwim River		No goal	65,000-120,000		
Kwethluk River	6.2%	6,000-11,000	4,100-7,500	5,231	4,100-1,5000
Tuluksak River	0.7%	1,000-2,100	Discontinue	3,937	400-2,500
George River	2.7%	3,100-7,900	1,800-3,300	5,309	2,000-6,700
Kogrukluk River	7.3%	5,300-14,000	4,800-8,800	3,653	5,000-16,000
Tatlawiksuk River	1.1%	No goal	No goal		
Takotna River	0.3%	No goal	No goal		

[a] Presented for comparison only.

Note: Black dots show the location of the enumeration weirs, bold river segments represent systems monitored by aerial surveys, the bracket indicates the location of the W-1 fishing district, and some major communities are shown in text boxes.

Figure 1.–Map of Kuskokwim River.
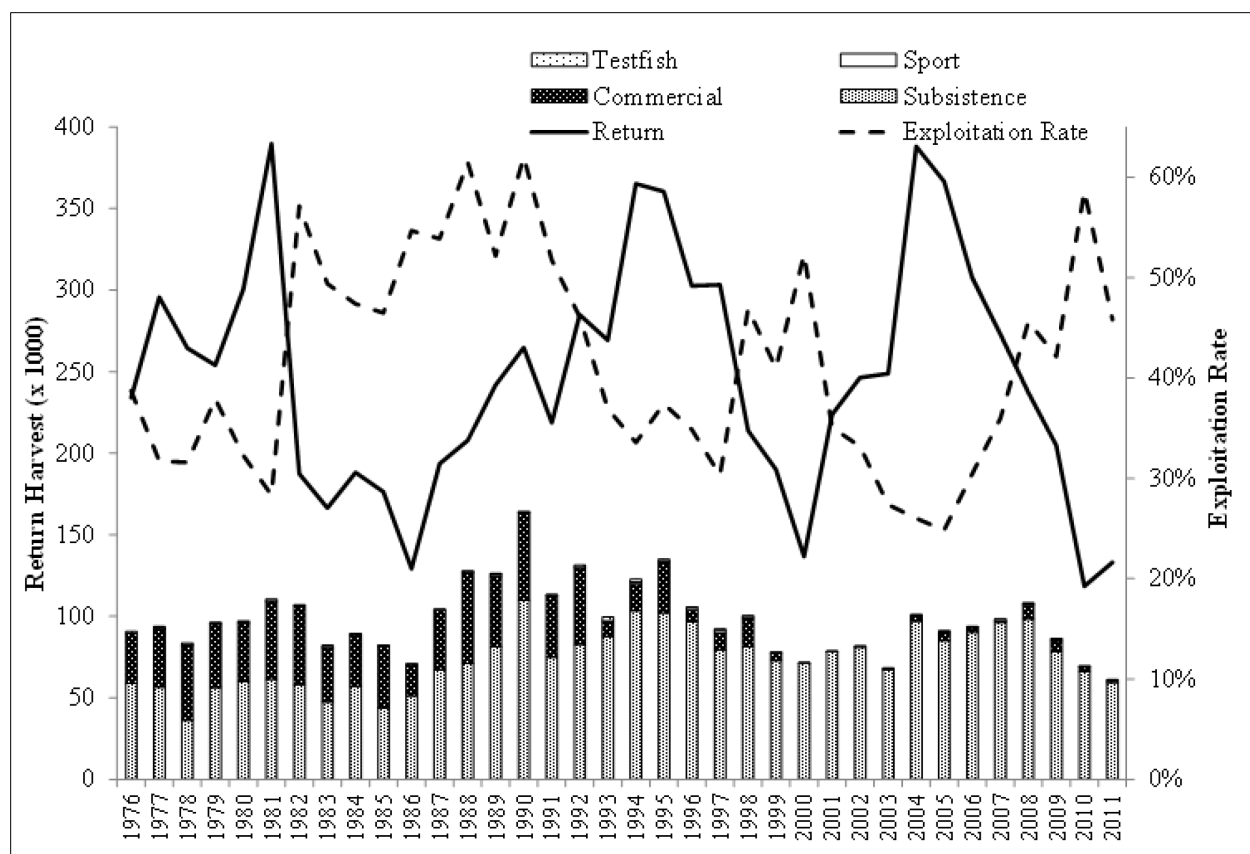
Source: Bue et al. 2012.

Figure 2.–Estimated historical total annual run, harvest, and exploitation rate of Kuskokwim River Chinook salmon.
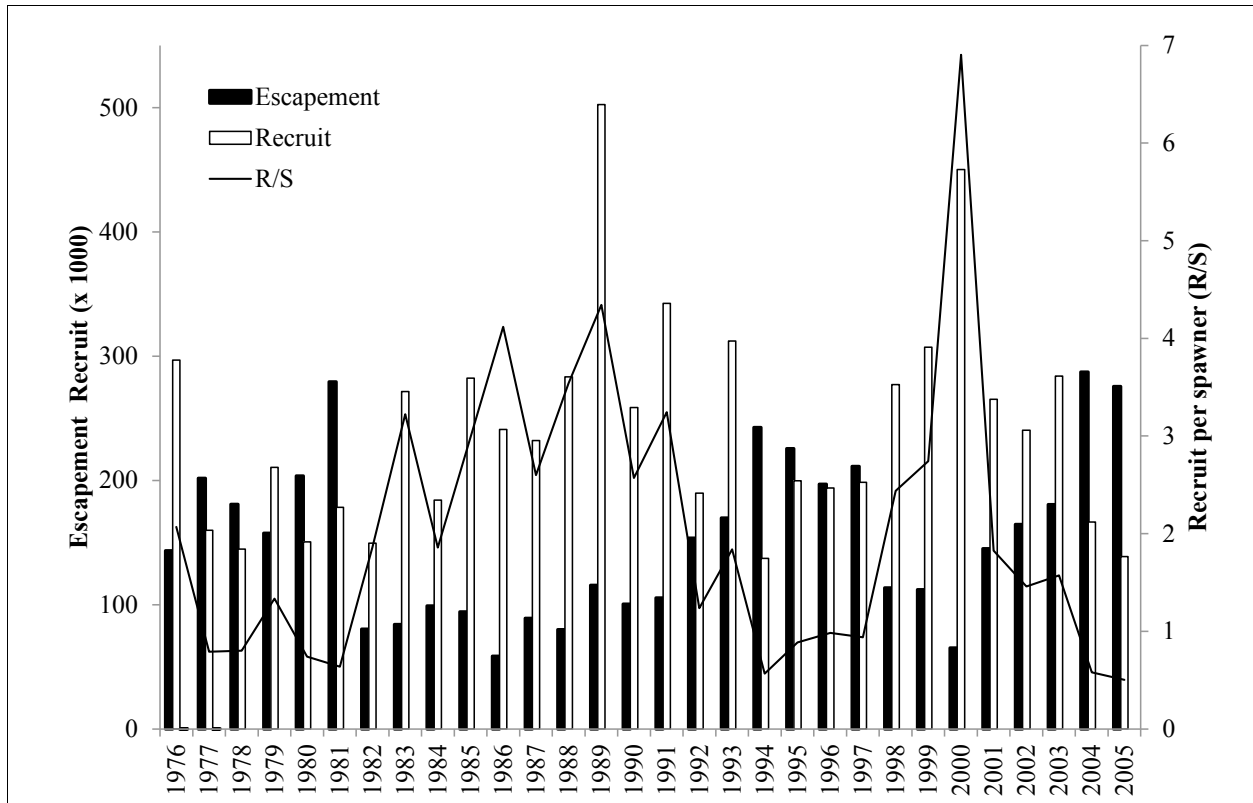
Figure 3.–Estimated historical escapement (number of spawners), brood year recruitment (total number of Chinook salmon offspring that originates from a brood year's escapement), and recruit per spawner (R/S) of Kuskokwim River Chinook salmon.
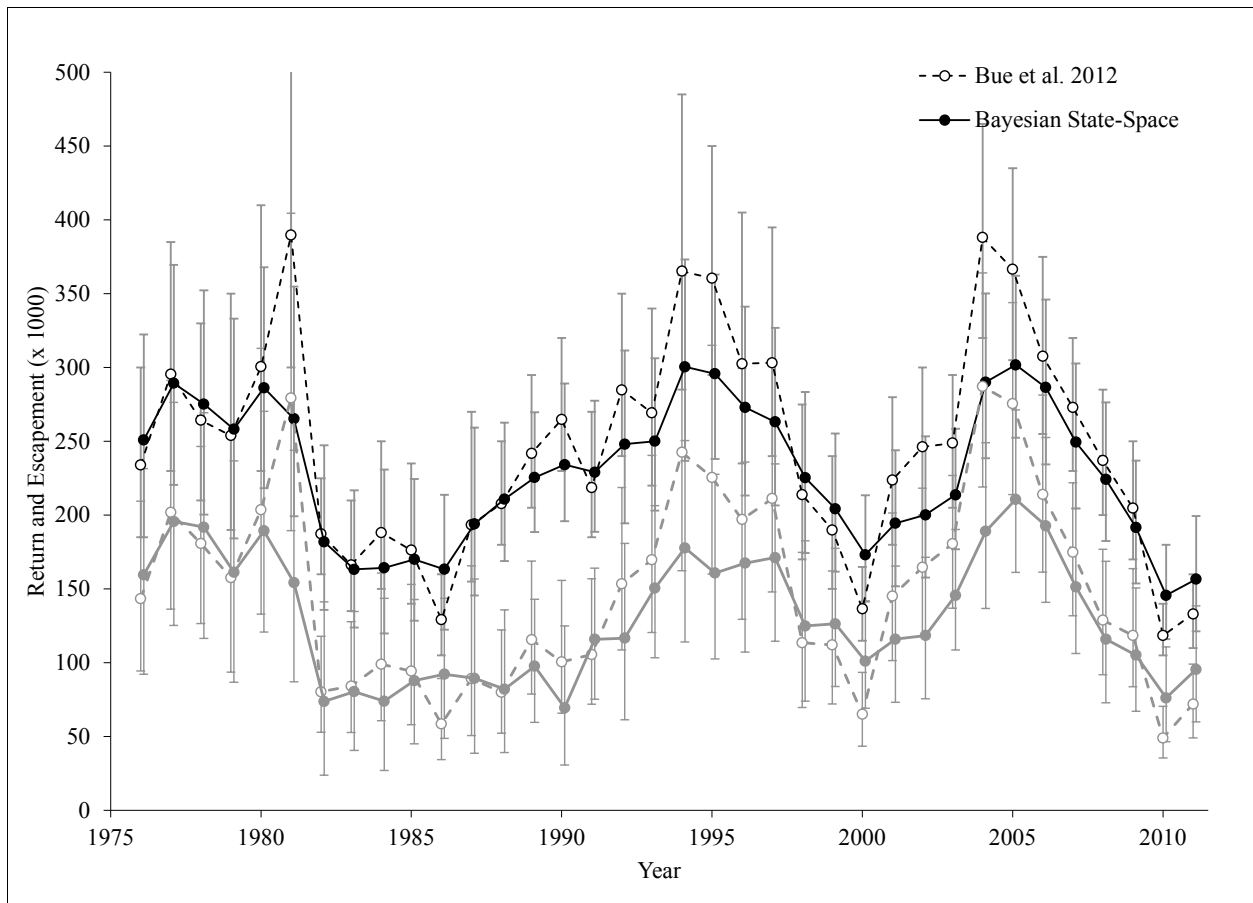
Source: Bue et al. 2012.

Note: Vertical line indicates 95% confidence interval (Bue et al. 2012) and credible interval (Bayesian state-space).

   Figure 4.–Estimates of annual run (black and white circle) and escapement (gray and white circle) from Bue et al. (2012); and modeled annual run (black and solid circle), and escapement (gray and solid circle) from the Bayesian state-space model.
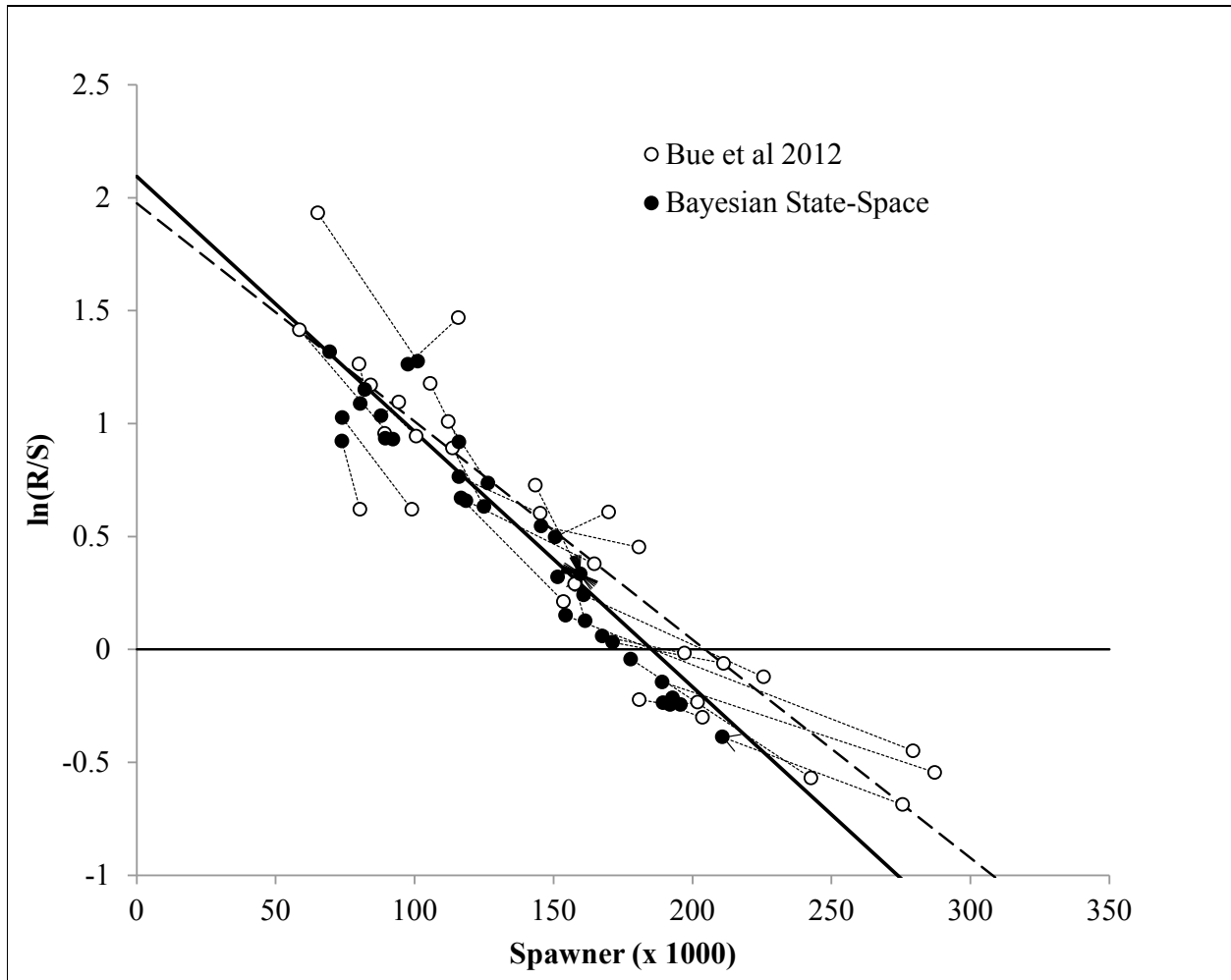
Note: Arrows indicates shrinkage from Bue et al. (2012) to Bayesian estimates.

Figure 5.–Linear relationship between ln(*R*/*S*) and spawners (escapement) for Bayesian state-space model (solid circle, solid line) and Bue et al. (2012) (white circle, dashed line).
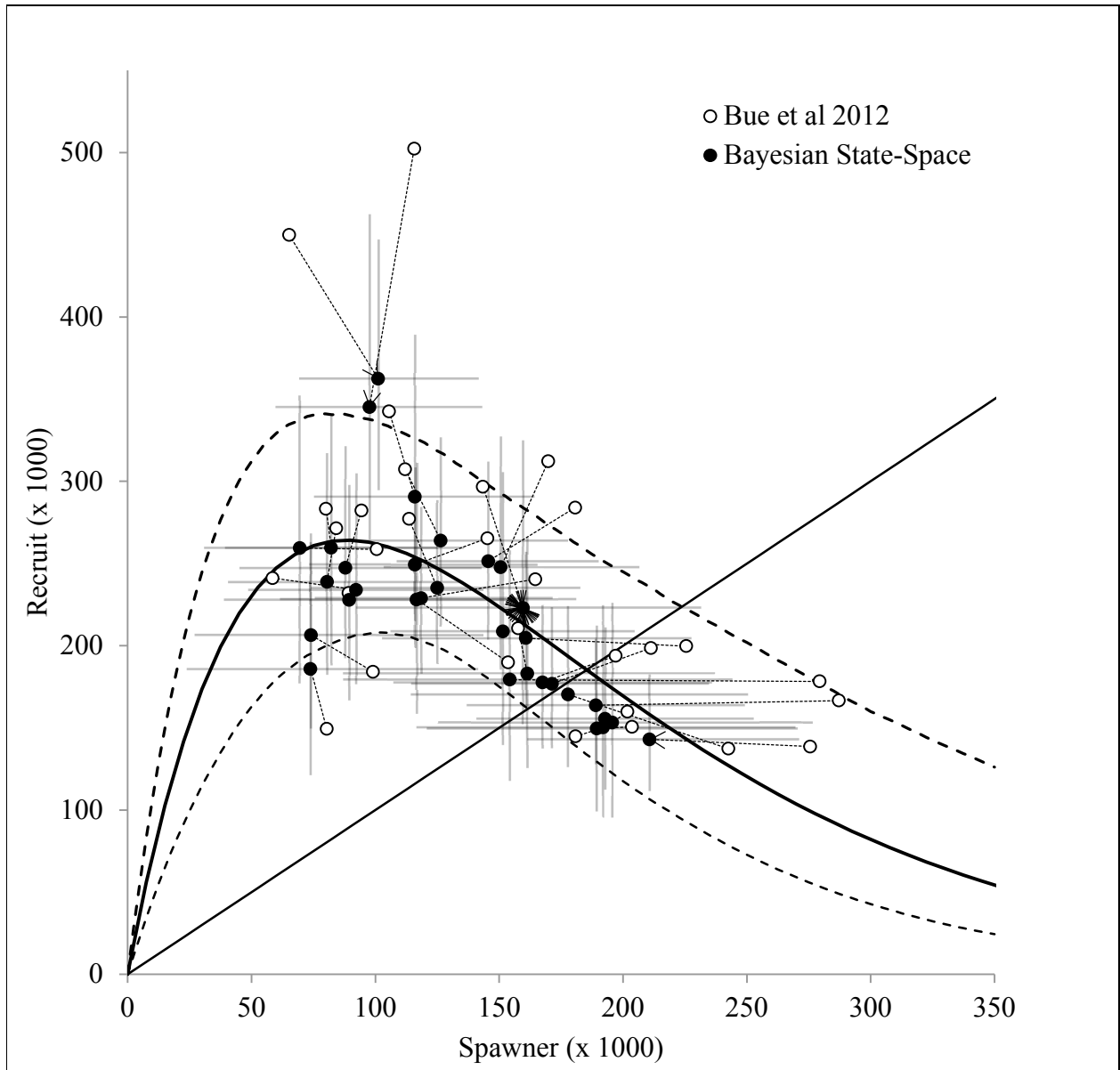
Note: Arrows indicates shrinkage from original (Bue et al. 2012: white circle) to Bayesian estimates (black circle). Thin dotted lines indicates 95% credible interval (CI) for Bayesian state-space model. Vertical and horizontal line indicates 95% CI of the spawner-recruit points.

Figure 6.–Bayesian state-space model of the Ricker spawner-recruit relationship.
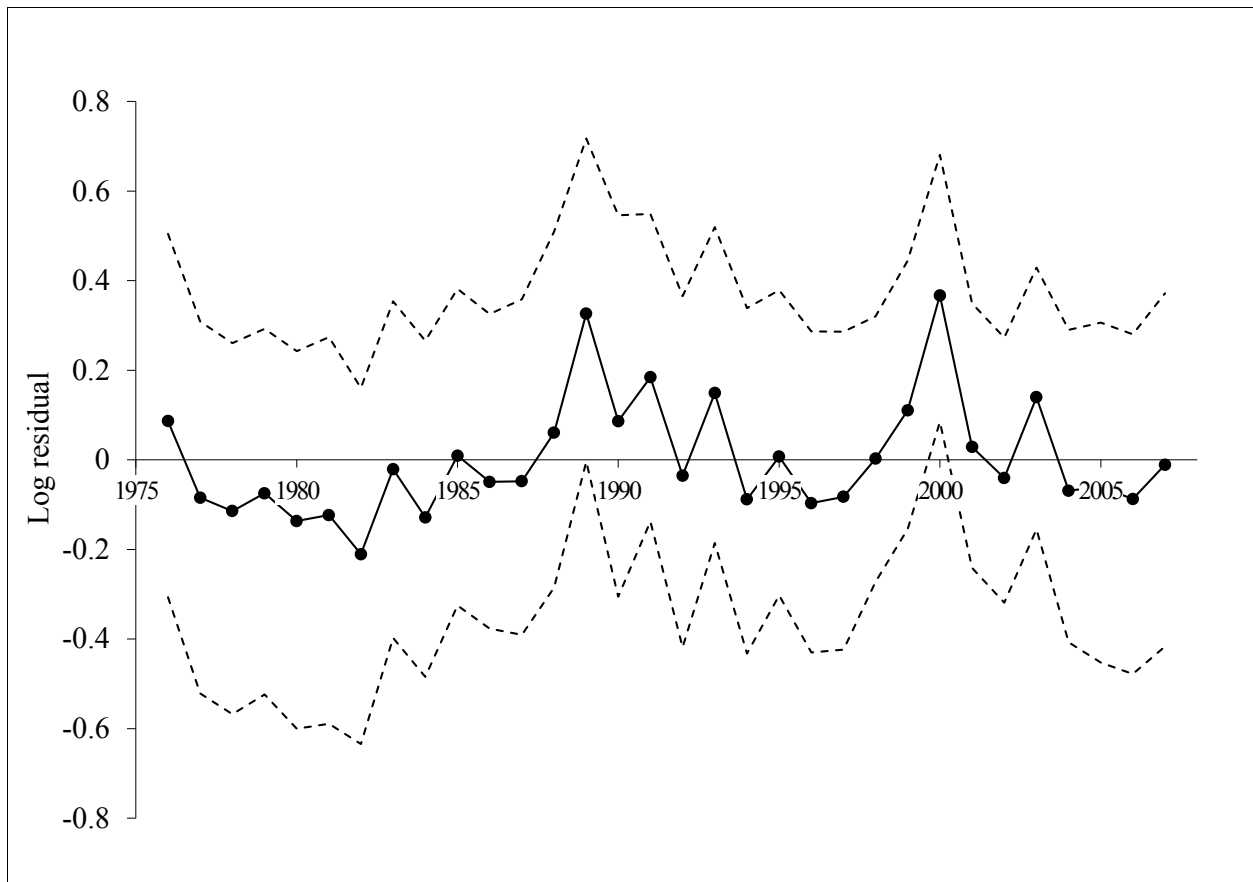
Note: Solid line shows the posterior median, and dashed lines bracket the 95% credibility interval.

Figure 7.–Productivity residuals (log) between modeled and observed brood year escapement, as estimated from Bayesian state space model fitted to Kuskokwim Chinook salmon data, brood years 1976-2007.
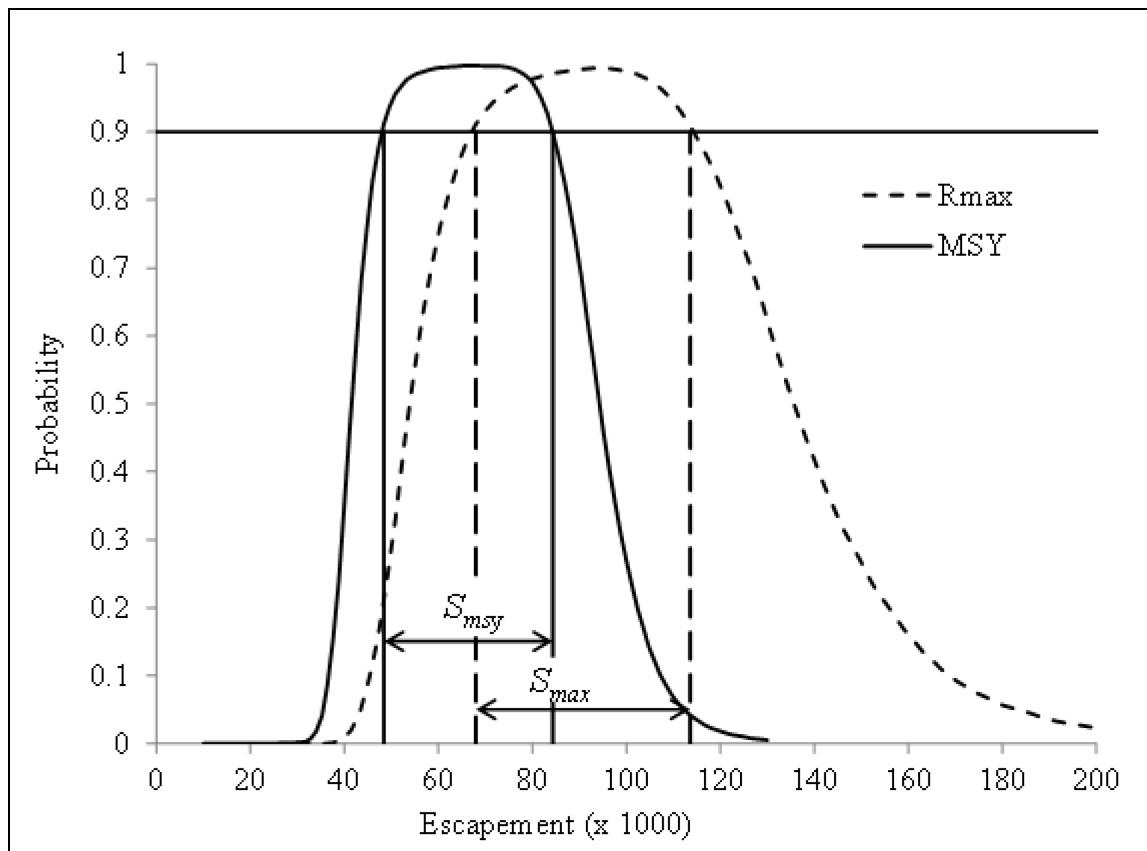
Figure 8.–Probability profiles of escapement size achieving: 1) optimal yield exceeding 90% of MSY (solid line), and 2) optimal recruit exceeding 90% of the maximum recruit (dashed line). Range of escapement intersecting 90% of probability corresponds to S*msy* range and S*max* range respectively.
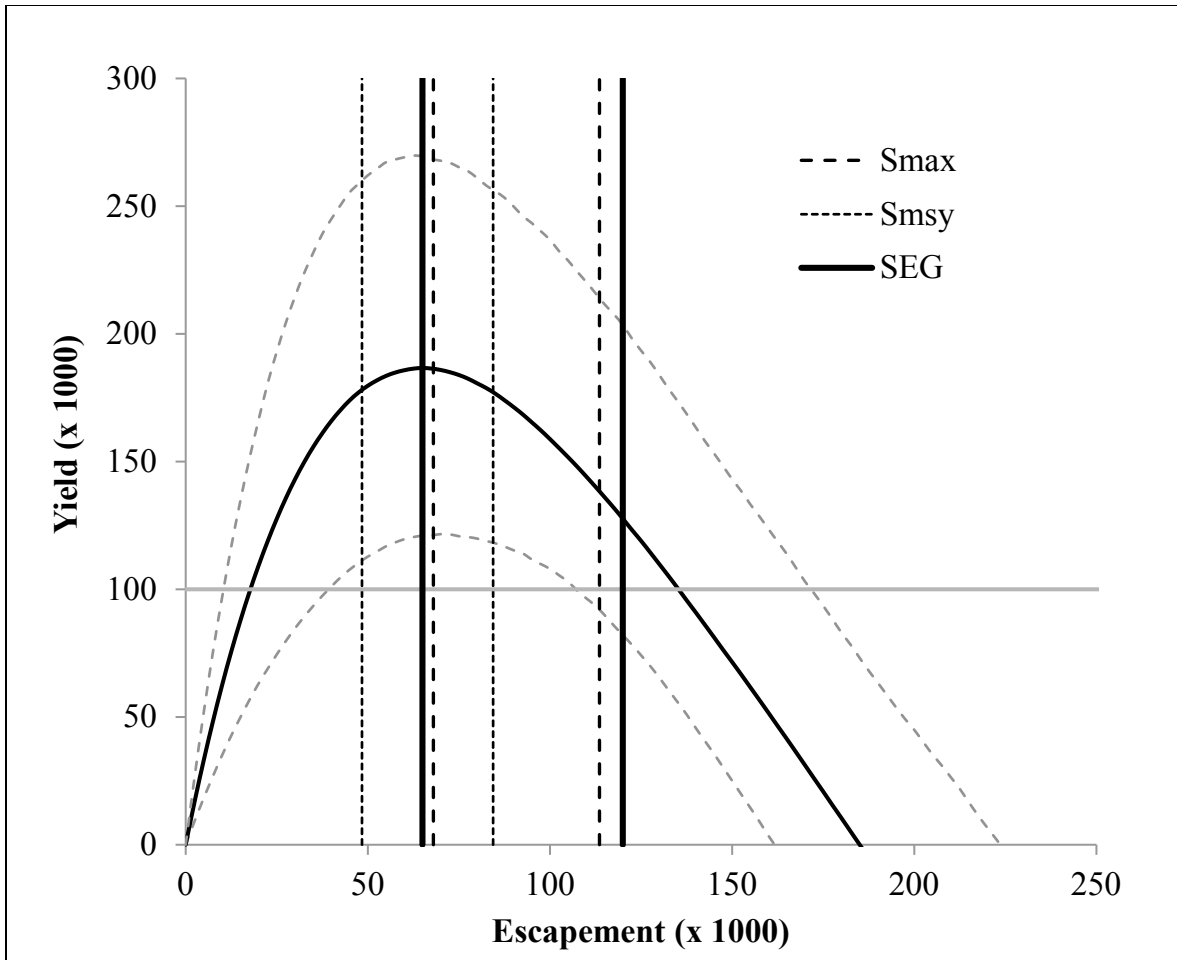
Note: Predicted yield of both S_{msy} and S_{max} ranges exceeds 100,000 fish.

Figure 9.–Expected yield curve (solid line) with 95% CI (dash line), and ranges of S_{msy}, S_{max}, and recommended escapement goal (SEG).
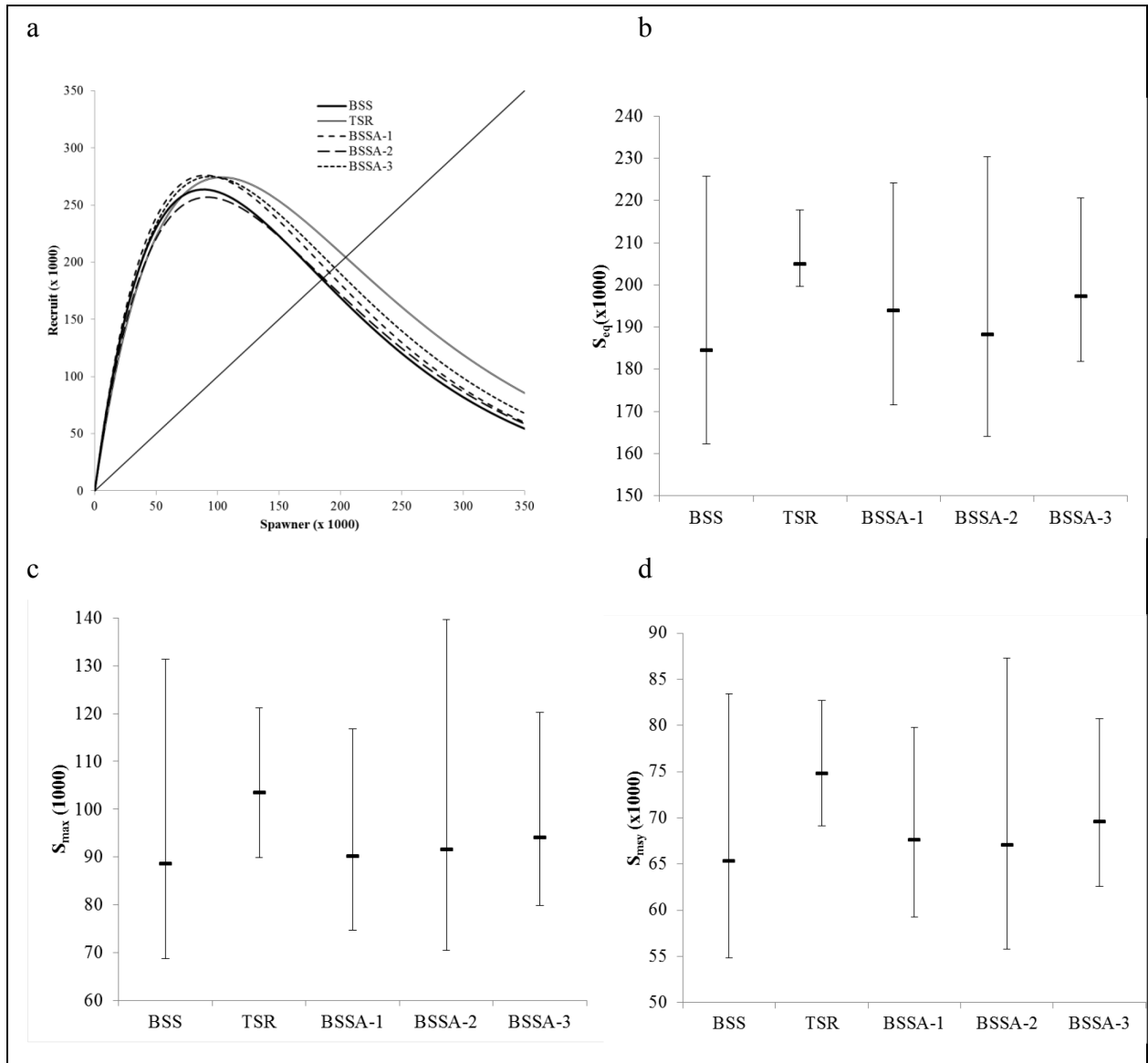
Figure 10.–Comparison of spawner-recruit curve (a) estimates of S_{eq} (b), S_{max} (c), and S_{msy} (d) among the baseline (BSS), traditional spawner-recruit (TSR), alternative data: CV original (BSSA-1), efn 100 (BSSA-2), and CV original plus efn 100 (BSSA-3).
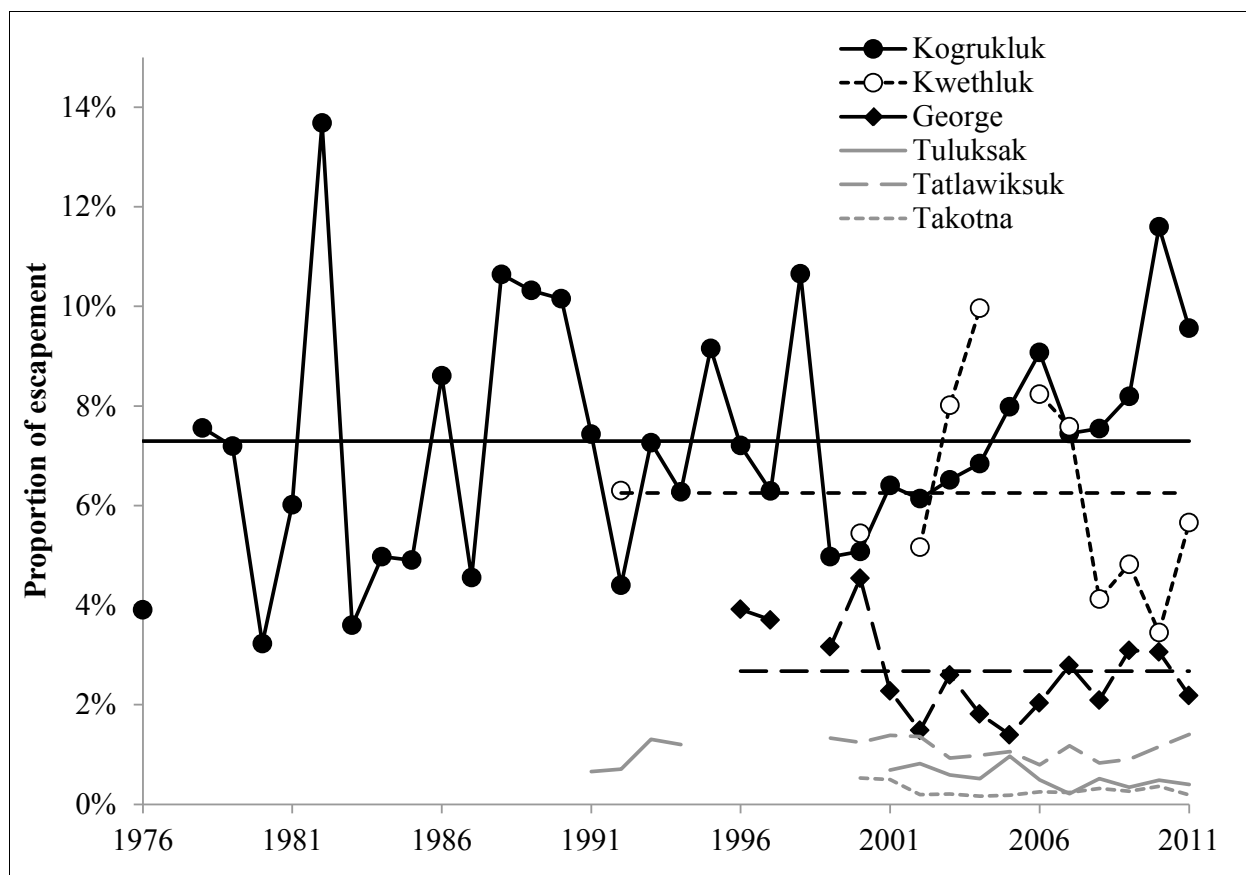
Note: The horizontal line indicates average proportion.

Figure 11.–Proportion of tributary escapements to total drainagewide escapement across years.

APPENDIX A

Appendix A1.–Kuskokwim River Chinook salmon; dataset used for the Bayesian State-Space model.

| | | Harvest | | | | | Coefficient of Variation (CV) | |
| | Annual | | | | | Annual | Harvest | |
Year	Run	Commercial	Subsistence	Sport	Test Fish	Run	Commercial	Subsistence
1976	233,966	30,735	58,606	NA	1,206	0.13	0.02	0.10
1977	295,559	35,830	56,580	33	1,264	0.13	0.02	0.10
1978	264,325	45,641	36,270	116	1,445	0.17	0.02	0.10
1979	253,969	38,966	56,283	74	979	0.16	0.02	0.10
1980	300,572	35,881	59,892	162	1,033	0.15	0.02	0.10
1981	389,791	47,663	61,329	189	1,218	0.14	0.02	0.10
1982	187,354	48,234	58,018	207	542	0.08	0.02	0.10
1983	166,333	33,174	47,412	420	1,139	0.11	0.02	0.10
1984	188,237	31,742	56,930	273	231	0.13	0.02	0.10
1985	176,292	37,889	43,874	85	79	0.13	0.02	0.10
1986	129,167	19,414	51,019	49	130	0.11	0.02	0.10
1987	193,464	36,179	67,325	355	384	0.15	0.02	0.10
1988	207,817	55,716	70,943	528	576	0.08	0.02	0.10
1989	241,857	43,217	81,175	1,218	543	0.10	0.02	0.10
1990	264,801	53,504	109,778	394	512	0.08	0.02	0.04
1991	218,704	37,778	74,820	401	117	0.10	0.02	0.01
1992	284,845	46,872	82,654	367	1,380	0.10	0.02	0.04
1993	269,305	8,735	87,684	587	2,483	0.11	0.02	0.02
1994	365,246	16,211	103,343	1,139	1,937	0.13	0.02	0.02
1995	360,513	30,846	102,110	541	1,421	0.10	0.02	0.03
1996	302,603	7,419	96,413	1,432	247	0.14	0.02	0.03
1997	303,188	10,441	79,381	1,788	332	0.13	0.02	0.02
1998	213,873	17,359	81,213	1,464	210	0.13	0.02	0.03
1999	189,939	4,705	72,775	279	98	0.12	0.02	0.01
2000	136,617	444	70,825	105	64	0.09	0.02	0.05
2001	223,707	90	78,009	290	86	0.11	0.02	0.02
2002	246,295	72	80,982	319	288	0.10	0.02	0.02
2003	248,789	158	67,134	401	409	0.09	0.02	0.02
2004	388,135	2,300	97,110	857	691	0.10	0.02	0.04
2005	366,601	4,784	85,090	572	557	0.09	0.02	0.01
2006	307,662	2,777	90,085	444	352	0.10	0.02	0.02
2007	273,060	179	96,155	1,478	305	0.08	0.02	0.02
2008	237,074	8,865	98,103	708	420	0.09	0.02	0.05
2009	204,746	6,664	78,231	904	470	0.10	0.02	0.02
2010	118,506	2,732	66,056	354	292	0.08	0.02	0.02
2011	133,059	748	59,245	633	337	0.10	0.02	0.03

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Appendix A2.–Page 2 of 2.

					Run Age Composition (%)								
Year	0.2	1.1	1.2	2.1	1.3	2.2	1.4	2.3	1.5	2.4	1.6	2.5	EFN[a]
1976	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1977	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1978	0	0.154	12.771	0	15.024	0.006	59.36	0.976	3.415	8.293	0.001	0	25
1979	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1980	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1981	0	0.234	7.516	0	33.104	0.007	55.31	0.021	3.794	0.016	0.001	0	25
1982	0	0.074	6.384	0	28.567	0.013	60.54	0.041	4.309	0.064	0.003	0	25
1983	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1984	0	0.195	16.303	0.0170	43.783	0.081	34.72	0.261	4.327	0.267	0.042	0	25
1985	0	0.181	18.048	0	35.381	0.097	42.77	0.033	3.412	0.024	0.057	0	25
1986	0	0.578	8.910	0	47.424	0.017	37.53	0.053	5.442	0.039	0.004	0	25
1987	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1988	0	0.041	13.734	0	47.158	0.014	33.41	0.046	5.556	0.034	0.003	0	25
1989	0	0.041	15.719	0	30.201	0.649	49.59	0.299	3.064	0.432	0.003	0	25
1990	0	1.139	20.861	0	47.701	0.017	27.82	0.055	2.358	0.041	0.004	0	25
1991	0.030	0.041	11.904	0	33.08	0.887	50.39	0.573	2.568	0.385	0.017	0.128	25
1992	0	2.488	26.734	0	33.042	0.331	35.12	0.089	2.032	0.158	0.003	0	25
1993	0	0.152	28.264	0	30.005	0.069	37.05	0.285	3.862	0.277	0.003	0.033	25
1994	0.020	0.183	10.724	0.0467	53.381	0.439	32.71	0.478	1.619	0.392	0.003	0	25
1995	0	0.045	17.193	0	28.837	0.012	52.51	0.081	1.253	0.07	0.003	0	25
1996	0	0.042	9.697	0	42.466	0.107	36.54	0.203	10.908	0.034	0.003	0	25
1997	0	0.032	27.694	0	23.28	0.011	47.72	0.036	1.195	0.026	0.002	0	25
1998	0	0.137	7.511	0	49.313	0.016	40.1	0.051	2.834	0.038	0.004	0	25
1999	0	0.167	7.842	0	28.08	0.124	61.7	0.051	1.994	0.038	0.004	0	25
2000	0	0.096	14.028	0	40.963	0.022	40.96	0.069	3.802	0.051	0.005	0	100
2001	0	0	10.974	0	30.154	0	53.72	0	5.150	0.001	0	0	100
2002	0	0.088	21.2	0	35.731	0.026	39.58	0	3.377	0	0	0	100
2003	0	0.174	20.353	0	43.187	0	32.51	0	3.776	0	0	0	100
2004	0	0.360	38.802	0	30.51	0.113	28.95	0	1.262	0	0	0	100
2005	0	0.218	18.455	0	46.373	0.003	33.39	0.169	1.341	0.047	0	0	100
2006	0	0.324	25.072	0	30.182	0.017	39.63	0.052	4.690	0.035	0	0	100
2007	0	0.072	28.181	0	33.277	0	35.79	0.108	2.272	0.298	0	0	100
2008	0	0.229	19.642	0	48.745	0.030	28.55	0.571	2.190	0.084	0	0	100
2009	0	0.083	18.39	0	37.335	0.411	42.41	0.147	1.138	0.161	0	0	100
2010	0	0.150	20.682	0	41.964	0.056	34.35	0	2.757	0.036	0	0	100
2011	0	0.118	27.806	0	38.559	0.087	31.71	0.256	1.329	0.033	0.046	0	100

[a] Effective sample size.

APPENDIX B

```
rm(list=ls(all=TRUE))
library(coda)
library(emdbook)
library(MASS)
library(gtools)
library(gplots)
library(Hmisc)
library(rbugs)
library(R2WinBUGS)
#library(R2OpenBUGS)

####################################################################
####    import data and create dat file for WinBUGS   ############
####################################################################

# Set file and program locating directory
working_dir='C:/Projects/Kuskokwim_River/Chinook_reconst/Hamachan/BEG'

# Read data
a<-read.table('C:/Projects/Kuskokwim_River/Chinook_reconst/Hamachan/BEG/kusko data 6-
12-12.txt',header=T)
# fyear: first year
fyear=a$year[1]
# lyear: last year
lyear<-a$year[length(a$year)]
# fage: First return age
fage<-4
# lage: Last return age
lage<-7
# nage: The numnber of age classes
nages<-lage-fage+1
# nyrs: The numnber of Spawner years for data anaylses
nyrs<-lyear-fyear+1
# nryrs: The numnber of Recruit years for data anaylses
nRyrs<-lyear-fage-fyear+lage+1
# effnsamp: Effective sample size for age comp
#effnsamp<-25

################################################################
#  1.0: Create age classes
################################################################
# a_4: age 4 = sum of age1.2 & age 2.1
# a_5: age 5 = sum of age1.3 & age 2.2
# a_6: age 6 = sum of age1.4 & age 2.3
# a_7: age 7 = sum of age1.5 & age 2.4
# Ignore presence of other age classes
a$a_4<-a$a1.2+a$a2.1
a$a_5<-a$a1.3+a$a2.2
a$a_6<-a$a1.4+a$a2.3
a$a_7<-a$a1.5+a$a2.4
# Recalculate proportions based on the 4 age classes
a[,c('a_4','a_5','a_6','a_7')] <-
prop.table(as.matrix(a[,c('a_4','a_5','a_6','a_7')]),margin=1)

# Create age class frequency table x
x<-round(as.matrix(a[,c('a_4','a_5','a_6','a_7')]),4)
colnames(x)=NULL
x[is.na(x)]=0
a$efn[is.na(a$efn)] = 0
x<-round(x*a$efn,0)
```

-continued-

41

```
###################################################################
#  1.1: Combine harvests
###################################################################
# Combine commercial and test fish catch
a$Cobs_com<-a$Cobs_com+a$Cobs_test
# Combine Subsistence and Sport fish catch
a$Cobs_sport[is.na(a$Cobs_sport)] <- 0
a$Cobs_sub<-a$Cobs_sub+a$Cobs_sport
# Drop Sport fish catch data
a <- subset(a, select= -c(Cobs_test,Cobs_sport))


###################################################################
#  2.0: Create WinBUGS/OpenBUGS Model code
###################################################################
   #  Ricker Spawner recruit model with AR1 errors
   #  R[y]: total Recruit from brood Spawner year y
   #  Total of nyrs+nages-1 Brood years represnted in data
   #  The FIRST a.max = 7 DO NOT HAVE CORRESPONDING SPAWNING ABUNDANCES
   #  THE REMAINING Y-a.min = 33 DO (BROOD YEARS A+a.min=8 - 38)

mod<-function() {
# Ricker Spawner Recruit model: y is calender year

    for (y in nages+fage:nyrs+nages-1) {
      log.R[y] ~ dnorm(log.R.mean2[y],tau.R)
      R[y] <- exp(log.R[y])
      log.R.mean1[y] <- log(S[y-lage]) + lnalpha - beta * S[y-lage]
      log.resid[y] <- log(R[y]) - log.R.mean1[y]
    # RPS: Return per spawner
      RPS[y] <- R[y]/S[y-lage]
    }

    log.R.mean2[nages+fage] <- log.R.mean1[nages+fage] + phi * log.resid.0
    for (y in nages+fage+1:nyrs+nages-1) {
      log.R.mean2[y] <- log.R.mean1[y] + phi * log.resid[y-1]
    }
    lnalpha ~ dnorm(0,1.0E-6)%_%I(0,)
    beta ~ dnorm(0,1.0E-6)%_%I(0,)
    phi ~ dunif(-1,1)
    tau.R ~ dgamma(0.001,0.001)
    log.resid.0 ~ dnorm(0,tau.red)%_%I(-5,5)
    alpha <- exp(lnalpha)
    tau.red <- tau.R * (1-phi*phi)
    sigma.R <- 1 / sqrt(tau.R)
    sigma.red <- 1 / sqrt(tau.red)
    lnalpha.c <- lnalpha + (sigma.R * sigma.R / 2 / (1-phi*phi) )
    S.max <- 1 / beta
    S.eq <- lnalpha.c * S.max
    S.msy <- S.eq * (0.5 - 0.07*lnalpha.c)

    # BROOD YEAR RETURNS W/O SR LINK DRAWN FROM COMMON LOGNORMAL DISTN
    mean.log.R0 ~ dnorm(0,1.0E-6)%_%I(0,30)
    #normal prior on mean log recruitment for initial brood years without stock recruit
link (no information on escapement)
    tau.R0 ~ dgamma(0.001,0.001)
    #inverse gamma prior on error standard deviation on recruitments without stock
recruit link
```

-continued-

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```
sigma.R0 <- 1/sqrt(tau.R0)
for (y in 1:lage) {
     log.R[y] ~ dnorm(mean.log.R0,tau.R0)
     R[y] <- exp(log.R[y])
  }

# GENERATE MATURITY SCHEDULES
D <- sum(gamma[])
for (a in 1:nages) {
  gamma[a] ~ dgamma(0.005,0.005)
  pi[a] <- gamma[a] / D
     for (y in 1:nyrs+lage-fage) {
         g[y,a] ~ dgamma(gamma[a],1)
         p[y,a] <- g[y,a]/sum(g[y,])
       }
}

# CALCULATE THE NUMBERS AT AGE MATRIX
for(t in 1:nyrs){
  for(a in 1:nages){
     N.ta[t,a]<-R[t+nages-a]*p[t+nages-a,a]
  }
}

# MULTINOMIAL SCALE SAMPLING ON TOTAL ANNUAL RETURN N
# INDEX t IS CALENDAR YEAR
for (t in 1:nyrs) {
  N[t] <- sum(N.ta[t,1:nages])
  for (a in 1:nages) {
      q[t,a] <- N.ta[t,a] / N[t]
     }
  n[t] <- sum(x[t,1:nages])
  x[t,1:nages] ~ dmulti(q[t,],n[t])
}


# APPLY HARVEST TO GET INRIVER RETURN
for (t in 1:nyrs) {

 # Total Run Estimates
  log.N[t] <- log(N[t])
  sigma.N[t]<-sqrt(log(pow(cv.N[t],2)+1))
  tau.log.N[t]<-1/pow(sigma.N[t],2)
  N.hat[t] ~ dlnorm(log.N[t],tau.log.N[t])

# Total Comercial Harvest Estimates
# mu.com is commercial fishery harvest rate
  mu.com[t] ~ dbeta(0.1,0.1)
  sigma.H.com[t]<-sqrt(log(pow(cv.H.com[t],2)+1))
  tau.log.H.com[t]<-1/pow(sigma.H.com[t],2)
  H.com[t] <- mu.com[t] * N[t]
  log.H.com[t] <- log(H.com[t])
  Hhat.com[t] ~ dlnorm(log.H.com[t],tau.log.H.com[t])
# Total Subsistence Harvest Estimates
# U.sub is subsistence fishery harvest rate
  U.sub[t] ~ dbeta(0.1,0.1)
  sigma.H.sub[t]<-sqrt(log(pow(cv.H.sub[t],2)+1))
  tau.log.H.sub[t]<-1/pow(sigma.H.sub[t],2)
```

-continued-

```
# Estimated harvest is total run - commercial harvest times sub harvest rate
    H.sub[t] <- (N[t]-H.com[t])*U.sub[t]
    log.H.sub[t] <- log(H.sub[t])
    Hhat.sub[t] ~ dlnorm(log.H.sub[t],tau.log.H.sub[t])
  # Spawner is total run minus harvest
    S[t] <- N[t]-H.com[t]-H.sub[t]
  }
}
#write the model to a text file to be called by WinBUGS
bugfile<-paste(working_dir,'/model.txt',sep='')
write.model(mod,bugfile)

#################################################################
#  2.1: Create WinBUGS/OpenBUGS data file
#################################################################

#  Create WinBUGS/OpenBUGS data file (datnew)
datnew<-list(nyrs = lyear-fyear+1, nages=lage-fage+1, fage=fage, lage=lage,
x=x,
Hhat.com=a$Cobs_com,
Hhat.sub=a$Cobs_sub,
N.hat=a$Nobs,
cv.N=a$cv_N,
cv.H.sub=a$cv_Cobs_sub,
cv.H.com=a$cv_Cobs_com)

# Create WinBUGS/OpenBUGS initial valuses
D.init <- 50
gamma.init <- D.init*prop.table(apply(x,2,sum))
pi.init <- gamma.init/sum(gamma.init)
p.init <- matrix(pi.init,nrow=nyrs+nages-1,ncol=nages,byrow=T)
g.init <- matrix(gamma.init,nrow=nyrs+nages-1,ncol=nages,byrow=T)
x.init <- prop.table(x,margin=1)
x.init <- t(apply(x.init,1,function(x) if(is.na(x[1])) pi.init else x))
S.init <- datnew$N.hat - datnew$Hhat.com - datnew$Hhat.sub
N.ta.init <- matrix(NA,nrow=length((fyear-nages+1):(lyear+nages-1)),ncol=nages)
N.ta.init[nages:(nages+nyrs-1),] <- datnew$N.hat*x.init
R.init <- numeric(length((fyear-lage):(lyear-fage)))
for(i in 1:(nyrs+nages-1)){
   counts<-diag(N.ta.init[i:(i+nages-1),])
   R.init[i]=sum(counts,na.rm=T)/sum(p.init[i,!is.na(counts)])
   }
log.R.init<-log(R.init)
mean.log.R0.init<-log(mean(R.init[1:lage]))
rec <- a$Return[1:(nyrs-fage)]
spawn <- datnew$N.hat[1:(nyrs-fage)]-datnew$Hhat.com[1:(nyrs-fage)]-
datnew$Hhat.sub[1:(nyrs-fage)]
lnrps <- log(rec/spawn)
fit <- lm(lnrps~spawn)
sumfit <- summary(fit)
```

-continued-

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```
tau.R.init <- 1/sumfit$sigma^2
tau.R0.init <- tau.R.init
lnalpha.init <- as.numeric(coef(fit)[1])
beta.init <- as.numeric(-coef(fit)[2])
mu.com.init <- datnew$Hhat.com/(datnew$N.hat)
U.sub.init <- datnew$Hhat.sub/(datnew$N.hat-datnew$Hhat.com)
log.resid.0.init <- 0
phi.init <- 0.3
fisherZ.init <- 0.5*log((1+phi.init)/(1-phi.init))
sdinit <- 0.2
Req.init <- lnalpha.init/beta.init
beta.BH.init <- (exp(lnalpha.init)-1)/Req.init

# Create WinBUGS/OpenBUGS inital value: inits1
inits1 <- list(lnalpha = lnalpha.init,
log.R = log.R.init,
beta = beta.BH.init,
gamma = gamma.init,
g = g.init,
mean.log.R0 = mean.log.R0.init,
mu.com = mu.com.init,
U.sub = U.sub.init,
tau.R = tau.R.init,
tau.R0 = tau.R0.init,
log.resid.0 = log.resid.0.init,
phi = 0
)

set.seed(1)
inits2 <- list(lnalpha = lnalpha.init+rnorm(1,0,sdinit),
log.R = log.R.init+rnorm(nRyrs,0,sdinit),
beta = beta.BH.init*rlnorm(1,0,sdinit),
gamma = gamma.init*rlnorm(nages,0,sdinit),
g = g.init*rlnorm(nRyrs*nages,0,sdinit),
mean.log.R0 = mean.log.R0.init+rnorm(1,0,sdinit),
mu.com = mu.com.init*rlnorm(nyrs,0,sdinit),
U.sub = U.sub.init*rlnorm(nyrs,0,sdinit),
tau.R = tau.R.init*rlnorm(1,0,sdinit),
tau.R0 = tau.R0.init*rlnorm(1,0,sdinit),
log.resid.0 = log.resid.0.init,
phi = 0.4
)

# pass the initials to WinBUGS
inits<-list(inits1,inits2)

#Define the parameters (nodes) of interest
parameters <-
c('lnalpha','lnalpha.c','alpha','beta','sigma.R','sigma.R0','sigma.red','mean.log.R0',
    'phi','pi','D','R','S','N','log.resid.0','g','gamma',
    'mu.com','H.com','H.sub','log.resid','RPS','S.max','S.eq','S.msy'
    )
```

-continued-

```
#Run WinBUGS using the bugs() function
starttime=Sys.time()
sim <- bugs(data=datnew, inits=inits, parameters.to.save=parameters,
model.file='model.txt',n.chains=2,
    n.iter=25000,n.burnin=12500,n.thin=5,debug = TRUE, codaPkg=FALSE,DIC=TRUE,
    working.directory=working_dir)
Sys.time()-starttime
print(sim$summary[,1:2])
plot(sim)


#run convergence diagnostics
sim1 <- as.mcmc.bugs(sim)
gelman.diag(sim)

#process the posterior samples
#extract the posterior samples from the bugs object.
#The bugs object is automatically imported back into R from bugs once the model is
finished running.
post.samp <- sim$sims.array
#create a data frame of posterior samples
post.samp <- as.data.frame(apply(post.samp,3,function(x) as.numeric(x) ))

nvars<-dim(post.samp)[2]
nsamps<-dim(post.samp)[1]

int<-25
for(j in seq(1,nvars,int)){
windows(h=6,w=12)
par(mfrow=c(5,10),mai=c(0.2,0.2,0.2,0.2))

# Trace plost for Chain1
for(i in 0:(int-1)){
    mindat<-min(post.samp[,i+j])
    maxdat<-max(post.samp[,i+j])
# plot density
    plot(density(post.samp[1:(nsamps/2),i+j]),col='blue',main=names(post.samp)[i+j],xli
m=c(mindat,maxdat))
    lines(density(post.samp[(nsamps/2+1):nsamps,i+j]),col='red')
# plot trace plot
    plot(post.samp[1:(nsamps/2),i+j],col='blue',main=names(post.samp)[i+j],ylim=c(minda
t,maxdat),type='l')
    lines(post.samp[(nsamps/2+1):nsamps,i+j],col='red')
}
}
```

-continued-

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```
###############################################################################
#   Graphics
###############################################################################
###############################################################################
#   Extract data
###############################################################################

# Extract Ricker alpha vector
alpha <- post.samp[,substr(names(post.samp),1,3)=='alp']
# Extract Ricker lnalpha vector
lnalpha <- post.samp[,substr(names(post.samp),1,10)=='lnalpha']
# Extract Ricker beta vector
lnalpha.c <- post.samp[,substr(names(post.samp),1,10)=='lnalpha.c']
# Extract Ricker beta vector

beta <- post.samp[,substr(names(post.samp),1,4)=='beta']
# Extract Ricker phi vector
phi <- post.samp[,substr(names(post.samp),1,3)=='phi']
# Extract sigma.redsidual vector
sigma.red <- post.samp[,substr(names(post.samp),1,7)=='sigma.r']
# Extract Ricker S.msy vector
S.msy <- post.samp[,substr(names(post.samp),1,4)=='S.ms']
# Replace negative S.msy to NA
S.msy <- ifelse(S.msy<0, NA, S.msy)
# Calculate R.msy vector
R.msy <- S.msy * exp(lnalpha.c - beta * S.msy)
# Calculate MSY vector
MSY <- R.msy - S.msy
# Extract Ricker S.max vector
S.max <- post.samp[,substr(names(post.samp),1,4)=='S.ma']
# Replace negative S.max to NA
S.max <- ifelse(S.max<0, NA, S.max)
# Extract Ricker S.eq vector
S.eq <- post.samp[,substr(names(post.samp),1,4)=='S.eq']
# Replace negative S.eq to NA
S.eq <- ifelse(S.eq<0, NA, S.eq)
# Calculate R.max vector
R.max <- S.max * exp(lnalpha.c - beta * S.max)


#create matrix of Recruit
R<-as.matrix(post.samp[,substr(names(post.samp),1,2)=='R['])
#create matrix of Spawnwer
S<-as.matrix(post.samp[,substr(names(post.samp),1,2)=='S['])
#create matrix of Total Run
N<-as.matrix(post.samp[,substr(names(post.samp),1,2)=='N['])

windows(record=TRUE)
```

-continued-

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```
###############################################################################
#  Smsy Profile
###############################################################################
hist(S.msy, freq = FALSE, main = 'Smsy Histogram')
ummary(S.msy)
print(c(round(quantile(S.msy,0.025,na.rm=TRUE)),round(quantile(S.msy,0.975,na.rm=TRUE)
)))


###############################################################################
#  Optimal Yield Profile Plot
###############################################################################
# Calculate minimum, maximum, interval for spanwer
Smin <- round(min(S.msy,na.rm=TRUE)/2,-4)
Smax <- round(1.5/mean(beta,na.rm=TRUE),-4)
intvl <- round(Smax-Smin)/100
# Define range of spawner and recruit: 101
Sx <- seq(Smin,Smax,intvl)
Rx <- numeric(101)
# Calculate freqnecy of exceeding 90%MSY yield
for (j in 1:101){
      Rx[j] <- sum(floor((Sx[j] * exp(lnalpha.c - beta * Sx[j])-
Sx[j])/(0.9*MSY)),na.rm=TRUE)
    }

# CPlot Yield Profile
    plot(Sx,Rx/nsamps,type='l', ylab='Probability',xlab='Escapement', main='90% MSY
Optimal Yield Profile')


###############################################################################
#  Yield Plot
###############################################################################
# Calculate minimum, maximum, interval for spanwer
Smin <- 0
Smax <- 350000
intvl <- 2500
# Define range of spawner and recruit: 101
Sx <- seq(Smin,Smax,intvl)
nl <- length(Sx)
Rxm <- numeric(nl)
Rxu <- numeric(nl)
Rxl <- numeric(nl)
# Calculate freqnecy of exceeding 90%MSY yield
for (j in 1:nl){
      Rxm[j] <- median(Sx[j] * exp(lnalpha.c - beta * Sx[j])-Sx[j],na.rm=TRUE)
      Rxl[j] <- quantile(Sx[j] * exp(lnalpha.c - beta * Sx[j])-Sx[j],0.025,na.rm=TRUE)
      Rxu[j] <- quantile(Sx[j] * exp(lnalpha.c - beta * Sx[j])-Sx[j],0.975,na.rm=TRUE)
    }

# CPlot Yield Profile
    plot(Sx,Rxu,type='l', lty = 2, ylim=c(0,max(Rxu)), xlim=c(0,max(Sx)-10000),
ylab='Yield',xlab='Escapement', main='Yield curve')
    lines(Sx,Rxm, lty = 1)
    lines(Sx,Rxl, lty = 2)
    abline(v=c(46800,84500) )
    abline(v=c(66110,111700),lty=4, col='red' )

legend('topright',c('Median','95% Range'),lty=c(1,2),bty='n')
temp <- cbind(Sx,Rxl,Rxm,Rxu)
```

-continued-

```
###############################################################################
#   Smax Profile Plot
###############################################################################
# Calculate minimum, maximum, interval for spanwer
Smin <- round(min(S.max,na.rm=TRUE)/2,-4)
Smax <- round(2.5/mean(beta,na.rm=TRUE),-4)
intvl <- round(Smax-Smin)/100
# Define range of spawner and recruit: 101
Sx <- seq(Smin,Smax,intvl)
Rx <- numeric(101)
# Calculate freqnecy of exceeding 90%MSY yield
for (j in 1:101){
      Rx[j] <- sum(floor((Sx[j] * exp(lnalpha.c - beta *
Sx[j]))/(0.9*R.max)),na.rm=TRUE)
   }

# CPlot Yield Profile
    plot(Sx,Rx/nsamps,type='l', ylab='Probability',xlab='Escapement', main='90% Rmax
Optimal Profile')


###############################################################################
#   Spawner-Recruit Plot
###############################################################################
# Calculate mean and 95% range for S and R
Rmean <- apply(R[,(nages+fage):(nyrs+nages-1)],2,mean)
Rerr <- 2*apply(R[,(nages+fage):(nyrs+nages-1)],2,sd)
R.est.u <- apply(R[,(nages+fage):(nyrs+nages-1)],2,function(x) quantile(x,0.975))
R.est.l <- apply(R[,(nages+fage):(nyrs+nages-1)],2,function(x) quantile(x,0.025))
Smean <- apply(S[,1:(nyrs-fage)],2,mean)
Serr <- 2*apply(S[,1:(nyrs-fage)],2,sd)
S.est.u <- apply(S[,1:(nyrs-fage)],2,function(x) quantile(x,0.975))
S.est.l <- apply(S[,1:(nyrs-fage)],2,function(x) quantile(x,0.025))

#  Plot Bayesian estimates with 95% CI
plotCI(Smean,Rmean, ui = R.est.u, li = R.est.l, err = "y", xlim = c(0,300000),ylim =
c(0,500000), xaxt='n', yaxt='n', main = 'Spawner-Recruit', xlab='Spawner (x 1000)',
ylab ='Recruit (x 1000)')
#  Draw a new axis labels for x and y
axis(1, at = x <- seq(0, 300000, by = 50000),  labels = paste(x/1000, sep = "" ))
axis(2, at = y <- seq(0, 500000, by = 100000),  labels = paste(y/1000, sep = "" ))
plotCI(Smean,Rmean, ui = S.est.u, li = S.est.l, err = "x", xlim = c(0,300000),ylim =
c(0,500000), add = TRUE)
#  Plot Reconstructed estimates
points(spawn, rec, pch=18, col='red')
Sxx <- seq(0,500000,1000)
lines(Sxx, Sxx * exp(mean(lnalpha.c) - mean(beta) * Sxx))
lines(Sxx, Sxx * exp(fit$coefficients[1] + fit$coefficients[2]*Sxx), col='red', lty=2)
lines(Sxx,Sxx)
legend('topright',c('Bayesian','Traditional'),lty=c(1,2),col=c(1,2),bty='n')


plot(Smean, log(Rmean/Smean), ylab = 'ln(R/S)', xlab = 'S',xlim = c(0,300000), ylim =
c(-1,2.5))
abline(mc <- lm(log(Rmean/Smean) ~ Smean))
points(spawn, log(rec/spawn), pch=18, col='red')
abline(mc <- lm(log(rec/spawn) ~ spawn), col='red')
abline(h=0)
legend('topright',c('Bayesian','Traditional'),lty=c(1,1),col=c(1,2),bty='n')
```
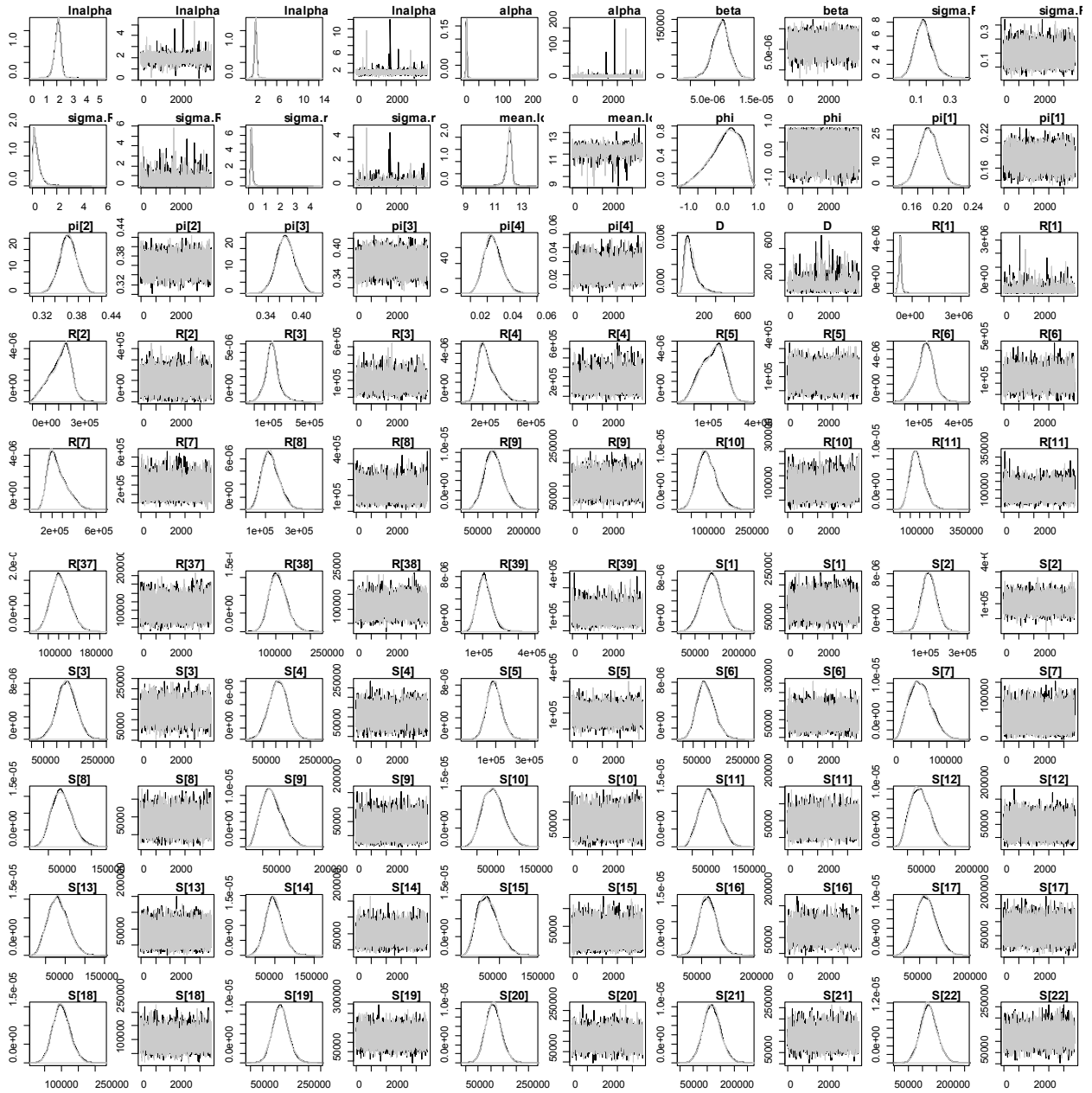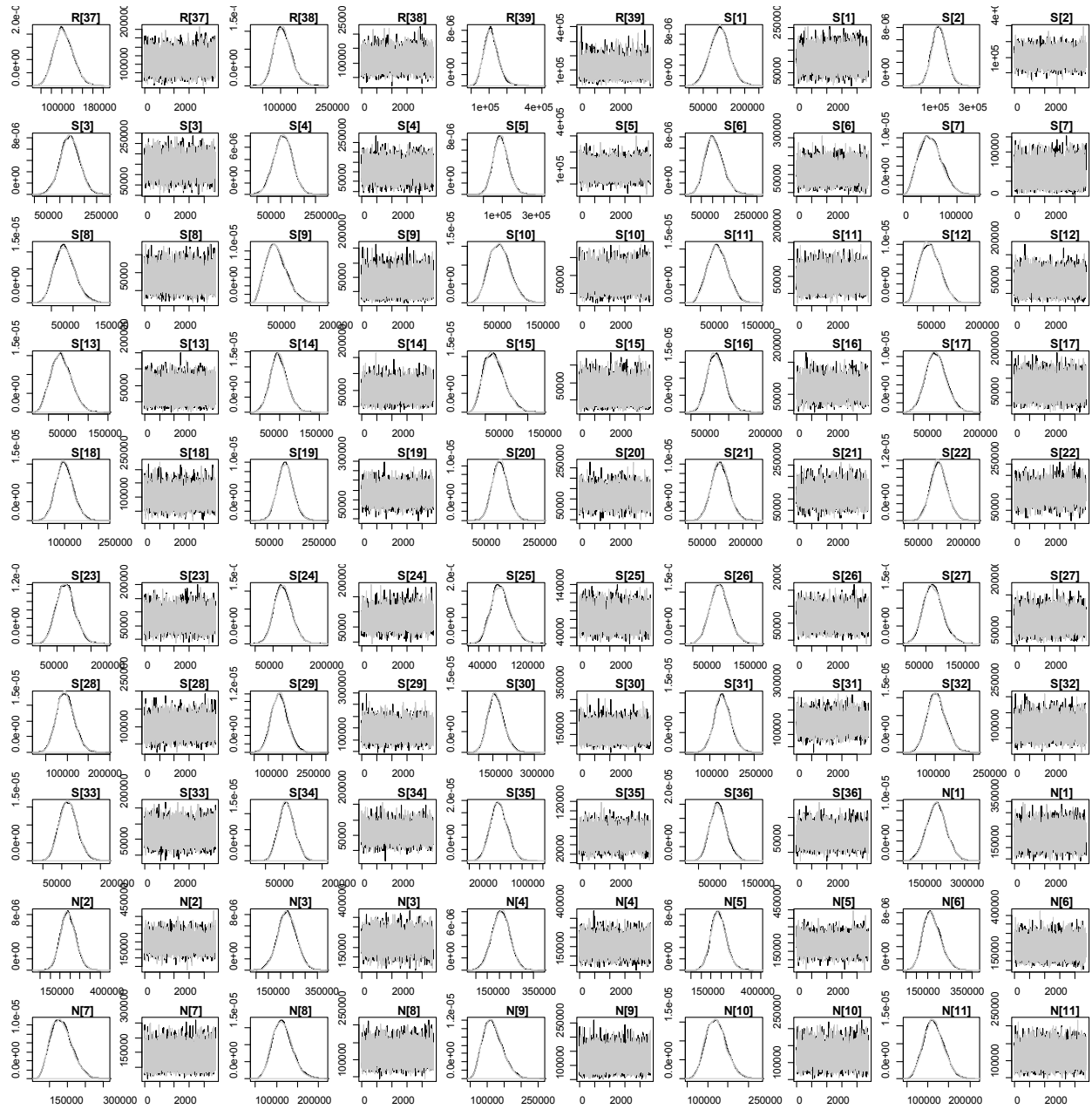
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```
###############################################################################
#  Time Series: Total Run and Escapement
###############################################################################
# Calculate mean and 95% range for S(escapement) and N(Total run)
Sn <- apply(S,2,mean)
Sn.est.u <- apply(S,2,function(x) quantile(x,0.975))
Sn.est.l <- apply(S,2,function(x) quantile(x,0.025))
Nn <- apply(N,2,mean)
Nn.est.u <- apply(N,2,function(x) quantile(x,0.975))
Nn.est.l <- apply(N,2,function(x) quantile(x,0.025))
yr <- seq(1976,2011)
plotCI(yr,Nn, ui = Nn.est.u, li = Nn.est.l, err = "y", ylim = c(0,400000), main =
'Time Series', yaxt='n', xlab='Year', ylab ='Number')
axis(2, at = y <- seq(0, 500000, by = 100000),  labels = paste(y/1000, sep = "" ))
lines(yr,Nn)
plotCI(yr,Sn, ui = Sn.est.u, li = Sn.est.l, err = "y", ylim = c(0,400000), add = TRUE)
lines(yr,Sn, col='red',lty=2)
legend('topright',c('Run','Escapement'),lty=c(1,2),col=c(1,2),bty='n')
# Add Reconstructed run and escapement
lines(yr,a$Nob, col='blue')
lines(yr,(a$Nob-a$Cobs_com-a$Cobs_sub), col='blue', lty=2)
```
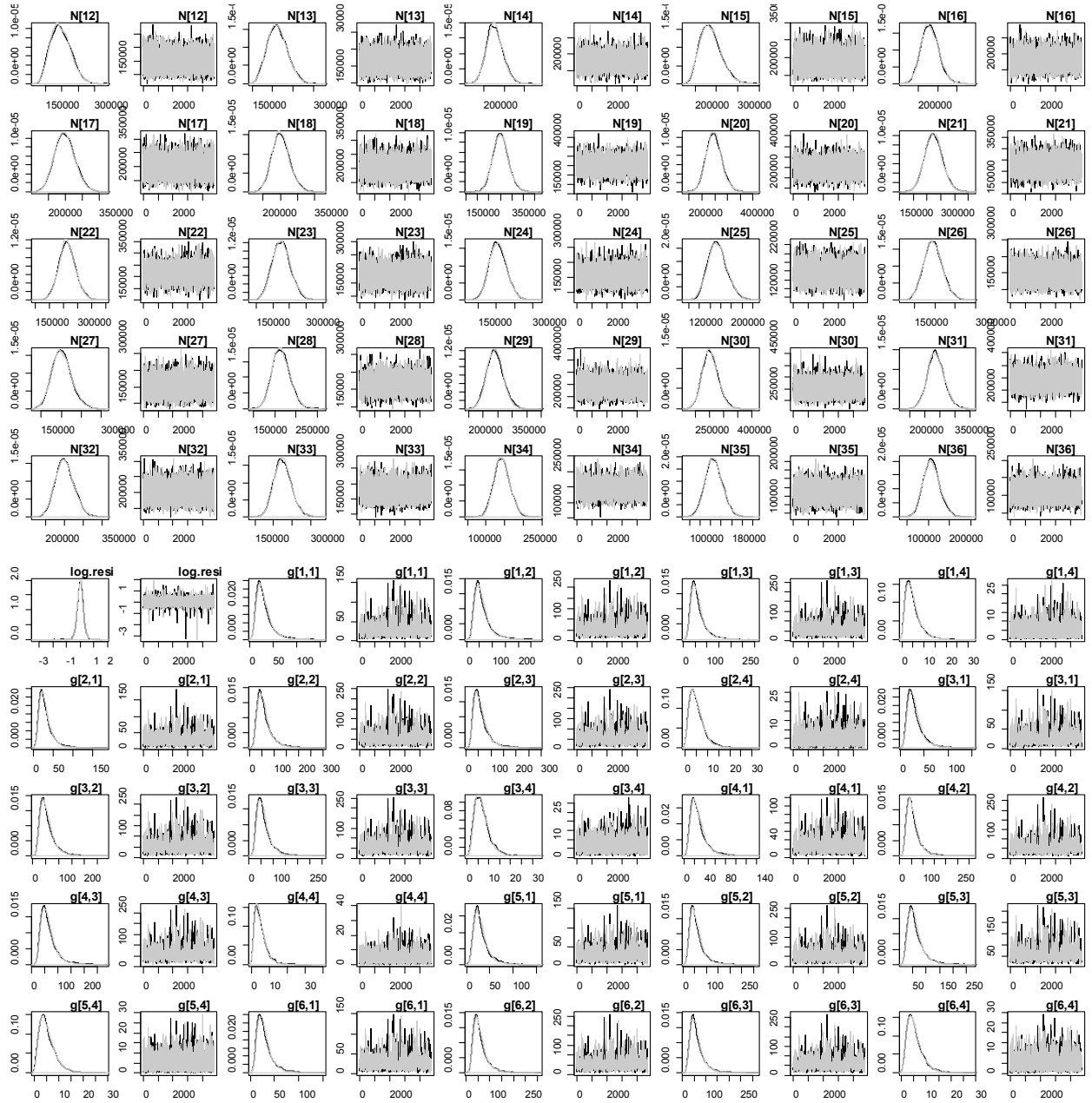
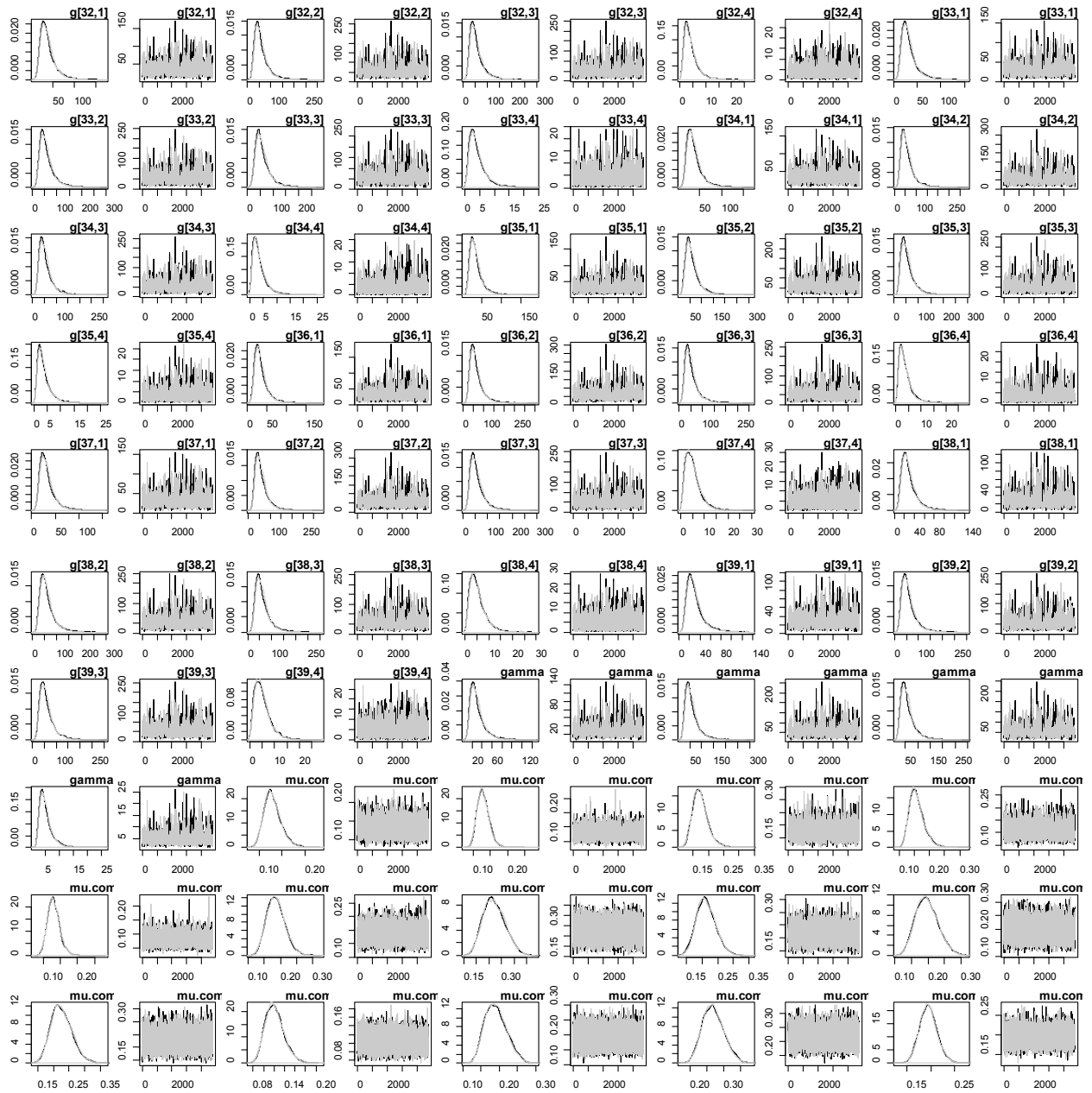# APPENDIX C

Appendix C1.–Bayesian state-space model parameter profiles.
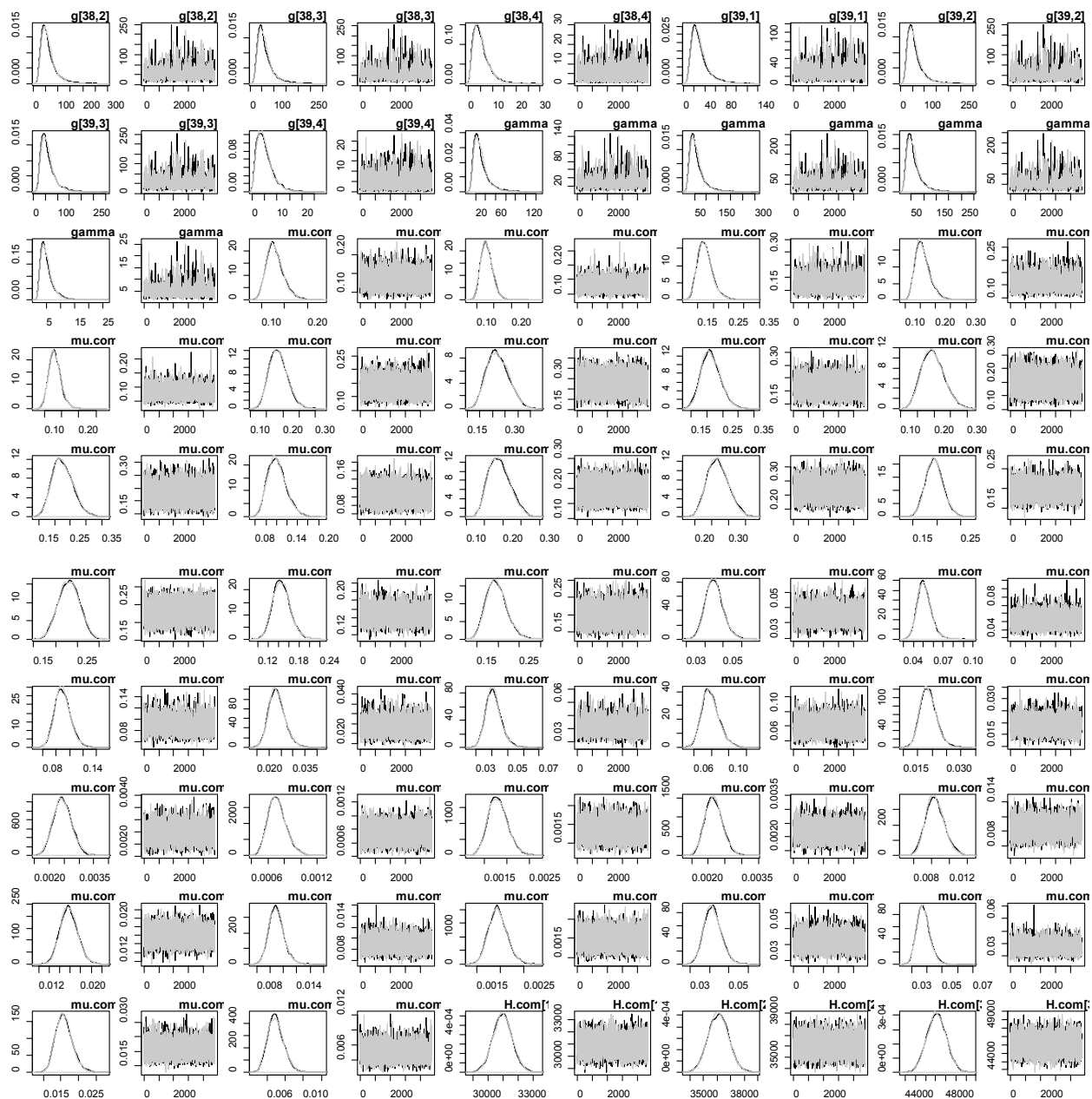

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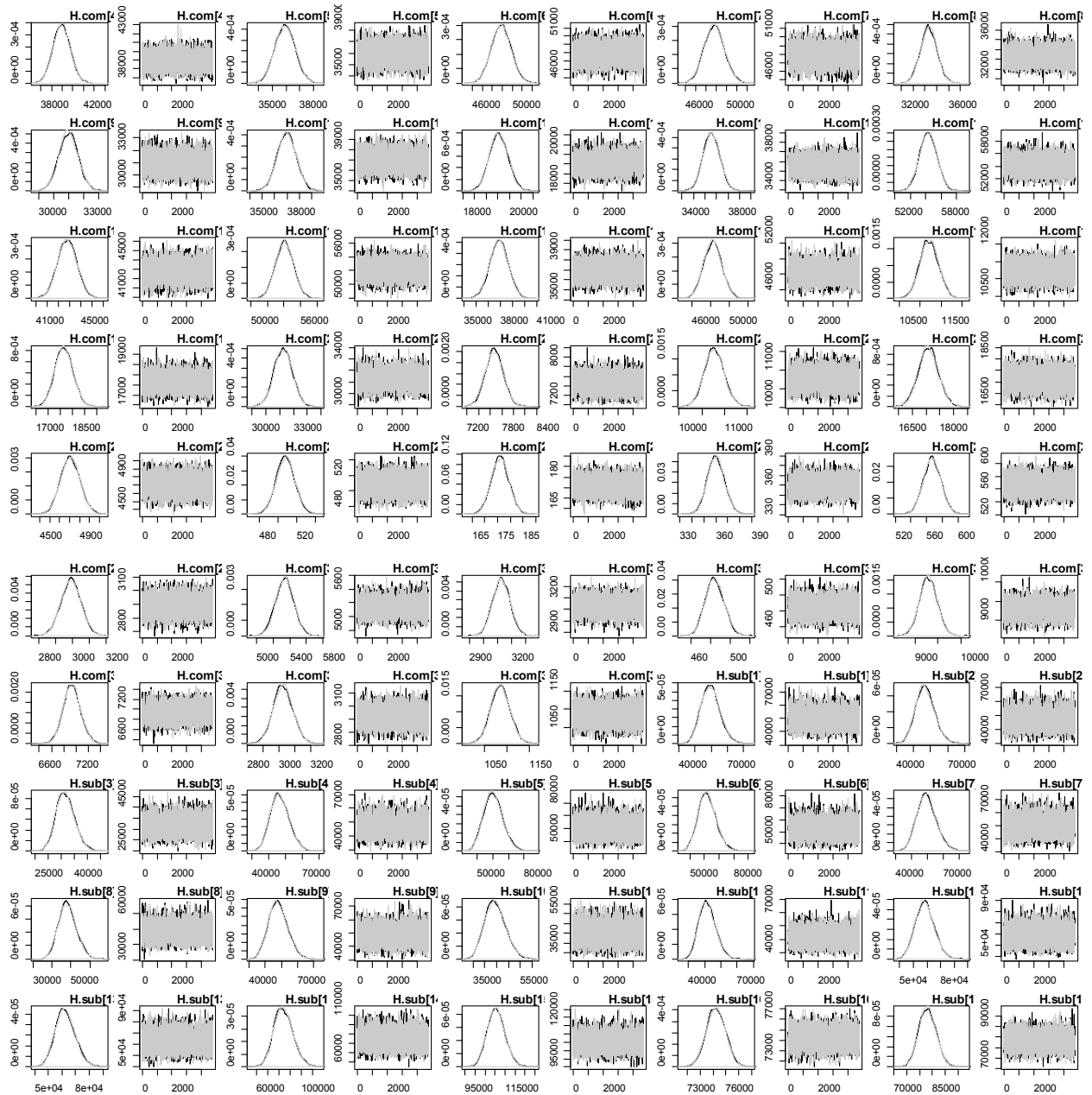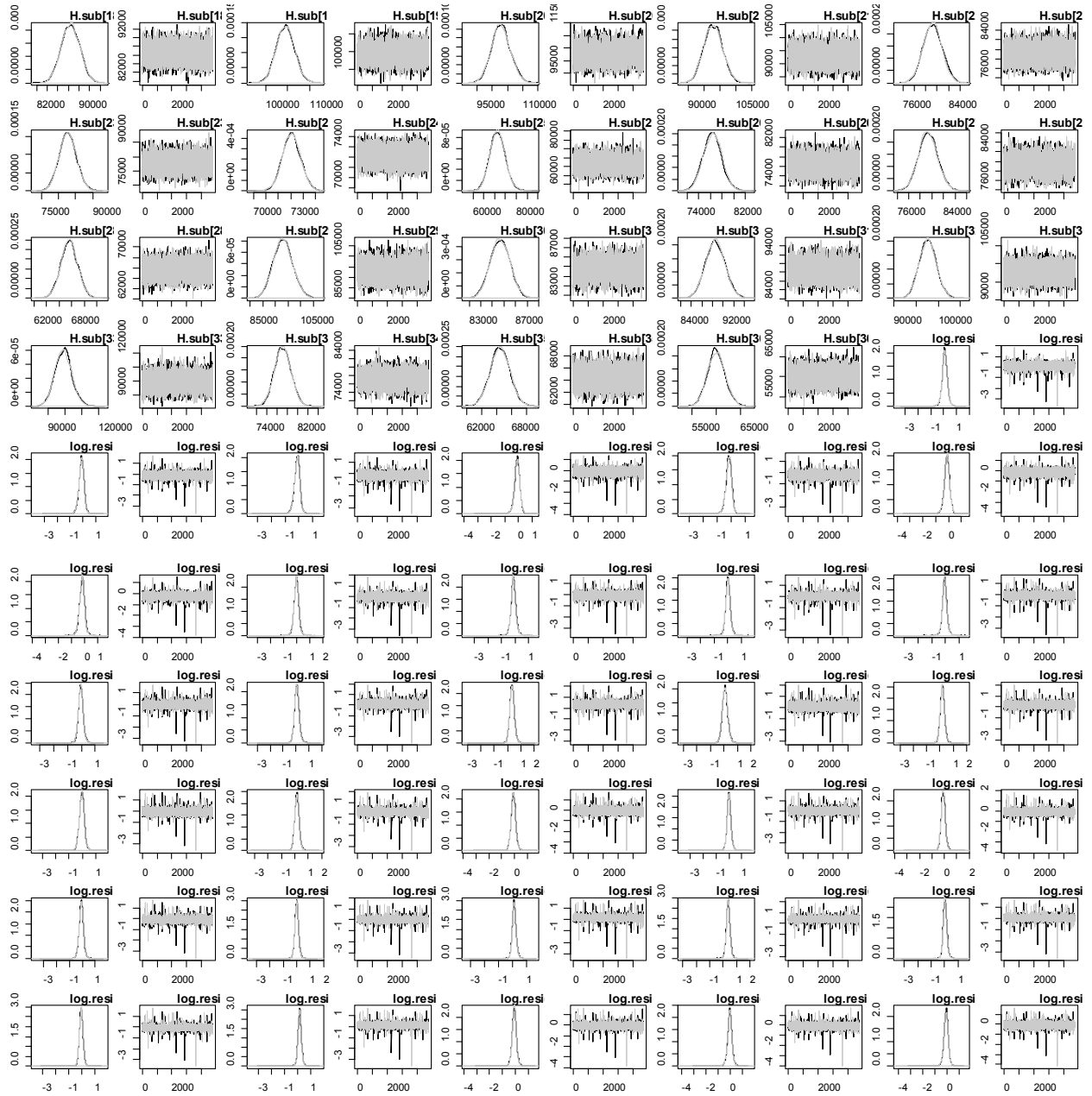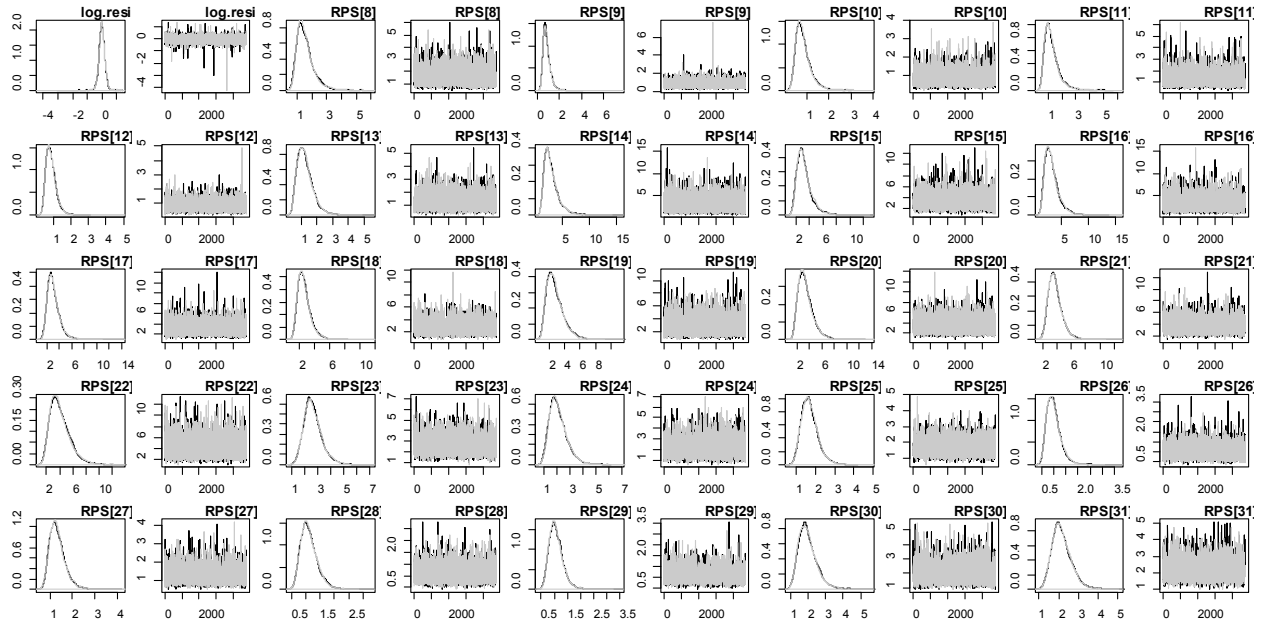
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Note: Close overlaps of the two lines suggests reliable model convergence. Black and grey lines show results from different initial points.