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

by

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and

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January 2013

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

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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)

Measures (fisheries)

fork length	FL
mideye to fork	MEF
mideye to tail fork	METF
standard length	SL
total length	TL

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

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FISHERY MANUSCRIPT SERIES NO. 13-0X

RUN RECONSTRUCTION, SPAWNER-RECRUIT ANALYSIS, AND ESCAPEMENT GOAL RECOMMENDATION FOR LATE-RUN CHINOOK SALMON IN THE KENAI RIVER

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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.sf.adfg.state.ak.us/statewide/divreports/html/intersearch.cfm This publication has undergone editorial and peer review.

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ABSTRACT

An age-structured state-space spawner-recruit model was fit to estimates of relative and absolute abundance, harvest, and age composition for Kenai River late-run Chinook salmon *Oncorhynchus tsawytscha* from 1986 to 2012. Bayesian statistical methods were employed, which allowed for realistic assessment of uncertainty in the presence of measurement error, serial correlation, and missing data. It is recommended that an interim sustainable escapement goal of 15,000 to 30,000 fish be adopted for Kenai River late-run Chinook salmon, evaluated by multiplying DIDSON-based estimates of inriver abundance by 1.31 to account for undetected Chinook salmon passing the sonar site, and subtracting harvest and catch-and-release mortality above the current sonar site. It is recommended this goal be considered for revision after the sonar site is moved upriver.

Key words: Chinook salmon, *Oncorhynchus tshawytscha*, Kenai River, spawning abundance, age composition, escapement goal, run reconstruction, spawner-recruit analysis, maximum sustained yield, measurement error, serial correlation, missing data, Bayesian statistics, OpenBUGS.

INTRODUCTION

Two stocks of Chinook salmon *Oncorhynchus tshawytscha* return to the Kenai River (Figure 1) to spawn. An early run enters the river from late April through June and spawns primarily in tributaries of the Kenai River. A late run enters the river from late June through early August, destined almost exclusively for mainstem spawning locations (Burger et. al 1985; Bendock and Alexandersdottir 1992).

Chinook salmon of Kenai River origin are harvested in several fisheries. The first measured harvest occurs in a recreational marine fishery near Deep Creek. A commercial set gillnet fishery along the eastern shore of Cook Inlet and, to a lesser degree, a commercial drift gillnet fishery, also harvest late-run Chinook salmon while targeting sockeye salmon *O. nerka*. Two single-net educational fisheries for the Kenaitze Indian tribe and the Village of Ninilchik have been authorized since 1989 and 1994, respectively. A personal use dip net fishery at the mouth of the Kenai River also harvests late-run Chinook salmon while targeting sockeye salmon. Finally, a Chinook salmon sport fishery occurs in the Kenai River itself.

FISHERIES MANAGEMENT

In 1988, the Board of Fisheries (BOF) adopted management plans for the early and late runs (McBride et al. 1989). These plans defined the early run as prior to 1 July and the late run as after 30 June. The dates and regulations associated with each management plan were designed to manage the unique characteristics of tributary spawning Chinook salmon and mainstem spawning Chinook salmon.

The Kenai River late-run Chinook salmon fishery is managed according to provisions of the *Kenai River Late-Run King Salmon Management Plan* (5 AAC 21.359). In the original plan developed in 1988 the optimum spawning escapement was set at 22,300 fish, with management directives centered around projected escapement levels of less than 15,500 fish, 15,500 to 19,000 fish, and greater than 22,300 fish. In 1999, the management plan was revised with a BEG established as a range of 17,800 to 35,700 Chinook salmon. In 2011 the BEG was redefined as an SEG because of uncertainty in escapement estimates due to the measurement error associated with split-beam target-strength-based (TS-based) sonar passage estimates of the number of Chinook salmon entering the river. The current management objective, as outlined in the plan, is to achieve adequate escapement defined as a sustainable escapement goal from 17,800 to 35,700 Chinook salmon. Regulations for the Kenai River late-run Chinook salmon sport fishery include a daily bag and possession limit of one and a seasonal limit of two. Also, multiple hooks are prohibited, several areas of the drainage are closed to fishing for Chinook salmon, fishing from a motorized vessel is prohibited on Mondays, and guided anglers are restricted to fishing five days per week (Tuesday through Saturday) twelve hours per day (6:00 a.m. to 6:00 p.m.).

RESEARCH

A comprehensive stock assessment program was initiated in the mid-1980s to provide information for use in management of the Chinook salmon fisheries. This stock assessment has gone through several phases. During the initial phase (1986-1994), dual-beam sonar technology was deployed at river mile 8.6 (rm 9) to estimate migrating fish. Target strength (TS) and range (distance from sonar transducer) were used to classify fish as Chinook salmon versus other species (Eggers et al. 1995). During the next phase (1995-2010), split-beam sonar technology was used to generate TS-based estimates of inriver run abundance and to evaluate the achievement of escapement goals.

Research conducted in the 1990s began to indicate that target strength and range alone were ineffective for distinguishing between Chinook and sockeye salmon (Eggers 1994). Tethered fish and netting studies (Burwen et al. 1998) showed that many sockeye salmon exceeded the minimum TS threshold and migrated mid-river, thus creating the potential for misclassifying sockeye salmon as Chinook salmon. Burwen et al. (1998) concluded that the TS-based sonar passage estimates were not accurate and recommended that the estimates be treated as an index rather than as an absolute number of fish. Subsequently, the TS-based sonar passage estimates were considered along with other indices of Chinook salmon abundance, such as catch rates in the inriver netting program and the inriver sport fishery, to assess run strength and to manage the fishery.

Radio-telemetry projects were conducted in 1996 and 1997 to estimate sport-fishery exploitation rates. These estimates, combined with creel survey estimates of harvest, provided independent estimates of inriver Chinook salmon abundance during the late run, when the potential to misclassify sockeye was assumed to be the greatest (Hammarstrom and Hasbrouck 1998, 1999). An inriver gill-netting program was standardized in 1998 with respect to drift location, timing, and procedures (Reimer et al. 2002). In 2001 a pilot netting study investigated size selectivity and several other aspects of the netting program (Reimer 2003). Experiments conducted by tethering fish in front of the sonar (Burwen and Fleischman 1998, Burwen et al. 2003) found that duration of the returning echo (“echo length”) was a better predictor of fish size than was TS (a measure of echo loudness).

In 2002, as a result of the above research findings, three improvements to the sonar and inriver netting programs were implemented. The first improvement was to modify an existing inriver gillnetting program just downstream of the rm 9 sonar site. A 5” mesh gillnet was added, and drifted alternately with the existing 7.5” mesh net, to capture salmon more representative of the size composition of fish entering the river (Reimer 2004). All gillnets were replaced with nets constructed of multi-fiber mesh, which captures fish more effectively than did the original cable-lay nylon. Catch rates from the standardized inriver netting program have provided an important index of inriver run strength since 2002. The second improvement was to develop an alternative “*ELSD*” estimate of inriver abundance, based on echo length standard deviation from the split-beam sonar and length measurements from the inriver gillnetting program. This information was combined to estimate the fraction of migrating fish that were Chinook salmon (Fleischman and Burwen 2003), which was then multiplied by total (all species) upstream fish passage estimates from the split-beam sonar ("total upstream passage"). The third improvement was to develop a second alternative estimate of inriver abundance based on sonar and netting data. The "*net-apportioned split-beam sonar*" estimate is the product of Chinook salmon catch proportions from the inriver netting program (Reimer 2004), and total upstream fish passage (all species) from the sonar program (Miller et al. 2005).

Also in 2002, ADF&G began testing dual-frequency identification sonar (DIDSON) in the Kenai River. DIDSON uses a lens system that provides high resolution images that approach the quality achieved with conventional optics (Simmonds and MacLennan 2005), with the added advantage that images can be obtained in dark or turbid waters. Fish size measured from DIDSON images enabled discrimination of large Chinook salmon from smaller fish in the Kenai River (Burwen et al. 2007). In 2008, when high-resolution and long-range models of DIDSON became available (Burwen et al. 2010), DIDSON was deployed side-by-side with split-beam sonar on the south bank of the river. Beginning in 2010, DIDSON was deployed on both banks and produced estimates of inriver Chinook salmon abundance at a frequency sufficient for inseason management use. The 2010 DIDSON findings confirmed that TS-based estimates were subject to contamination by misclassified sockeye salmon (Miller et al. *in preparation* a). In 2011, limited onsite experiments found substantial numbers of large Chinook salmon migrating behind the left-bank transducer (Miller et al. *in preparation* b), and these findings were confirmed in 2012 (Miller et al. *in preparation* c). Tidally induced fluctuations of water level precluded counting these fish, and investigations of alternative sites were conducted in 2011and 2012 (personal communication, D. Burwen, ADF&G Anchorage).

In the mid-1990s, it became apparent that advances in genetic stock identification (GSI) technology (Adams et al. 1994) had potential for resolving some important Kenai River Chinook salmon stock assessment issues, such as stock-specific run timing and catch allocation. GSI is used to determine the stock composition for fish of unknown stock origin (e.g. fish migrating upstream in a river or harvested in a fishery; the "mixture") by comparing their genetically-coded information to the genetically-coded information from fish of known stock origin (the "baseline"). Collection of tissue samples for development of a GSI baseline within the Kenai River drainage began in 2005 (Begich et al. 2010). Collection of mixture samples by the inriver netting project began in 2003, and by the inriver creel survey downstream of the Soldotna Bridge in 2006. Beginning in 2007, this was supplemented by mixture samples from the harvest upstream of the Soldotna Bridge. In 2011, a preliminary Kenai River drainage Chinook salmon baseline was developed from a subset of populations and the same set of SNPs markers reported in Barclay et al. (2012) for a Cook Inlet wide baseline. The preliminary baseline includes more than 2,000 Chinook salmon collected over 11 spawning locations between 2003 and 2009, representing 10 populations.

In 2010, Bromaghin et al. (2010) developed a new approach for modeling radio-telemetry, CPUE, and weir count data, fitting a stock-specific abundance and run-timing (SSART) model to obtain estimates of coho salmon abundance in the Kasilof River. The department modified the model to utilize genetic stock identification (GSI) data from the inriver netting program and inriver creel survey, estimates of passage from weirs on the Funny and Russian rivers and Slikok Creek, estimates of harvest from the inriver creel survey and statewide mail survey (SWHS), and daily CPUE from the inriver netting project. Preliminary SSART model estimates have been generated for years 2007-2011 (Eskelin and Miller 2010).

OBJECTIVES

The department is currently transitioning to management of Kenai River Chinook salmon based on DIDSON/ARIS[1] assessment technology. Ultimately, this assessment will take place upstream of the current site where there is little if any tidal influence. Thus far, steps in this transition have included the commencement of DIDSON-based abundance estimates in 2010 (Miller et al. *in preparation* a), discontinuation of TS-based estimates in 2011 (Miller et al. *in preparation* b), and discontinuation of split-beam sonar in 2012 (Miller et al. *in preparation* c). In the absence of TS-based estimates during 2011-2012, Kenai Chinook salmon stocks were managed conservatively based on multiple indices of abundance. This report provides the foundation for the next step, which is management based on DIDSON estimates obtained at rm 9, in 2013. Objectives of the report are as follows:

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. The model assumes a Ricker spawner-recruit relationship and time-varying productivity. It has an age-structured framework, which enables realistic depiction of observation error in inriver abundance, age composition, and harvest. The model is fit to multiple sources of information on historical abundance, as well as data on age composition and harvest, permitting simultaneous reconstruction of historical abundance and estimation of stock productivity and capacity. By constructing an integrated model, uncertainty associated with the reconstructed run is integrated directly into the spawner recruit analysis and to management reference points such as spawning escapement providing maximum yield (S_{MSY}). Sensitivity analyses are conducted to assess robustness of the results to assumptions of the run reconstruction and spawner-recruit analyses.

2) Recommend an interim sustainable escapement goal (SEG) based on DIDSON estimates of inriver abundance at rm 9. Normally, such a recommendation would be timed to coincide with a regularly scheduled Board of Fisheries meeting. However the extraordinary importance of Kenai River and associated Cook Inlet salmon fisheries has necessitated an out-of-cycle review.

3) Provide an updated summary of abundance, harvest, and age composition statistics for this stock during 1986-2012.

METHODS

DATA SOURCES

The state-space model requires the following input data: (1) estimates and associated coefficients of variation (CV) of annual harvest downstream of (also referred to as below) and upstream of (also referred to as above) rm 9; (2) estimates of annual age composition for harvest below rm 9 and for the inriver run at rm 9 (Table 1); and, (3) estimates of annual relative and absolute abundance, with CVs for the absolute measures (Tables 2 and 3). Sources of these data components are described in the following sections.

[1] ARIS is the next generation of multi-beam imaging sonar technology. It produces images comparable to DIDSON or better.

Annual Harvest

Harvest below rm 9

Kenai River late-run Chinook salmon are harvested by recreational anglers and by commercial set gillnet and commercial drift gillnet fisheries in Cook Inlet marine waters; by personal use and subsistence/educational fisheries near the river mouth, and by sport anglers inriver. Commercial harvests were obtained from mandatory fish tickets issued at the fish processors (Shields and Dupuis 2012). Personal use harvests were estimated from returned harvest reports (Dunker 2010). Annual harvests in the subsistence/educational fishery are reported directly to Division of Sport Fish staff (Begich and Pawluk 2010). Sport harvests between the river mouth and rm 9 were estimated with an onsite creel survey (Perschbacher 2012a,b). Estimates of harvest in the Cook Inlet marine recreational fishery were obtained with a statewide mail survey (Jennings et al. 2011).

Stock composition of fish harvested in the Upper Subdistrict Set Gillnet fishery ("east-side setnet fishery") was estimated by genetic stock identification in 2010 and 2011 (Appendix B). Estimates of the proportion of Kenai River fish in the harvest (0.647 in 2010; 0.727 in 2011) were applied to east-side setnet harvests for those years, but not other marine harvests. The average (0.687) was applied to east-side setnet fishery harvests for 1986 – 2009 and 2012.

Commercial, personal use, and subsistence harvests are known with relatively high precision. Estimates of sampling error were available from the onsite creel survey and statewide mail survey. Uncertainty associated with imputing the proportion of Kenai River fish in the east-side setnet fishery was not quantified. For the state-space model, CVs for the total harvests below rm 9 were assumed to be 0.10. Previous experience leads us to believe that the results are not sensitive to choice of this number.

Harvest above river rm 9

Sport harvests between rm 9 and Soldotna Bridge were estimated with an onsite creel survey (Perschbacher 2012a,b). Estimates of sport harvest upstream of Soldotna bridge were obtained with a statewide mail survey (Jennings et al. 2011). Estimates of sampling error from the onsite creel survey and statewide mail survey were squared, summed, and divided by the summed harvest estimates to obtain CVs for the total harvests above rm 9.

Age Composition

The largest components of the total run were sampled for age composition (McKinley and Fleischman 2010). Age composition of the harvest below rm 9 was estimated by counting scale annuli (Mosher 1969) from fish sampled ($n_y \gg 100$) from the commercial east-side set gillnet fishery (Tobias and Willette 2012). Age composition of the inriver run at rm 9 was estimated from fish sampled ($n_y \gg 100$) at the rm-9 inriver gillnetting project.

Measures of abundance

DIDSON-based estimates of late-run Chinook salmon passage during 2010 through 2012 reported here are preliminary estimates from Miller et al. (*in preparation* a,b,c). Annual catch rates from the inriver test gillnet fishery (NCPUE; Perschbacher 2012a,b) were obtained by summing daily catch rates from 1 July through 10 August. Net apportioned split-beam sonar estimates of Chinook salmon passages (NASB), and estimates based on ELSD during 2002 through 2011 were obtained from Miller et al. (2004, 2005, 2007a,b, 2010, 2011, 2012, *in* *preparation* a,b,c.). Annual catch rates (guided anglers only) from the inriver sport fishery (SCPUE; Perschbacher 2012a,b) were obtained by summing daily estimates during 1 through 31 July. Values used for daily CPUE on unsampled days were the mean of sampled days from the same time strata. Annual catch rates from the commercial east-side set gillnet fishery (CCPUE; Shields and Dupuis 2012) were obtained by conducting a Bayesian hierarchical analysis of daily catch rates, assuming normally distributed arrival times to the fishery (personal communication, Xinxian Zhang, ADF&G Soldotna).

Radio-telemetry-based mark-recapture estimates of inriver run were available for 1996 and 1997 (MRTLM; Hammarstrom and Hasbrouck 1998, 1999). Preliminary estimates of inriver run were also available for 2007 through 2011 from a genetic mark recapture experiment (MRGEN) by fitting a stock-specific abundance and run-timing model (SSART) to genetic allele frequency, radio-telemetry, harvest, and weir data (Eskelin and Miller 2010).

Details of the annual measures of abundance are provided in Table 2 with actual values of these measures in Table 3.

STATE-SPACE MODEL

The state-space model integrates the run reconstruction with stock dynamics, and all parameters including historical abundance, stock productivity, and capacity are estimated simultaneously. However it can be helpful to think of the model as having two components, a run reconstruction (RR) sub-model that synthesizes multiple sources of information on annual run abundance, and a stock dynamics (SD) sub-model that synthesizes production, age at maturity, and harvest. The RR sub-model depends on five “index” measures (NCPUE, NASB, SCPUE, CCPUE, ELSD; defined in Table 2) to quantify the relative abundance among years; DIDSON estimates of midriver abundance to anchor the time series with absolute numbers of fish; and mark-recapture estimates of inriver abundance (MRTLM and MRGEN; defined in Table 2) to supply information on the ratio of midriver to total inriver abundance (see below). The five relative abundance indices have positive relationships with one another (Figure 2) and show common trends through time (Figure 3).

For illustrative purposes, we disconnected the RR sub-model from the remainder of the state-space model and fitted it separately to produce intermediate run reconstruction estimates of inriver run abundance (labeled as IR with error bars in Figure 3). These estimates differ from final state-space estimates of inriver run because they do not consider the influence of other relationships (e.g., the spawner-recruit relationship) in the state-space model. The effect of fitting the state-space model is generally to “shrink” the inriver run estimates towards less extreme values, because the knowledge of inriver run from the RR sub-model illustrated in Figure 3 is counter-balanced against knowledge derived from the SD sub-model.

DIDSON estimates had insufficient contrast during 2010 through 2012 to expect positive relationships with the other measures. However, NCPUE, NASB, SCPUE, and CCPUE also exhibit narrow ranges of values during these same years. In the model, each index has a linear relationship to true (midriver, inriver, or total) abundance. The fitted relationships are shown in Figure 4.

The rm 9 sonar site is subject to tidal influence, and the sonar transducers must be placed such that they remain submerged during the lowest tides. At high tide they are distant from shore and unable to sample the entire cross section of the river. Because of this constraint, some Chinook salmon swim behind the transducers and go undetected by the sonar.[2] The fraction, $p_{MR,}$ of Chinook salmon that migrate "midriver" and are detected by the sonar at rm 9 cannot be estimated directly, because fluctuating water levels at the site would require continual re-deployment of transducers to ensonify the entire width of river. For this reason, reconstruction of Chinook salmon historical abundance also requires one or more unbiased estimates of Chinook salmon inriver run. The current analysis employs telemetry-based mark-recapture estimates in 1996 and 1997 (MRTLM) and preliminary estimates from genetic mark-recapture in 2007 through 2011 (MRGEN) to provide these estimates of inriver run.

In the full state-space model, abundance of Kenai River late-run Chinook salmon is driven by a Ricker (1975) stock recruit relationship, which is the most common choice for Pacific salmon stocks in Alaska. Productivity varies over time, fluctuating around a central tendency. Age at maturity is also allowed to fluctuate annually around a central tendency. Specifics of how model parameters (quantities) explain (predict) the observed data (abundance, harvest, age composition) are described below.

MODEL DETAILS

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

$$R_y = S_y \ \alpha \ e^{-\beta S} \tag{1}$$

where S is the number of spawners, parameter α (number of recruits-per-spawner in the absence of density dependence) is a measure of productivity, and parameter β is a measure of density dependence. The inverse of β is the number of spawners that produces the theoretical maximum return (S_{MAX}).

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

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

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

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

and the $\{\varepsilon_{Wy}\}$ are independently and normally distributed process errors with "white noise" variance σ^2_W.

Age at maturity was modeled hierarchically, i.e., it was allowed to vary, to a specified extent, between cohorts. Age at maturity vectors[3] $\underline{\boldsymbol{p}}_{\boldsymbol{y}}$ = (p_{y4}, $p_{y5,}$ p_{y6}, p_{y7}) from year y returning at ages 4-7

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[2] Chinook salmon passage behind the transducers was hypothesized for years, but not confirmed until an additional DIDSON was deployed to sample behind the left-bank transducer in 2011.

[3] These age proportions are maturity/survival schedules for a given brood year (cohort), across calendar years. In contrast, Equation 14 describes age proportions in a given calendar year, across brood years.

were drawn from a *Dirichlet*($\gamma_4,\gamma_5,\gamma_6,\gamma_7$) distribution. Age-3 fish, which averaged less than 2% of total run[4], were not included in the model. The Dirichlet parameters can also be expressed in an alternate form, where

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

is the (inverse) scale, or dispersion, of the annual age-at-maturity vectors, reflecting consistency of age-at-maturity among brood years. The location parameters

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

are proportions that sum to one, reflecting the age-at-maturity central tendencies.

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 *R* from year *y-a*:

$$N_{ya} = R_{y-a}\ p_{y-a,a} \tag{6}$$

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

$$N_{y\cdot} = \sum_a N_{ya} \tag{7}$$

Annual harvest *H* of Kenai-origin Chinook salmon below (downstream of) the stock assessment projects at rm 9 was modeled as the product of the annual harvest rate below rm 9 and total run:

$$H_{By} = \mu_{By} N_{y\cdot}\,. \tag{8}$$

Inriver run *IR* at rm 9 was:

$$IR_y = N_{y\cdot} - H_{By}\,. \tag{9}$$

Midriver run *MR* (number of fish migrating between the sonar transducers at rm 9) was the product of inriver run and the fraction p_{MR} of Chinook salmon migrating midriver and therefore detectable by the sonar:

$$MR_y = IR_y\ p_{MR}\,. \tag{10}$$

Annual harvest above rm 9 was the product of the annual harvest rate above rm 9 and inriver run abundance:

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

[4] Age-3 fish comprised 0 to 8% of total run in 1986-2012.

Finally, spawning escapement S was inriver run abundance minus harvest above rm 9:

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

Sampling Distributions of Observed Data

Observed data included estimates of annual harvest below and above rm 9 (1986-2012), direct estimates of inriver run (MRTLM 1996-1997 and MRGEN 2007-2011), direct estimates of midriver run (DIDSON 2010-2012), five indices of inriver run relative abundance (NCPUE, NASB, SCPUE, CCPUE, and ELSD), and age composition estimates. Sampling distributions (likelihood functions) for the data follow.

Estimated midriver run of Chinook salmon from the DIDSON was:

$$DS_y = MR_y e^{\varepsilon_{DSy}} \tag{13}$$

where the $\{\varepsilon_{DSy}\}$ were normal$(0,\sigma^2_{DSy})$, and

$$\sigma^2_{DSy} = \ln\left(CV^2\left(DS_y\right)+1\right) \tag{14}$$

Estimated inriver runs of Chinook salmon from MRTLM and MRGEN were:

$$\hat{IR}_y = IR_y e^{\varepsilon_{IRy}} \tag{15}$$

where the $\{\varepsilon_{IRy}\}$ were normal$(0,\sigma^2_{IRy})$ and the variances followed Equation 14.

Estimated annual harvest of Kenai River Chinook salmon below rm 9 was:

$$\hat{H}_{By} = H_{By} e^{\varepsilon_{HBy}} \tag{16}$$

where the $\{\varepsilon_{HBy}\}$ were normal$(0,\sigma^2_{HBy})$. Point estimates $\{\hat{H}_{By}\}$ were obtained by multiplying commercial fishery receipts by 0.7, which is the fraction of east-side set net fishery harvest estimated to originate from the Kenai River in 2010 and 2011 (Appendix B). Coefficients of variation $\{CV_{HBy}\}$ were assumed to be 10%.

Estimated annual harvest of Kenai River Chinook salmon above rm 9 was:

$$\hat{H}_{Ay} = H_{Ay} e^{\varepsilon_{HAy}} \tag{17}$$

where the $\{\varepsilon_{HAy}\}$ were normal$(0,\sigma^2_{HAy})$. Point estimates $\{\hat{H}_{Ay}\}$ and CVs were obtained from inriver creel survey and statewide mail survey.

Five indices of abundance were available (Table 3). Each comprised an independent measure of relative abundance:

$$I_{iy} = q_i X_y \varepsilon_{iy} \tag{18}$$

where q_i is a factor of multiplication relating true abundance to index i, X_y is the generic true abundance (midriver run MR for NCPUE, NASB, and ELSD; inriver run IR for SCPUE; and total run N for CCPUE) and the $\{\varepsilon_{iy}\}$ are independently and normally distributed process errors with variance σ^2_{Ii}. Parameters q_i and σ^2_{Ii} are estimated from the data.

The model predicts the age composition of the total run, however the data originated from two major components of the run: the harvest downstream of rm 9 and the inriver run at rm 9 (Table 1). Estimates of the age composition of the total run were obtained by weighting the age composition estimates from each component by relative abundance of each component, obtained from the run reconstruction submodel. Because the precision of age composition estimates is usually overstated, an "effective sample size" of n_{Ey} = 100 was used. Surrogate scale-age counts x_{ya} were obtained that summed to n_{Ey} rather than n_y. The x_{ya} were modeled as multinomially distributed, with order parameter n_{Ey} and proportion parameters as follows:

$$q_{y,a} = \frac{N_{y,a}}{\sum_a N_{y,a}} \tag{19}$$

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 OpenBUGS (Lunn et al. 2000), which is a Bayesian software program. This methodology allows for inclusion of the effects of measurement error, serially correlated process errors, and missing data in the analysis; and provides a more realistic assessment of uncertainty than is possible with classical statistical methods.

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 content of the data. See Ericksen and Fleischman (2006), Szarzi et al (2007), Fleischman and Borba (2009), Fleischman and Evenson (2010), Fleischman et al (2011), and Fleischman et al. (*in press*) for similar applications of the methods used in this paper.

Prior Distributions

Non-informative priors (chosen to have a minimal effect on the posterior) were used for most parameters. Initial returns R_{1979}-R_{1985} (those with no linked spawner abundance) were modeled as drawn from a common lognormal distribution with median μ_{logR} and variance σ^2_{logR}. Normal priors with mean zero, very large variances, and constrained to be positive, were used for ln(α) and β (Millar 2002), as well as for μ_{logR} and p_{MR}. The initial model residual v_0 was given a normal prior with mean zero and variance $\sigma^2_W/(1-\phi^2)$. Diffuse conjugate inverse gamma priors were used for σ^2_W and σ^2_{logR}. Annual harvest rates $\{\mu_{USy}$ and $\mu_{CAy}\}$ were given beta (0.1,0.1) prior distributions.

Sampling from the Posterior Distribution

Markov-Chain Monte Carlo samples were drawn from the joint posterior probability distribution of all unknowns in the model. For results presented here, a single Markov chain was initialized, a 10,000-sample burn-in period discarded, and >90,000 additional updates generated. The latter samples were used to estimate the marginal posterior medians, standard deviations, and percentiles. The diagnostic tools of OpenBUGS assessed mixing and convergence, and no major problems were encountered. 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)

$$S_{MSY} \cong \frac{\ln(\alpha')}{\beta}\left(0.5 - 0.07\ln(\alpha')\right) \qquad (20)$$

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

$$Y_S = R - S = Se^{\ln(\alpha') - \beta S} - S \qquad (21)$$

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

$$U_{MSY} \cong \ln(\alpha')\left(0.5 - 0.07\ln(\alpha')\right), \qquad (22)$$

escapement leading to maximum production:

$$S_{MAXR} = \frac{1}{\beta} \qquad (23)$$

and equilibrium spawning abundance, where return exactly replaces spawners:

$$S_{EQ} = \ln(\alpha')/\beta \qquad (24)$$

The quantity:

$$\ln(\alpha') = \ln(\alpha) + \frac{\sigma_R^2}{2(1-\phi^2)} \qquad (25)$$

in equations 20, 21, 22, and 24 adjusts for the difference between the median and the mean of a right-skewed lognormal error distribution from an 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 (0 to 40,000 by 800) for each MCMC sample, 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.

SENSITIVITY TO ASSUMPTIONS

Alternative versions of the analysis were conducted as a means to test for robustness of the results. For example, it is unlikely that all relative abundance indices are linearly related to abundance as shown in Figure 4. In alternative model 1a, we relaxed the linearity assumption for

CCPUE and allowed it to have an allometric relationship with true abundance. In alternative 1b we allowed four of five (all except NASB) to have allometric relationships:

$$I_{iy} = q_i IR_y^{r_i} \varepsilon_{iy} \tag{26}$$

where q_i and r_i are parameters of an allometric relationship between true abundance and index i, and the $\{\varepsilon_{iy}\}$ are independently and normally distributed process errors with variance σ^2_{Ii}. Parameters q_i, r_i, and σ^2_{Ii} were estimated from the data. We were unable to estimate allometric relationships for all five indices simultaneously due to mixing and convergence problems. Index CCPUE was perhaps most likely to depart from linearity because Chinook salmon from other stocks are represented in the marine commercial catch and the fishery targets sockeye salmon. Index NASB was perhaps most likely to be linearly related because 2010 daily sonar and netting data did not reveal any major departure from this assumption (Miller et al. *in preparation* a).

In alternative models (2a,b), we acknowledged that the choice of n_E = 100 was arbitrary, so we repeated the analysis with n_E = 50 and n_E = 200.

RESULTS AND DISCUSSION

HARVEST AND AGE COMPOSITION

Annual harvests of Kenai River late-run Chinook salmon below the sonar and netting stock assessments at rm 9 ranged from 727 fish in 2012 to over 21,000 fish in 2005 (Table 1). Annual harvests above rm 9 ranged from 196 fish in 2012 to nearly 20,000 fish in 1988. Age composition of the inriver run was predominately age-5 (1.3) and age-6 (1.4) fish, although fish harvested below rm 9 had a greater proportion of age-3 (1.1) and age-4 (1.2) fish.

The quantities above were estimated directly from stock assessment data, whereas those that follow were estimated by fitting the state-space model as described in the Methods section.

ABUNDANCE, TIME-VARYING PRODUCTIVITY, AND HARVEST RATES

Reconstructed estimates of inriver run abundance (IR; black line with error bars in Figure 3) were relatively high during 1986-1988, 1993-1995, and 2003-2005; but underwent a persistent decline starting in 2006. There were moderate year to year deviations from this trend among individual abundance indices, but generally the indices were in agreement. Estimates of abundance from the RR were more precise in 1996, 1997, and in 2002 - 2012 when direct estimates and/or multiple indices were available. Estimates were less certain in 1986-1995 and in 1998-2001 when only two relative abundance indices (SCPUE and CCPUE) were available.

There is a great deal of uncertainty about true escapement *S* in years without direct estimates of run abundance, with error CVs of up to 27% (Table 4, Figure 5a). Reconstructed total run abundance *N* (Figure 5c) and brood year returns *R* (Figure 5b) were less uncertain because they contain a harvest component, which was relatively well-estimated. Error CVs for *N* and *R* were 8-15% except for *R* at the beginning and end of the data series, when one or more age classes were missing (Table 4, Figure 5b,c). Productivity residuals show a persistent, though variable, decrease in productivity starting in 2004 (Figure 5d). Harvest rates on Kenai River late-run Chinook salmon ranged from 0.28 to 0.53 until 2012, when fishery restrictions reduced the harvest rate to 0.03 (Figure 5e).

Age at maturity has fluctuated moderately from brood year to brood year, likewise age composition has fluctuated from calendar year to calendar year (Figure 6). McKinley and

Fleischman (2010) noted a shift to earlier maturation beginning approximately with the 1990 brood year, however this no longer seems evident, given the added perspective of six more years of data (Figure 6). Total run abundance by age class is tabulated in Appendix C.

STOCK PRODUCTIVITY, CAPACITY, AND YIELD

Ricker relationships that could have plausibly generated the observed data are diverse (Figure 7), some varying substantially from the “point estimate” of the Ricker relationship, constructed from the posterior medians of ln(α) and β (Figure 7, heavy dashed line). The results reported below take into account the measurement error in both S and R as depicted by the error bars in Figure 7, essentially weighting the individual data pairs depending on how precisely they are estimated.

Compared to other Alaskan Chinook salmon stocks, productivity of Kenai River late-run Chinook salmon is moderate (α = 5.1), although note the wide 90% credibility interval (CI = 2.3 - 9.6; Table 4). Productivity of the stock has fluctuated over time, as evidenced by the moderately high serial correlation (CI of ϕ = 0.05 - 0.89; Table 5) in the spawner-recruit residuals (Figure 5d). Imprecise estimates of the productivity parameter α are typical of stocks with time-varying productivity and lower harvest rates.

The uncertainty about α is evident in the large variation in slope at the origin among the individual curves (Figure 7). Similarly, uncertainty about β is reflected in variability in the values of S leading to maximum recruitment S_{MAXR} = 1/β, and uncertainty about equilibrium abundance S_{EQ} is reflected by variability in where the curves intersect the replacement line. S_{EQ} is estimated with reasonably high certainty (CI = 41,410 – 80,160), as is spawning escapement leading to maximum sustained yield S_{MSY} (CI = 15,020 – 30,940; Table 5). Posterior medians of S_{EQ} and S_{MSY} are 52,690 and 19,930, respectively.

Given the wide diversity of plausible stock-recruit relationships (Figure 7), it is important to choose an escapement goal that performs well under most of those relationships, rather than one tailored to any single realization of the stock-recruit relationship. The optimal yield probability profiles in Figure 8 were generated by tallying, across plausible stock-recruit relationships, the success or failure of a given number of spawners to achieve stated percentages of maximum sustained yield (MSY). The profiles display the probability of achieving 70%, 80%, and 90% of MSY for specified levels of escapement. These probabilities, which are maximized near 20,000 spawning Chinook salmon (Figure 8), can be used to quantify yield performance of prospective escapement goals, taking into consideration the uncertainty about the true abundance, productivity, and capacity of the stock.

Expected sustained yield (numbers of fish over and above those necessary to replace spawners) is also maximized near 20,000 spawners (Figure 9). Under recent, reduced levels of productivity experienced during the 2004 through 2008 brood years, expected yield is reduced by about one half of the average expected yield.

Given that Kenai River Chinook salmon support a large sport fishery, and that catch rates in this fishery depend on abundance, the performance of different levels of escapement in producing maximal returns is a consideration in the development of an escapement goal. Returns and therefore run size are maximized at a higher level of escapement (S_{MAXR} = 31,080; Figure 10) than is maximum yield (S_{MSY} = 19,930; Figure 8).

SENSITIVITY ANALYSES AND REMAINING UNCERTAINTIES

Lacking a complete time series of direct estimates of historical abundance, this investigation of the stock dynamics of Kenai River Chinook salmon relied on indirect reconstruction of past quantities. The reconstruction was designed to extract maximum information from available data, being careful to preserve, assess, and acknowledge the associated uncertainty. Statistical methods were employed that are well suited to quantifying uncertainty arising from fitting a complex model. Nevertheless, several uncertainties remain, some of which are related to basic assumptions required by the analysis.

A key assumption associated with the run reconstruction model is that the five index variables are linearly related to the underlying and unknown true abundance. Because no direct estimates of abundance are available during the peak-abundance years of 2003 through 2005, there is not sufficient information in the data to relax this assumption entirely and estimate allometric relationships for all five indices. Model estimates were mildly to moderately sensitive to the choice of how many indices departed from a linear relationship. For example, estimates of total run abundance N during 2004 varied from 85,140 for model 1b to 106,500 for model 1a (Table 6). Also, S_{MSY} varied from 18,720 to 20,890 and p_{MR} from 0.772 to 0.795 (Table 6). In each case, the base model was intermediate between alternate models 1a and 1b. Other alternate models that varied effective sample size for age compositions did not reveal notable sensitivities (Table 6).

Another assumption is that telemetry- and GSI-based mark-recapture estimates of inriver run are unbiased. This assumption was necessary in order to estimate true inriver abundance for the spawner-recruit analysis, given that DIDSON misses an unknown fraction (1 - p_{MR}) of Chinook salmon at the rm-9 site. If mark-recapture estimates of the inriver run are too low (on average), then the current estimate of S_{MSY} is also too low; and vice-versa. This has obvious ramifications to selection of the escapement goal. In general, mark-recapture estimates contain some bias, however we do not believe that it is large in this case. There are seven such annual estimates, from two independently designed experiments that employed differing assumptions and technology. Furthermore the seven estimates are more or less in agreement with each other and are also consistent with limited direct measurements of p_{MR} at the rm-9 site (Miller et al. *in preparation* b). Improved information about true inriver abundance, and p_{MR}, will begin to be estimated during the 2013 season, when ARIS imaging sonar will be deployed at a new site at rm 14. Because tidal influence does not extend as high as rm 14, it will be possible to detect a very high fraction of Chinook salmon migrating past the rm-14 site. The rm-9 site will also continue to be operated in 2013, thereby permitting a comparison of abundance estimates between the two sites[5] and providing additional, and more precise, information about the midriver fraction p_{MR}. In addition, refinement of the 2007 through 2011 SSART estimates, and production of improved SSART estimates in 2012 and 2013[6], will clarify this issue.

The relative role of density-dependent and density-independent factors for Kenai River Chinook salmon also remains uncertain. Recent small runs have originated from large escapements (Figure 7), which is consistent with density dependence playing a large role. But the small Kenai River runs have also occurred at a time when productivity of Chinook salmon stocks is declining

[5] Harvest and spawning between the sites must and will be factored in to this analysis.
[6] Improvements are a weir was installed on Benjamin Creek in 2012 and an additional weir on Quartz Creek is planned for 2013.

statewide (ADF&G Chinook Salmon Research Team 2012). Given recently improved stock assessment capabilities, accurate estimates of upcoming runs originating from smaller escapements will provide helpful new information to improve understanding of Kenai River Chinook salmon dynamics.

Despite these uncertainties, several results are reasonably clear from the current analysis. First, productivity of Kenai River late-run Chinook salmon has fluctuated over time (Figure 5d). Second, the resulting trends in abundance (Figure 5c) are well estimated from the historical data (Figure 3), despite the lack of a complete set of direct estimates. For example, every version of the reconstruction developed during the current analysis, including those in Table 6, are in agreement that recent runs of Chinook salmon to the Kenai River have been among the smallest in recent history. Third, despite the small runs of recent years, a comprehensive analysis of stock productivity, capacity, and yield (fitting of state-space model) failed to find evidence that the stock has been over-exploited. For example, escapements have exceeded S_{MSY} in all but a few years and harvest rates have generally been well below U_{MSY} (Figure 5a, 5e).

ESCAPEMENT GOAL RECOMMENDATION

In this analysis, we have, to the extent possible, assessed and acknowledged the uncertainty involved in both the run reconstruction and population dynamics components of the analysis. Despite this uncertainty, there is good information about the level of escapement that will lead to optimal yields. The steeper the limbs of the optimal yield profile (OYP), and the greater the maximum probability, the better the information about sustained yield at different levels of escapement. Compared to other Alaska stocks of Pacific salmon that have been analyzed in a similar manner, the OYP for Kenai River late-run Chinook salmon (Figure 8) has greater maximum probability and is steeper than most other Chinook salmon stocks analyzed in this manner (Figure 11).

Based on the foregoing analysis, the Department recommends an interim sustainable escapement goal (SEG) of 15,000–30,000 Kenai River late-run Chinook salmon. At the lower bound of the recommended range there is a high probability of achieving near optimal yields, with greater than 95% probability of achieving greater than 70% of MSY, greater than 90% probability of achieving greater than 80% of MSY, and greater than 70% probability of achieving greater than 90% of MSY on average (Figure 8). At the upper bound of the recommended goal range these probabilities are reduced, but still relatively high. For example, there is a greater than 65% probability of achieving greater than 80% of MSY at escapements of 30,000 fish (Figure 8). The recommended goal is based on the actual escapement needed to sustain yields, so that it must be evaluated by accounting for undetected Chinook salmon passing the rm 9 sonar site. This is accomplished by multiplying DIDSON sonar estimates at rm 9 by 1.31 (or dividing by p_{MR} = 0.764), and subtracting estimated harvest and release mortality above rm 9.

Expected yield at escapements between 15,000 and 30,000 is approximately 35,000 fish (80% CI = 20,000 – 60,000). However it is important to recognize that the expectations of yield performance noted above are based on the central tendency of stock dynamics from brood years 1979 to 2008. During the most recent five brood years (2004-2008), log productivity residuals have been negative (Figure 5d), averaging -0.34 units, which is equivalent to a 29% decline in productivity (1-exp(-0.34)). Figure also shows revised yield expectations, should the reduced productivity of those recent brood years continue into the future. Under this scenario, expected yield would be less than 20,000 for escapements in the goal range (80% CI = 5,000-40,000), a reduction in yield of nearly 50% from average conditions.

Selection of an escapement goal always involves a tradeoff between risk to the stock (lower goals increase risk of overharvest) and risk to the fishery (higher goals increase risk of fishery restrictions). The recommended goal of 15,000 to 30,000 provides a small safety factor to reduce risk to the Chinook salmon stock. That is, the goal range is not centered with respect to maximum yield probabilities (Figure 8), nor with respect to expected sustained yields (Figure 9), being slightly higher than what would be required to symmetrically bracket these measures of yield performance. Along with the uncertainties discussed above, the primary reason for slightly elevating the recommended goal is that we have not yet experienced returns from escapements below 20,000 (Figure 12). The lowest escapement from which the return is complete was 23,830 (90% CI: 17,630-31,170) in 1997, which produced 59,000-88,370 (90% CI) returning adults (Table 4). Returns from the small 2009 escapement (22,320; 17,110-28,990) will commence as age-4 fish in 2013, and from the smaller 2010 escapement (16,320; 12,730-20,590) as age-4 fish in 2014 (Table 4).

Alaska salmon stocks are managed to provide sustained yield, and to the extent possible, maximum sustained yield. Our analysis concludes that, except for 2009-2011, historical escapements have exceeded the level of estimated S_{MSY}. By choosing an escapement goal that brackets S_{MSY} in a manner consistent with state policy, the lower bound of the recommended goal is less than the smallest measured historical escapement (Figures 12 and 13), thereby posing only modest risk to fisheries. Although this report does not address this, uncertainty associated with projecting Chinook salmon run abundance in real time during the fishing season remains an important challenge to managing these fisheries during periods of low Chinook salmon abundance.

An additional consideration is that Kenai River Chinook salmon support a large sport fishery, and catch rates in that fishery depend on abundance. Run abundance (N) depends on return (R), which is maximized at higher escapements (S_{MAXR} = 31,080; Figure 10) than is yield (maximized near S_{MSY} = 19,930; Figure 9). Thus, between 20,000 and 30,000 spawners there is a tradeoff between yield and run size. Sacrifices in yield performance arising from raising the goal are counterbalanced by increased run abundance, and vice versa. A partial set of the values used to produce Figures 6 and 9 is provided in Appendix C to facilitate further exploration of these tradeoffs.

We anticipate that our state of knowledge about this stock will continue to improve in the near future as improved stock assessments, including abundance estimates from the new sonar site, become available. We recommend that this goal be considered for revision on a regular basis as our understanding of Kenai River late-run Chinook salmon stock dynamics is updated.

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TABLES

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Table 1.–Harvest below and above river mile 9 (RM 9), age composition of harvest below RM 9, and age composition of inriver run at RM 9 for late-run Kenai River Chinook salmon, 1986–2012.

	Harvest and other mortality											Age composition proportions									
	Below river mile 8.6							Above river mile 8.6				Harvest below river mile 8.6					Inriver run at river mile 8.6				
Year	Marine sport	Comm set [a]	Comm drift	Pers use	Subsis	Inriver sport	Total	Sport	Hook rel. mort.	Total	CV	3	4	5	6	7	3	4	5	6	7
1986	630	13,619	1,834				16,083	9,872	316	10,188	0.05	0.01	0.23	0.37	0.34	0.03	0.00	0.12	0.44	0.40	0.04
1987	1,218	14,536	4,551				20,305	13,100	123	13,223	0.06	0.02	0.13	0.33	0.51	0.01	0.00	0.02	0.28	0.69	0.01
1988	1,487	8,834	2,217				12,538	19,695	176	19,871	0.05	0.03	0.11	0.15	0.69	0.03	0.00	0.01	0.04	0.78	0.17
1989	1,368	7,498	0		22		8,888	9,691	88	9,779	0.06	0.01	0.15	0.21	0.53	0.09	0.00	0.10	0.12	0.65	0.12
1990	1,605	2,843	621	91	13		5,173	6,897	69	6,966	0.07	0.01	0.30	0.30	0.34	0.05	0.00	0.12	0.15	0.69	0.05
1991	1,705	3,361	241	130	288		5,725	7,903	16	7,919	0.05	0.01	0.25	0.33	0.39	0.02	0.00	0.07	0.16	0.70	0.07
1992	2,115	7,363	543	50	402		10,473	7,556	234	7,790	0.06	0.02	0.15	0.28	0.50	0.04	0.00	0.07	0.16	0.75	0.02
1993	2,834	9,672	751	129	27		13,413	17,775	478	18,253	0.04	0.03	0.13	0.21	0.59	0.04	0.00	0.08	0.14	0.72	0.06
1994	1,869	10,700	460	13	392		13,434	17,837	572	18,409	0.04	0.04	0.13	0.15	0.60	0.07	0.00	0.06	0.11	0.78	0.05
1995	2,069	8,291	523	36	646		11,565	12,609	472	13,081	0.05	0.03	0.24	0.31	0.35	0.06	0.00	0.22	0.21	0.50	0.06
1996	2,038	7,944	365	45	294		10,686	8,112	337	8,449	0.06	0.04	0.19	0.34	0.40	0.02	0.00	0.08	0.34	0.57	0.01
1997	2,931	7,780	489	339	26		11,565	12,755	570	13,325	0.06	0.08	0.15	0.30	0.45	0.02	0.00	0.04	0.22	0.72	0.02
1998	1,784	3,495	332	271	2		5,884	7,515	595	8,110	0.07	0.12	0.24	0.23	0.39	0.02	0.00	0.15	0.14	0.68	0.03
1999	1,004	6,501	575	488	4	1,170	9,742	12,425	682	13,107	0.08	0.02	0.26	0.25	0.44	0.03	0.00	0.12	0.21	0.61	0.05
2000	1,052	2,531	270	410	6	831	5,100	14,391	499	14,890	0.05	0.09	0.13	0.39	0.38	0.01	0.00	0.04	0.31	0.62	0.03
2001	920	4,128	619	638	8	1,336	7,649	15,144	825	15,969	0.07	0.12	0.40	0.15	0.32	0.01	0.00	0.12	0.19	0.66	0.03
2002	427	6,511	415	606	6	1,929	9,894	10,678	665	11,343	0.07	0.13	0.30	0.36	0.20	0.01	0.02	0.18	0.19	0.58	0.03
2003	200	10,174	1,240	1,016	11	823	13,464	16,120	1,803	17,923	0.09	0.04	0.52	0.24	0.19	0.02	0.01	0.30	0.20	0.49	0.00
2004	1,660	14,897	1,526	792	10	2,386	21,271	14,988	1,019	16,007	0.07	0.06	0.24	0.43	0.26	0.01	0.01	0.14	0.25	0.59	0.01
2005	1,040	15,183	1,839	775	11	2,287	21,135	15,927	1,267	17,194	0.08	0.03	0.27	0.21	0.48	0.02	0.00	0.07	0.18	0.70	0.04
2006	898	6,840	1,051	1,034	11	3,322	13,156	12,490	830	13,320	0.08	0.13	0.35	0.22	0.27	0.03	0.01	0.27	0.13	0.49	0.10
2007	797	8,445	912	1,509	6	1,750	13,419	9,690	670	10,360	0.07	0.05	0.43	0.23	0.29	0.01	0.00	0.20	0.29	0.42	0.09
2008	517	5,203	653	1,362	15	1,011	8,761	10,128	370	10,498	0.08	0.10	0.20	0.28	0.41	0.02	0.02	0.07	0.20	0.63	0.08
2009	256	3,839	859	1,189	4	1,132	7,279	7,904	626	8,530	0.07	0.14	0.51	0.12	0.22	0.01	0.00	0.29	0.11	0.55	0.04
2010	558	4,567	538	865	21	445	6,994	6,762	264	7,026	0.06	0.20	0.26	0.34	0.19	0.01	0.04	0.20	0.34	0.36	0.06
2011	880	5,596	593	1,243	5	458	8,775	6,894	479	7,373	0.07	0.05	0.34	0.25	0.35	0.01	0.02	0.30	0.19	0.46	0.02
2012	50	484	191	0	0	2	727	101	95	196	0.06	0.10	0.18	0.37	0.36	0.00	0.02	0.10	0.40	0.44	0.04

[a] Kenai River fish only, based on 2010–2011 genetic sampling of setnet fishery.

Table 2.–Annual measures of Kenai River Chinook salmon abundance used to reconstruct historical run sizes.

Measure	Acronym	Citation	Years	Definition	Strengths / Weaknesses
Multibeam imaging sonar estimate	DIDSON	Burwen et al 2010	2010–2012	Upstream midriver passage of Chinook salmon between transducers placed at fixed distances from shore. Netting data provide length distribution for apportionment.	Provides precise fish length measurement and species classification, improved detection and tracking of migrating fish. Brief historical record.
Catch rate in inriver test fishery	NCPUE	Perschbacher 2012	2002–2012	Catch rate of king salmon from gillnets drifted inriver at the sonar site.	Entirely independent of sonar. Nets not deployed during rising tides.
Net-apportioned split-beam sonar	NASB	Miller et al. 2012	2002–2012	Total upstream fish passage from split-beam sonar multiplied by Chinook salmon proportions derived from inriver netting project	Combines strengths of sonar and netting projects. Nets not deployed during rising tides.
Catch rate in lower river sport fishery	SCPUE	Perschbacher 2012	1986–2011	Mean daily catch rate of Chinook salmon from inriver sport fishery, from creel survey interviews	Entirely independent of sonar. Sensitive to changes in regulations and fishing conditions.
Catch rate in commercial east-side setnet fishery	CCPUE	Shields and Dupuis 2012	1986–2011	Sum of daily catch rates of Chinook salmon in the eastside Cook Inlet setnet fishery adjacent to Kenai River mouth.	Entirely independent of sonar. Influenced by presence of non-Kenai stocks.
Estimated annual passage using sonar echo-length	ELSD	Miller et al. 2012	2002–2009	Upstream midriver passage as estimated by split-beam sonar, using echo length standard deviation to apportion species	Best estimates available from split-beam sonar. Less accurate than DIDSON, available for only 8 years
Radio-telemetry mark-recapture estimates	MRTLM	Hammarstrom and Hasbrouck 1999	1996–1997	Harvest estimated by creel divided by radio-telemetry estimate of exploitation rate	Provides some ability to quantify fraction of Chinook salmon detected by sonar in midriver. Probably subject to some bias.
Genetic mark–recapture estimates	MRGEN	Eskelin and Miller 2010	2007–2011	Stock-specific abundance and run-timing model fitted to weir, harvest, and genetic allele-frequency data	Provides some ability to quantify fraction of Chinook salmon detected by sonar in midriver. Probably subject to some bias; methods currently under development.

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Table 3.–Values of annual abundance measures used to reconstruct historical run size, late-run Kenai River Chinook salmon, 1986–2012.

Year	NCPUE	NASB	SCPUE	CCPUE	ELSD	DIDSON[a] (CV)	MRTLM (CV)	MRGEN[a] (CV)
1986			0.110	2,028				
1987			0.099	1,720				
1988			0.115	1,385				
1989			0.066	977				
1990			0.055	749				
1991			0.058	974				
1992			0.073	1,033				
1993			0.102	1,428				
1994			0.080	1,586				
1995			0.065	1,862				
1996			0.042	1,472			39,356 (0.14)	
1997			0.050	1,034			39,080 (0.14)	
1998			0.066	1,400				
1999			0.078	1,206				
2000			0.072	1,099				
2001			0.100	1,181				
2002	12.7	41,813	0.106	1,383	33,508			
2003	16.9	62,635	0.176	2,041	57,101			
2004	14.2	75,050	0.129	2,253	43,542			
2005	13.8	85,590	0.127	1,607	48,275			
2006	17.6	52,482	0.091	1,134	37,692			
2007	10.4	29,457	0.073	1,436	28,914			39,600 (0.16)
2008	12.2	36,011	0.060	808	24,589			52,530 (0.14)
2009	5.4	17,722	0.074	762	15,655			45,480 (0.20)
2010	3.0	12,501	0.039	834		19,000 (0.07)		18,830 (0.17)
2011	5.1	18,765	0.068	956		21,036 (0.02)		31,110 (0.18)
2012	3.0	13,896				21,914 (0.03)		

Note: Abbreviations defined in Table 2. CV = coefficient of variation.

[a] DIDSON and MRGEN estimates are preliminary and subject to revision until published.

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Table 4.–Parameter estimates for state-space model fitted to late-run Kenai River Chinook salmon data, calendar years 1986–2012. Posterior medians are point estimates, CVs are posterior standard deviations divided by posterior means.

Year	Total run N (CV)	Inriver run IR (CV)	Escapement S (CV)	Return R (CV)
1979				59,090 (0.60)
1980				51,930 (0.21)
1981				110,300 (0.14)
1982				92,810 (0.12)
1983				38,910 (0.15)
1984				35,920 (0.15)
1985				40,630 (0.14)
1986	77,850 (0.13)	61,620 (0.17)	51,410 (0.20)	52,150 (0.13)
1987	81,300 (0.13)	60,640 (0.17)	47,390 (0.21)	61,250 (0.13)
1988	72,990 (0.13)	60,410 (0.16)	40,470 (0.24)	63,040 (0.13)
1989	44,020 (0.14)	35,130 (0.18)	25,320 (0.24)	43,150 (0.14)
1990	37,370 (0.14)	32,150 (0.16)	25,140 (0.21)	45,090 (0.11)
1991	42,820 (0.13)	37,050 (0.16)	29,130 (0.20)	60,930 (0.09)
1992	51,760 (0.13)	41,220 (0.17)	33,400 (0.20)	51,580 (0.12)
1993	63,420 (0.14)	50,070 (0.17)	31,770 (0.27)	44,460 (0.13)
1994	60,060 (0.13)	46,540 (0.17)	28,100 (0.27)	51,930 (0.13)
1995	54,450 (0.13)	42,710 (0.16)	29,590 (0.23)	62,870 (0.13)
1996	48,020 (0.09)	37,010 (0.12)	28,530 (0.15)	53,460 (0.12)
1997	48,960 (0.08)	37,180 (0.11)	23,830 (0.17)	72,640 (0.12)
1998	50,660 (0.13)	44,700 (0.15)	36,550 (0.18)	94,760 (0.11)
1999	52,520 (0.12)	42,740 (0.15)	29,600 (0.22)	130,200 (0.11)
2000	50,680 (0.13)	45,530 (0.15)	30,620 (0.22)	75,130 (0.12)
2001	60,780 (0.14)	53,100 (0.16)	37,080 (0.23)	51,320 (0.12)
2002	66,420 (0.10)	56,520 (0.12)	45,120 (0.15)	69,250 (0.10)
2003	98,870 (0.11)	85,490 (0.12)	67,300 (0.16)	44,310 (0.10)
2004	101,200 (0.10)	79,900 (0.12)	63,950 (0.15)	22,510 (0.13)
2005	96,880 (0.10)	75,980 (0.13)	58,590 (0.17)	40,060 (0.10)
2006	74,450 (0.11)	61,460 (0.13)	48,140 (0.16)	29,110 (0.13)
2007	58,360 (0.08)	44,890 (0.10)	34,490 (0.13)	50,900 (0.21)
2008	52,180 (0.08)	43,480 (0.10)	32,920 (0.13)	37,820 (0.34)
2009	38,190 (0.09)	30,890 (0.12)	22,320 (0.16)	44,370 (0.48)
2010	30,510 (0.08)	23,370 (0.10)	16,320 (0.15)	
2011	36,650 (0.08)	27,700 (0.10)	20,290 (0.14)	
2012	29,370 (0.10)	28,640 (0.11)	28,440 (0.11)	

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Table 5.–Parameter estimates for state-space model fitted to late-run Kenai River Chinook salmon data, calendar years 1986–2012. Posterior medians are point estimates, 5th and 95th percentiles define 90% credibility intervals for the parameters. Parameter definitions are in the methods section.

Parameter	Posterior median	0.05 percentile	0.95 percentile	Posterior CV
$\ln(\alpha)$	1.62	0.84	2.27	0.28
α	5.1	2.3	9.6	0.63
β	0.000032	0.000016	0.000049	0.31
ϕ	0.52	0.05	0.89	0.51
σ_W	0.33	0.24	0.47	0.21
S_{MAXR}	31080	20320	62930	0.35
S_{EQ}	52690	41410	80160	0.20
S_{MSY}	19930	15020	30940	0.22
U_{MSY}	0.65	0.43	0.80	0.19
D	47	31	71	0.26
π_1	0.15	0.13	0.17	0.08
π_2	0.22	0.20	0.25	0.06
π_3	0.58	0.55	0.61	0.03
π_4	0.05	0.04	0.06	0.14
p_{MR}	0.764	0.644	0.901	0.10
$q_{NCPUE}\ 10^{-4}$	2.5	2.0	3.1	0.14
q_{NASB}	0.94	0.78	1.16	0.12
$q_{SCPUE}\ 10^{-6}$	1,7	1.5	2.0	0.09
q_{CCPUE}	0.02	0.02	0.03	0.08
q_{ELSD}	0.78	0.64	0.96	0.12
σ_{NCPUE}	0.32	0.22	0.52	0.29
σ_{NASB}	0.27	0.18	0.45	0.30
σ_{SCPUE}	0.21	0.15	0.29	0.20
σ_{CCPUE}	0.22	0.16	0.30	0.19
σ_{ELSD}	0.13	0.05	0.26	0.50

Table 6.–Posterior medians of key quantities, with base and alternate versions of state-space model. Noteworthy differences are in bold.

	Base Model	Alternative Models			
		CCPUE Allometric	*Indices Allometric except NASB*	*n.E= 50*	*n.E= 200*
α	5.1	4.9	5.1	5.0	5.1
β	3.2x10^{-5}	3.0x10^{-5}	3.4x10^{-5}	3.2x10^{-5}	3.2x10^{-5}
σ_R	0.33	0.35	0.33	0.51	0.55
ϕ	0.52	0.56	0.46	0.63	0.47
S_{EQ}	52,690	**55,010**	**48,410**	52,120	52,930
S_{MSY}	19,930	**20,890**	**18,720**	19,670	20,000
D	47	46	50	87	38
pMR	0.764	**0.795**	**0.772**	0.754	0.768
N_{2004}	101,200	**106,500**	**85,140**	101,000	101,200

FIGURES

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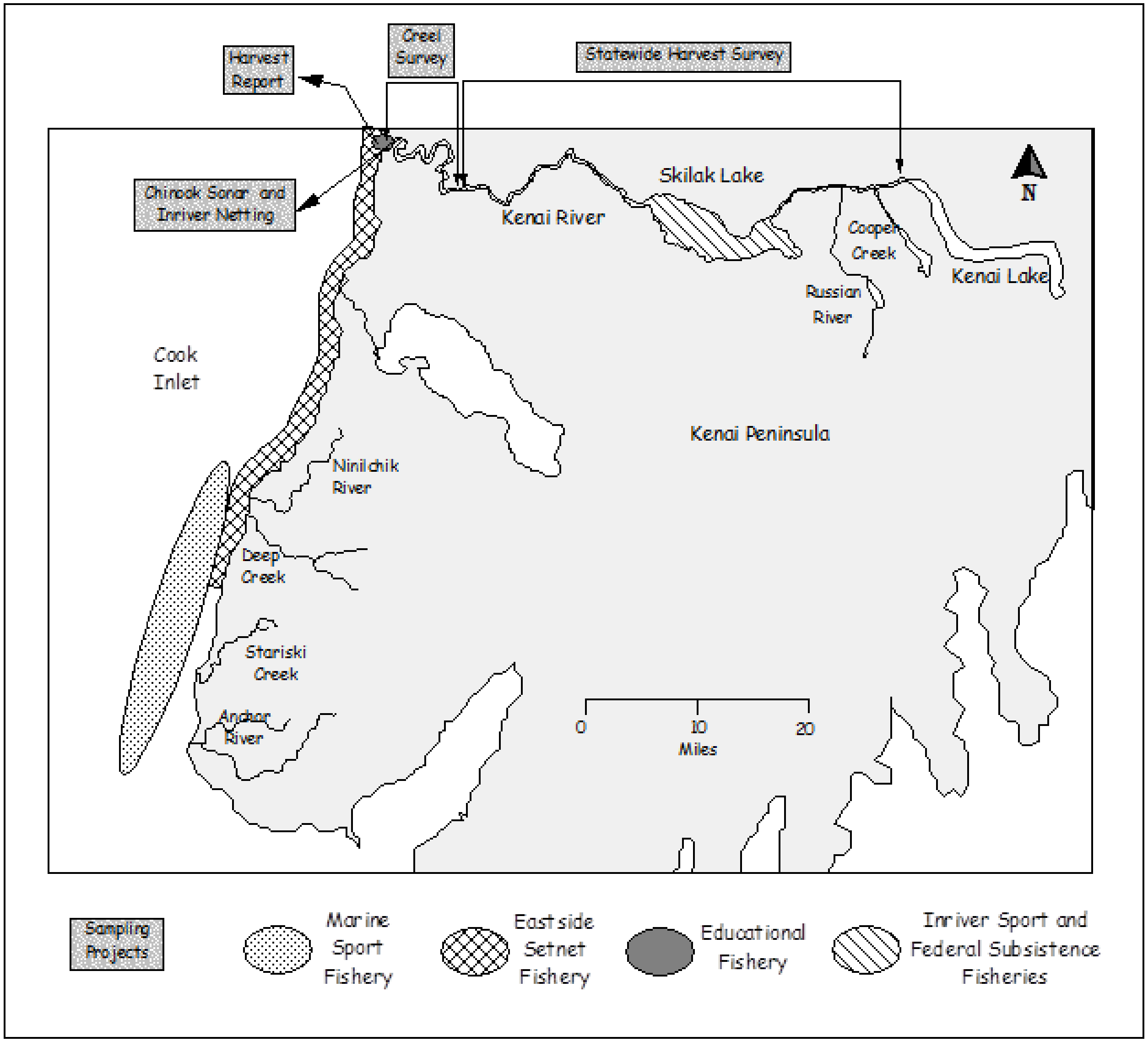

Figure 1.–Kenai River drainage.

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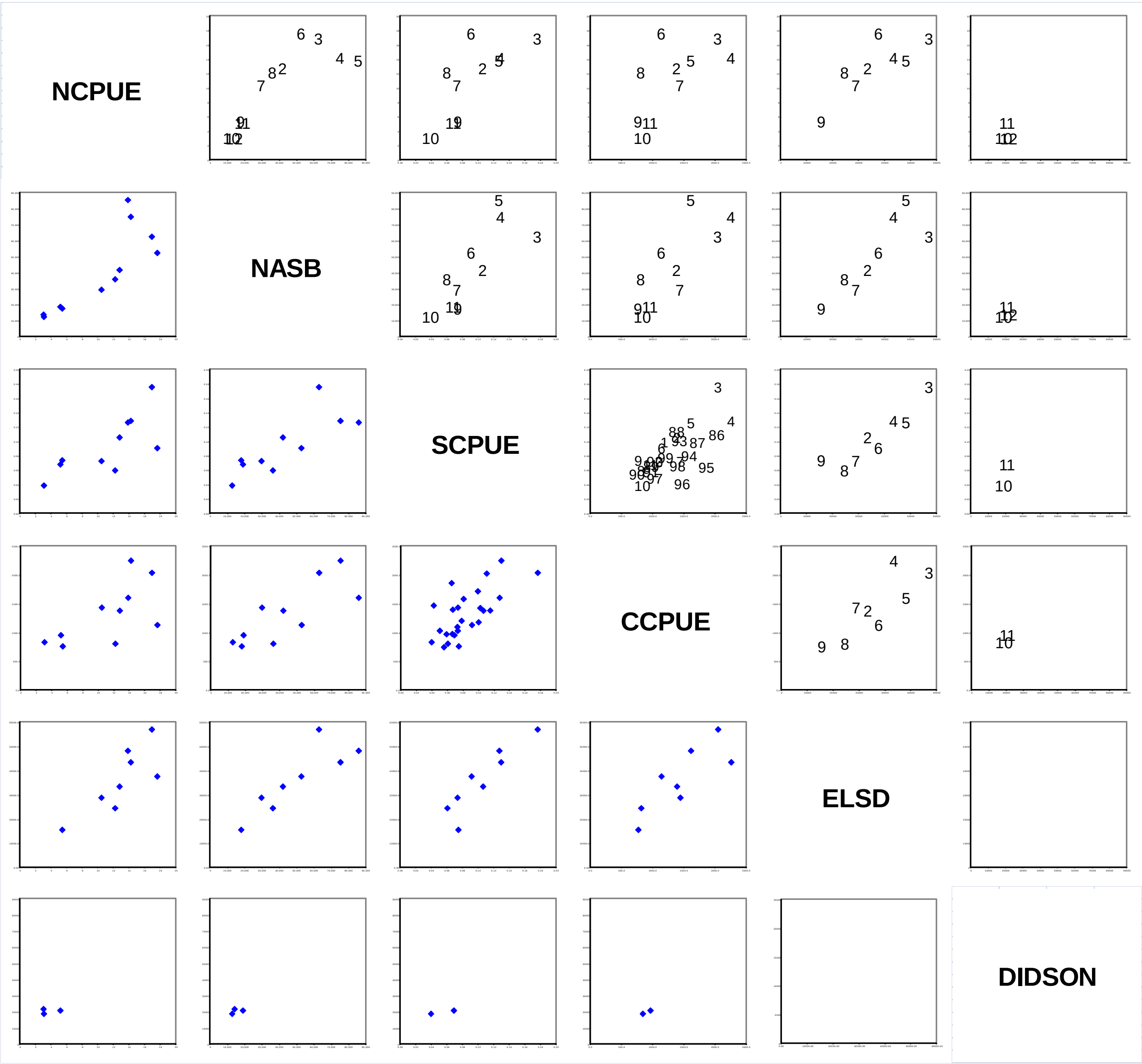

Figure 2.–Scatter plot matrix of key abundance measures for late-run Kenai River Chinook salmon, 1986–2012. Symbols defined inTable 2.

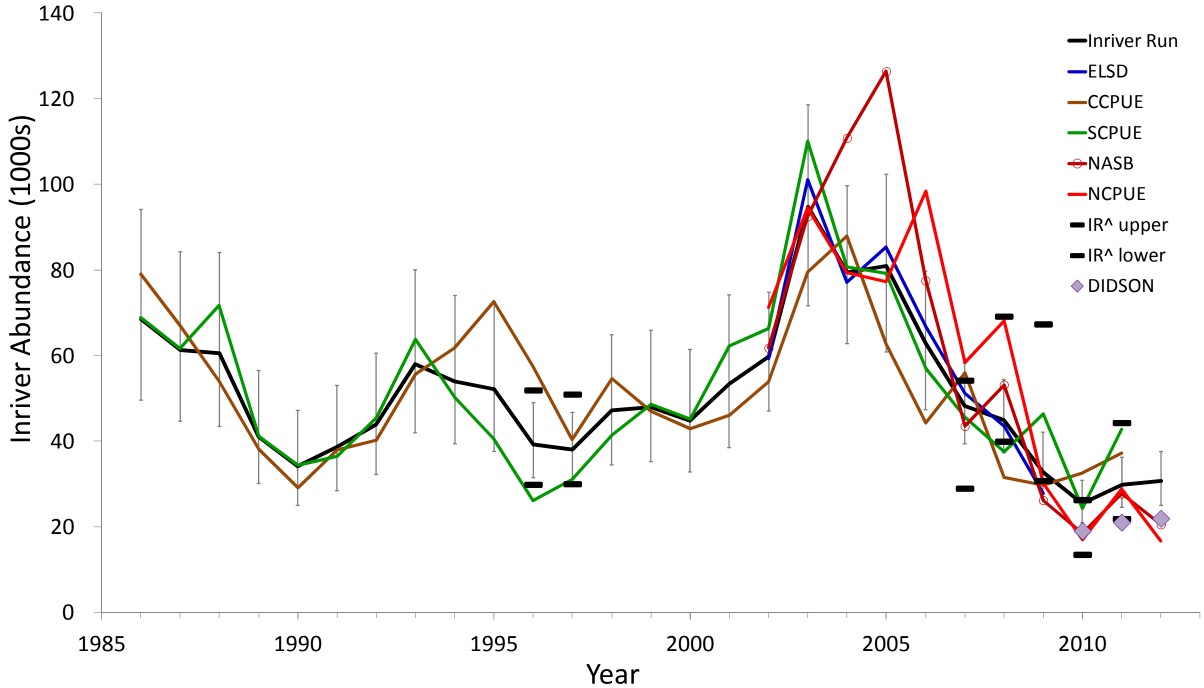

Figure 3.–Intermediate results from the run reconstruction component of the state-space model for late-run Kenai River Chinook salmon, illustrating how inriver run abundance was reconstructed from 5 measures of relative abundance: inriver gillnet catch rate (NCPUE), split-beam sonar salmon abundance apportioned by Chinook salmon fraction in test gillnets (NASB), catch rate in the lower-river sport fishery (SCPUE), catch rate in the marine commercial setnet fishery (CCPUE), and split-beam sonar estimates of Chinook salmon passage based on the following: echo-length standard deviation (ELSD) and 3 measures of absolute abundance (mark-recapture estimates [IR^] with lower and upper bounds of 95% interval based on telemetry (1996–1997), genetic stock identification (preliminary estimates, 2007–2011), and direct estimates of midriver run from imaging sonar (DIDSON point estimates, 2010–2012). Error bars bracket 95% credibility intervals of inriver run from the run reconstruction submodel. For plotting, relative abundance measures were converted to number of inriver Chinook salmon based on relationships in Figure 4. Values of inriver run plotted here differ from final estimates, which are also subject to influence of the population dynamics component of the state-space model.

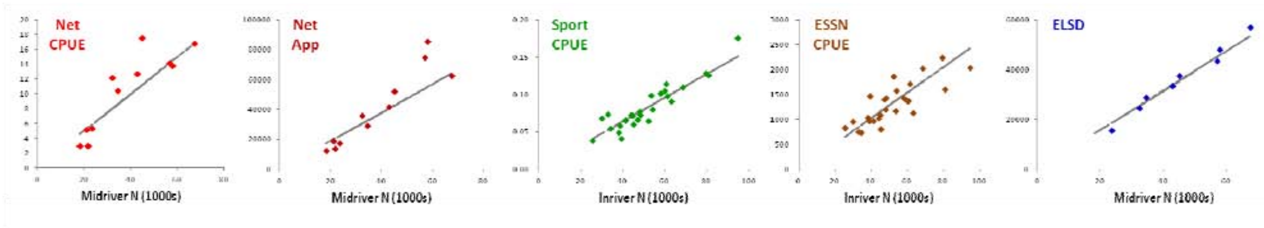

Figure 4.–Linear relationships between abundance measures and estimates of inriver N, from state-space model of Kenai River Chinook salmon data, 1986–2012. Slopes q and errors standard deviations σ of these relationships are given in Table 5.

.

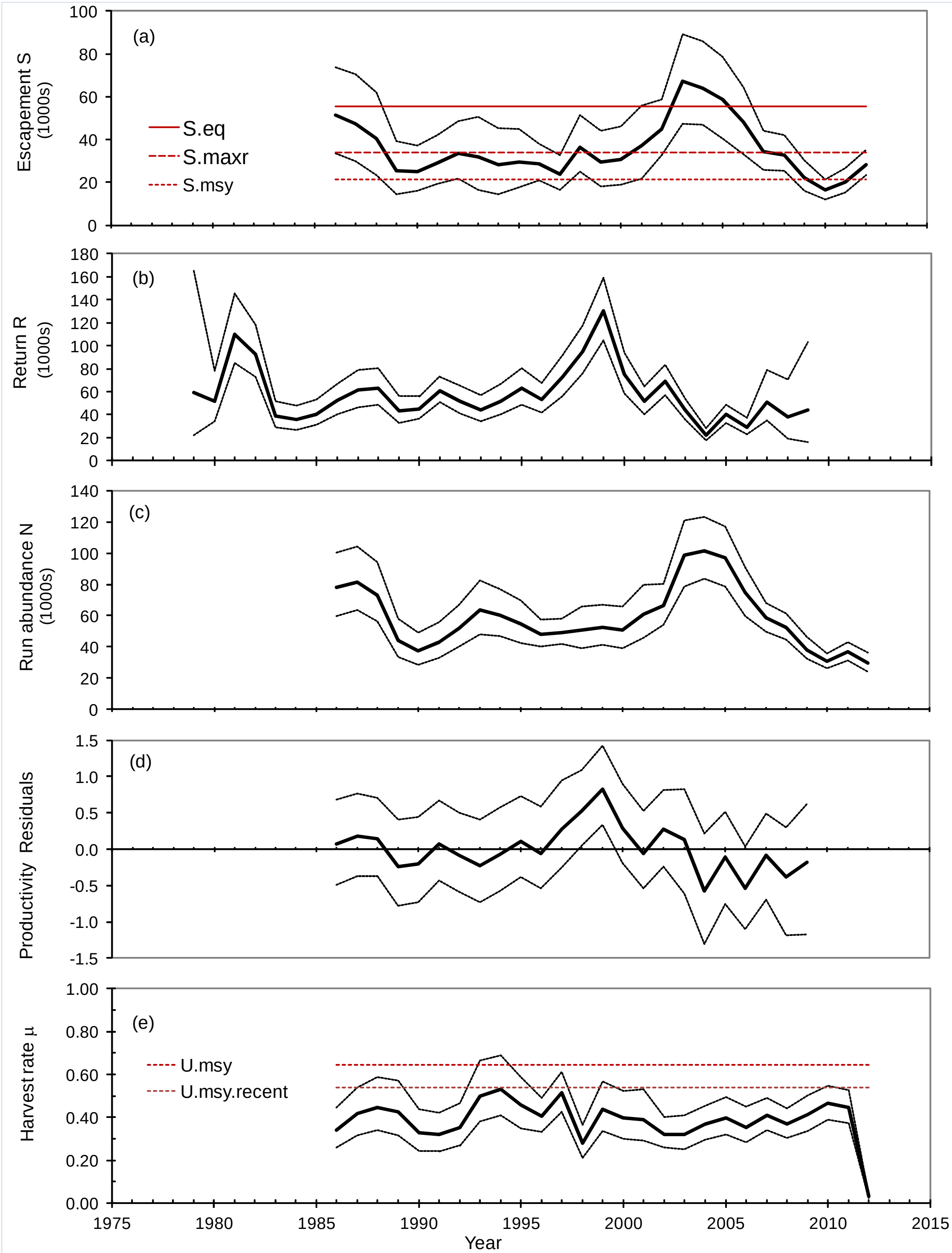

Figure 5.–Point estimates (posterior medians; solid lines) and 95% credibility intervals (bracketed by dashed lines) of (a) spawning escapement, (b) return by brood year, (c) run abundance, and (d) productivity residuals and (e) harvest rate from a state-space spawner-recruit model of Kenai River late-run Chinook salmon, 1986–2012. Posterior medians of optimal escapement $S_{EQ,}$ S_{MAXR}, S_{MSY}, and U_{MSY} are plotted as horizontal reference lines in (a) and (e).

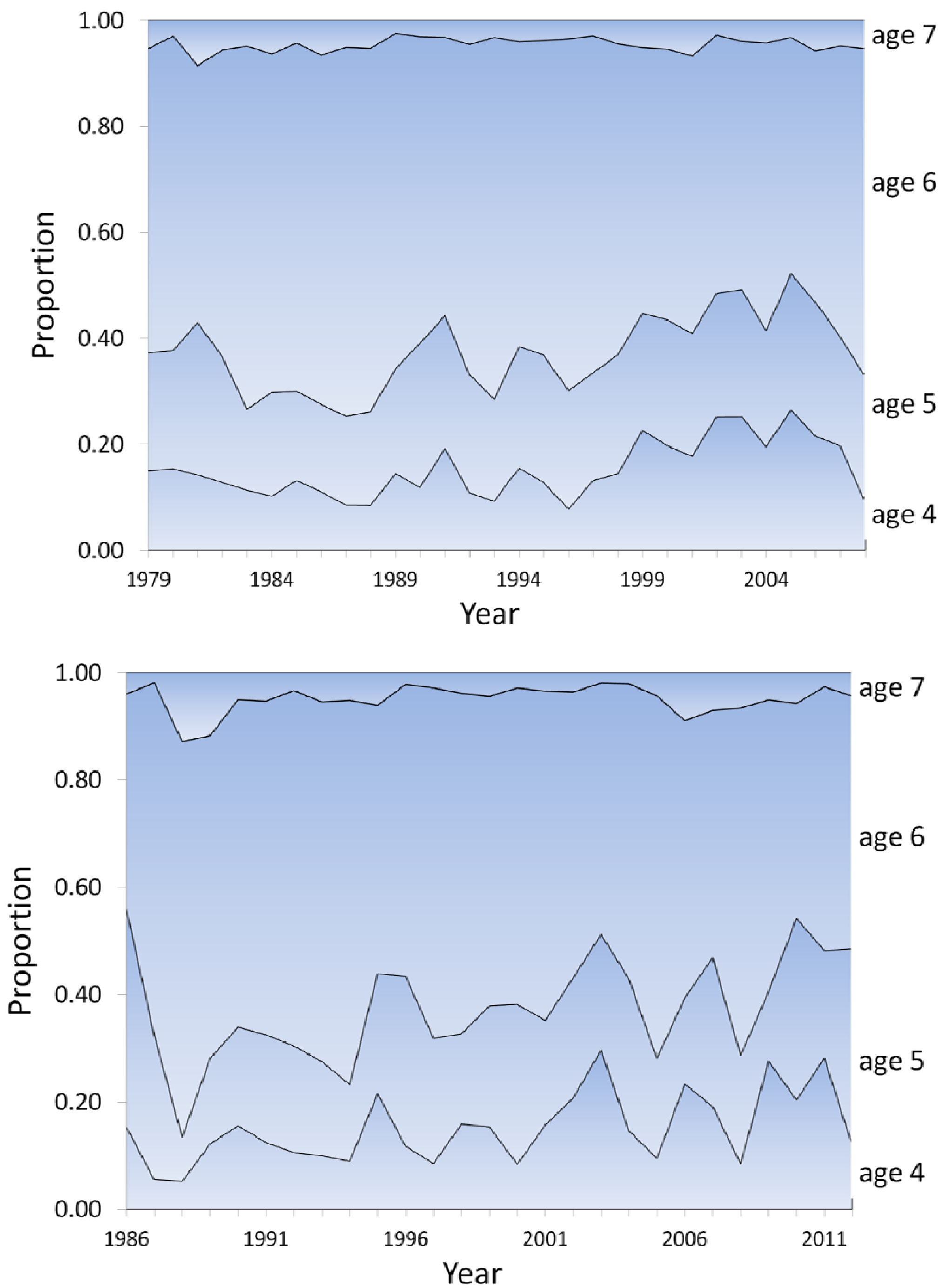

Figure 6.–Area graphs of age-at-maturity proportions by brood year (top), and age composition proportions by calendar year (bottom) for Kenai River late-run Chinook salmon . Spaces between the solid lines are posterior medians of proportions.

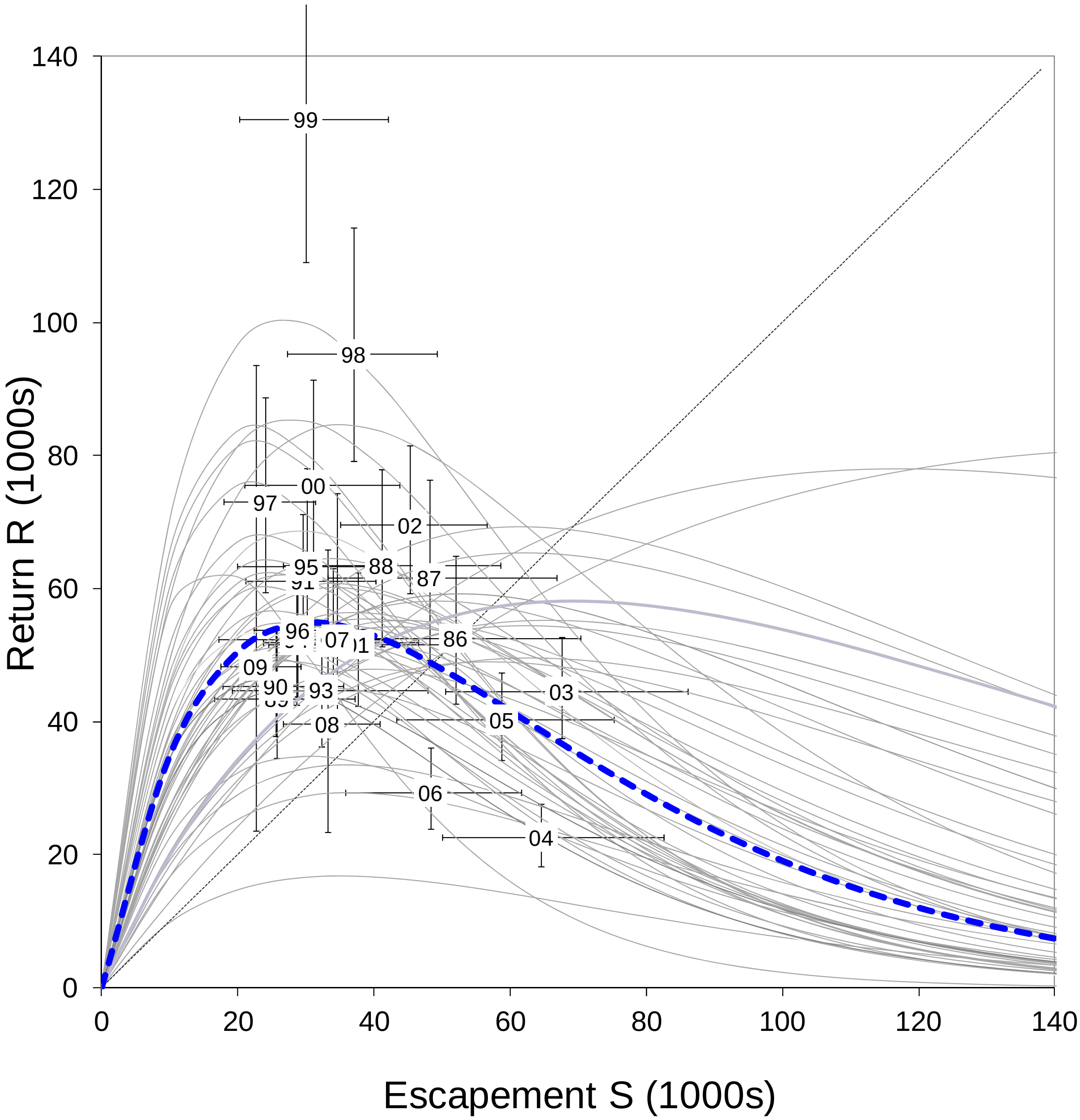

Figure 7.–Plausible spawner-recruitment relationships for Kenai River late-run Chinook salmon as derived from an age-structured state-space model fitted to abundance, harvest, and age data for 1986–2012. Posterior medians of R and S are plotted as brood year labels; error bars bracket 90% credibility intervals. The heavy dashed line is the Ricker relationship constructed from ln(α) and β posterior medians. Ricker relationships are also plotted for 75 paired values of ln(α) and β sampled from the posterior probability distribution, representing plausible Ricker relationships that could have generated the observed data. The diagonal dotted line is the replacement line (R = S).

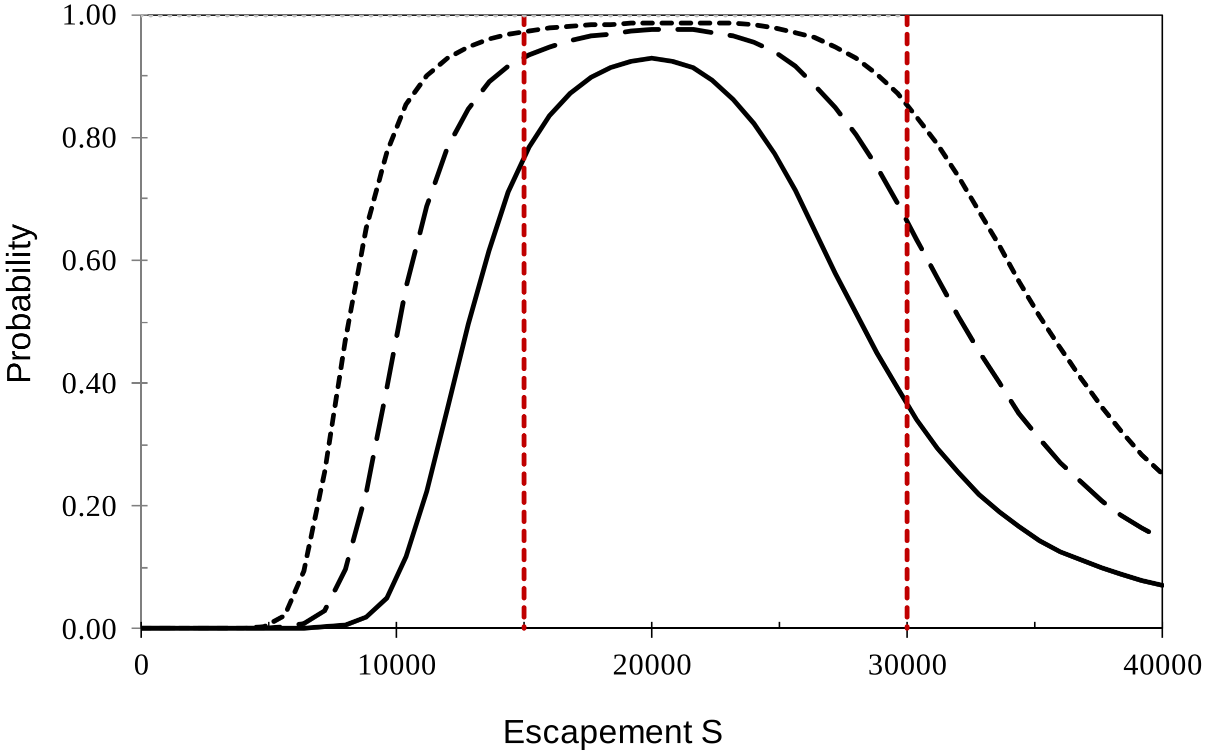

Figure 8.–Probability that a specified spawning abundance will achieve 70% (short dashes), 80% (long dashes), and 90% (solid line) of maximum sustained yield for late-run Kenai River Chinook salmon (curved profiles). Vertical lines show recommended escapement goal range.

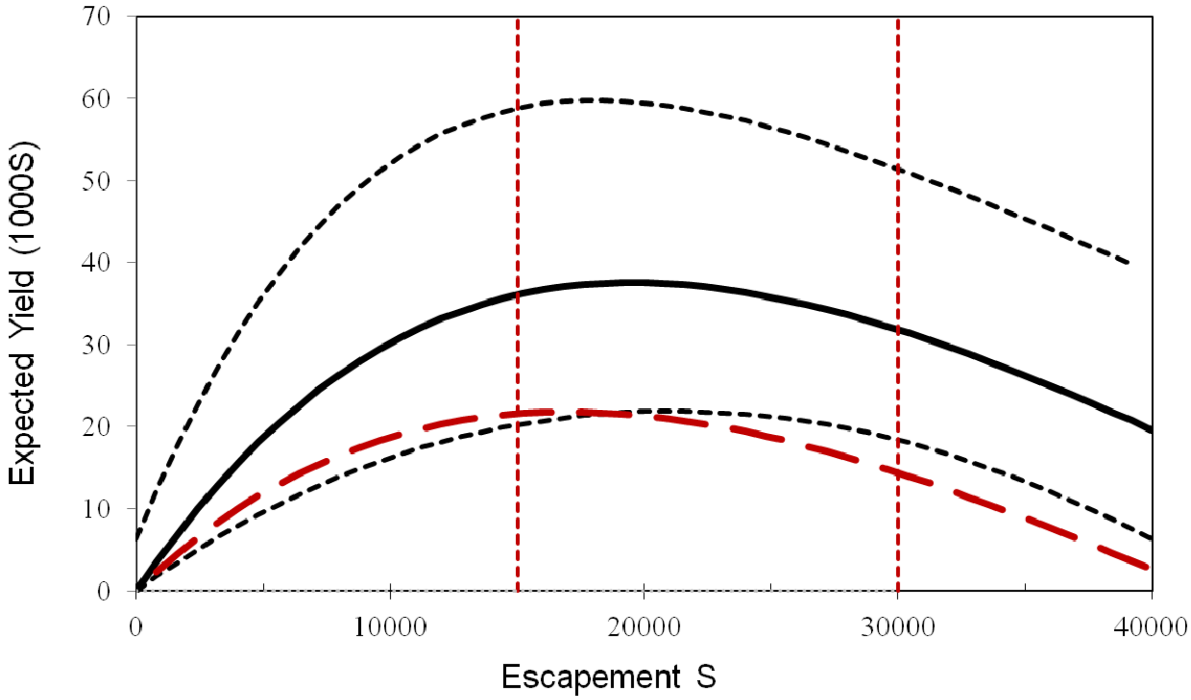

Figure 9.–Expected sustained yield (solid black line), and 80% interval (short dashed black lines) as a function of spawning escapement for late-run Kenai River Chinook salmon, assuming average productivity for brood years 1979–2008. Vertical lines bracket recommended escapement goal range. Expected sustained yield under recent, reduced productivity (brood years 2004–2008) is also shown (long dashed red lines).

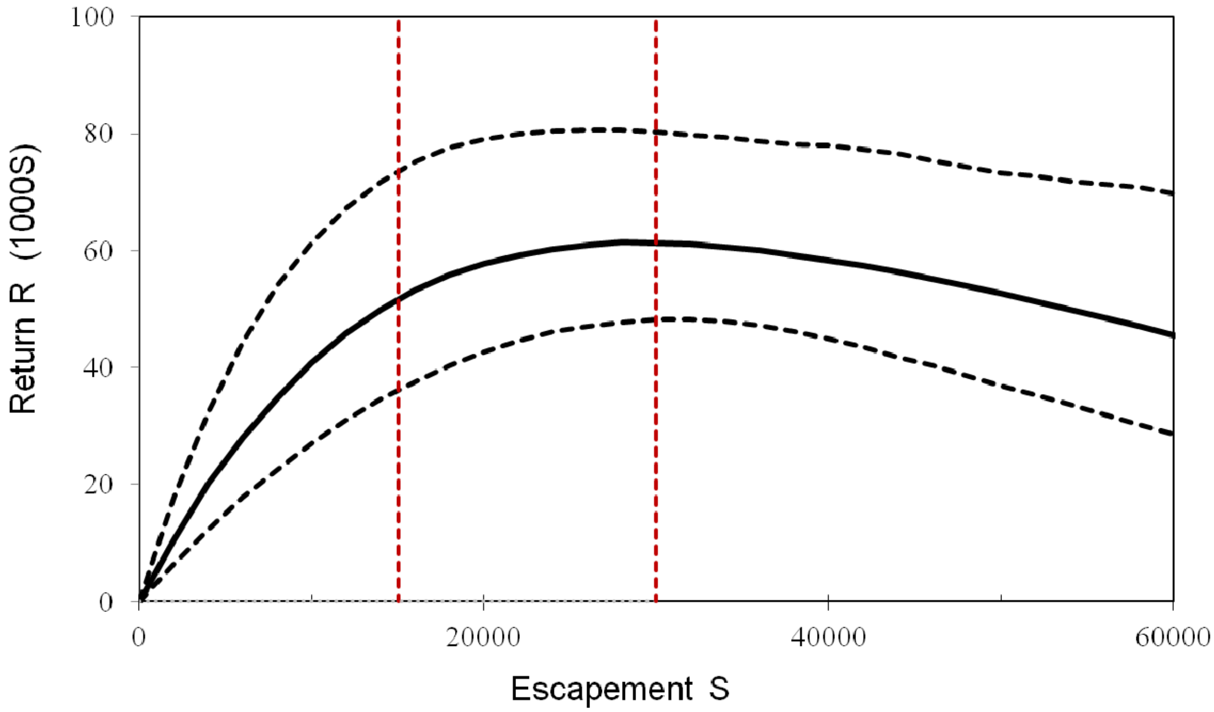

Figure 10.–Posterior median of expected return (solid line), and 80% interval (dashed lines) as a function of spawning escapement for late-run Kenai River Chinook salmon. Model assumes average productivity for brood years 1979–2008. Vertical lines bracket the recommended escapement goal range. The solid line is identical to the heavy dashed line in Figure 7.

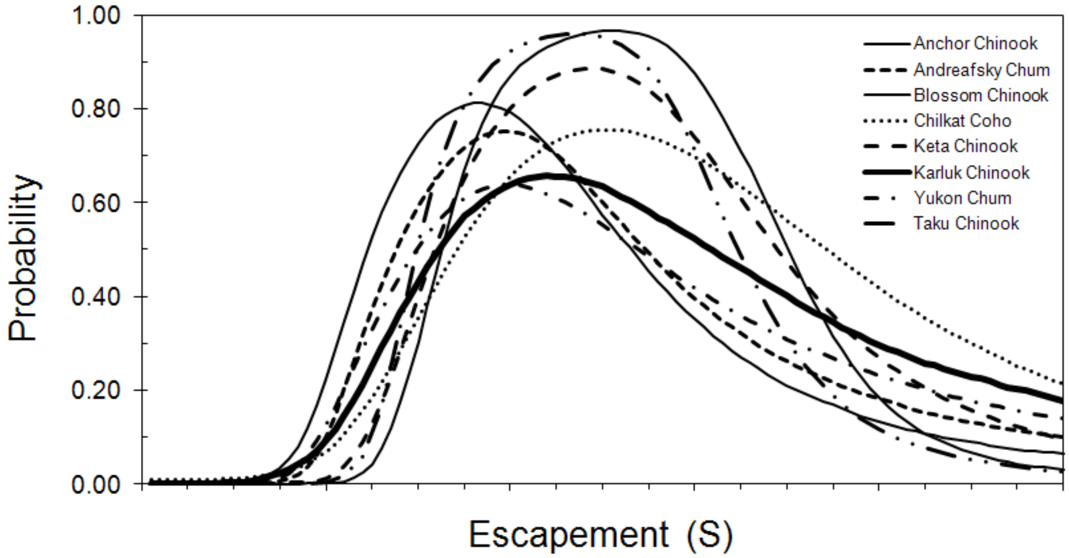

Figure 11.–Optimal yield profiles (OYPs; probability of achieving 90% of MSY) from similar Bayesian age-structured state-space analyses of spawner-recruit data for Anchor River Chinook salmon (Szarzi et al. 2007), Andreafsky River summer chum salmon (Fleischman and Evenson 2010), Chilkat River Coho salmon (Ericksen and Fleischman 2006), Blossom River Chinook salmon (Fleischman et al. 2011), Keta River Chinook salmon (Fleischman et al. 2011), Taku River Chinook salmon (McPherson et al. 2010), and Yukon River fall chum salmon (Fleischman and Borba 2009). The 90% OYP for Karluk River Chinook salmon from Figure 6 is in bold. The horizontal axis (escapement) is scaled differently for each stock such that the range of escapements brackets the value of optimal escapement S_{MSY}. This figure is from Fleischman et al. *in press*.

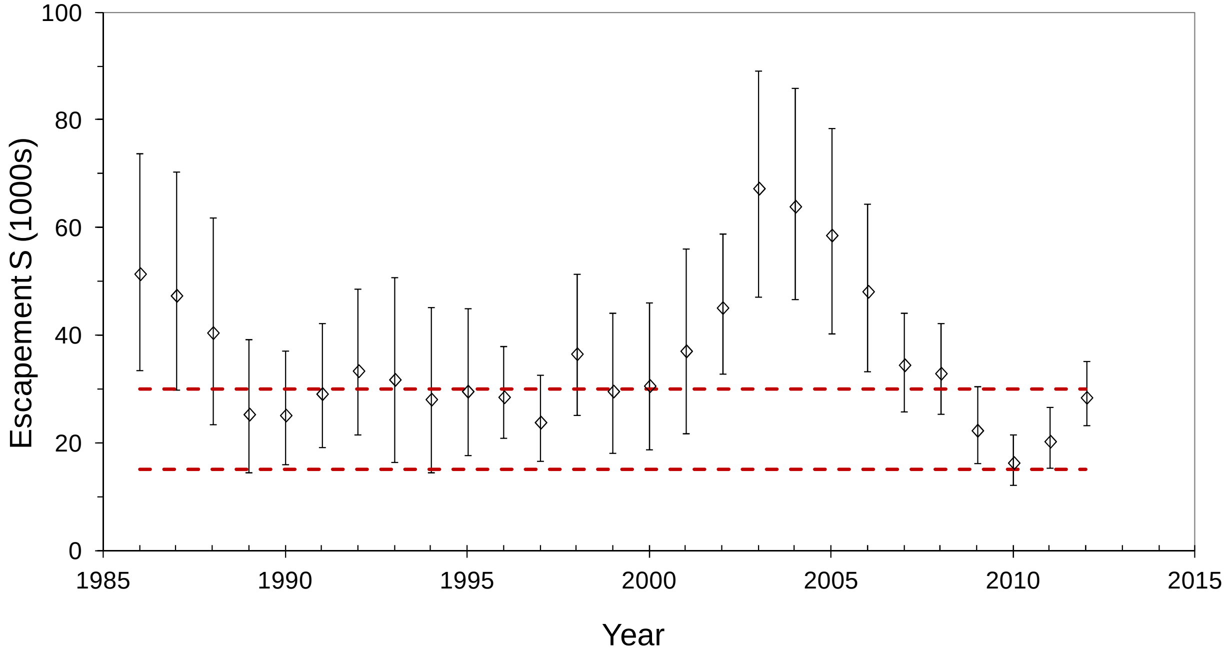

Figure 12.–Historical estimates of escapement and 95% credibility intervals obtained by fitting a state-space model to late-run Kenai River Chinook salmon data, 1986–2012. Horizontal dotted lines bracket the recommended escapement goal range of 15,000 to 30,000 fish.

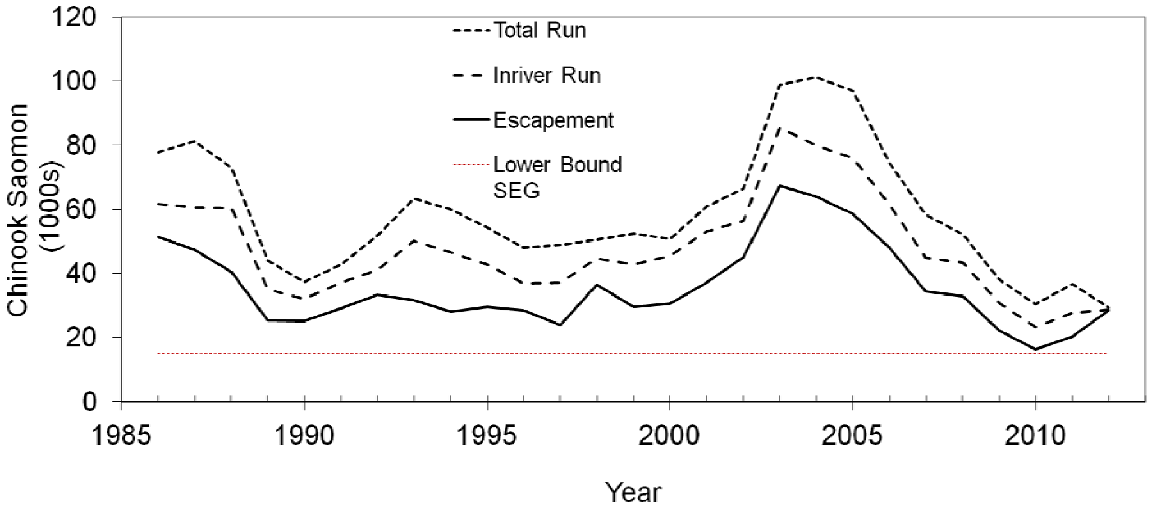

Figure 13.–Posterior medians of spawning escapement (solid line), inriver run abundance (long dashed line), and total run abundance (short dashed line) from 1986 to 2012 obtained from fitting a state-space model to late-run Kenai River Chinook salmon data.

APPENDIX A: WINBUGS CODE AND DATA

Appendix A1.–OpenBUGS model code for state-space model of Kenai River Chinook salmon data, 1986–2012. Block updaters must be disabled prior to compiling. Prior distributions in green font; sampling distributions of the data in blue. Not all notation corresponds directly to text of report.

```
model{
 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]
  RS.resid[y] <- exp(log.resid[y])
  lnalpha.y[y] <- lnalpha + log.resid[y]
  alpha.y[y] <- exp(lnalpha.y[y])
  }
 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)I(0,)
 beta ~ dnorm(0,1.0E-1)I(0,)
 phi ~ dnorm(0,1.0E-4)I(-1,1)
 tau.white ~ dgamma(0.001,0.001)
 log.resid.0 ~ dnorm(0,tau.red)I(-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)

# BROOD YEAR RETURNS W/O SR LINK DRAWN FROM COMMON LOGNORMAL DISTN
 mean.log.R ~ dnorm(0,1.0E-4)I(0,)
 tau.R ~ dgamma(0.1,0.1)
 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 = 32 MATURITY SCHEDULES, ONE PER BROOD YEAR
 D.scale ~ dunif(0,1)
 D.sum <- 1 / (D.scale * D.scale)
 pi[1] ~ dbeta(1,1)
 pi.2p ~ dbeta(1,1)
 pi.3p ~ dbeta(1,1)
 pi[2] <- pi.2p * (1 - pi[1])
 pi[3] <- pi.3p * (1 - pi[1] - pi[2])
 pi[4] <- 1 - pi[1] - pi[2] - pi[3]
```

-continued-

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

# 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=31 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 (Matt's code)
    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]
            }
        }

# MULTINOMIAL SCALE SAMPLING ON TOTAL ANNUAL RETURN N
# INDEX t IS CALENDAR YEAR
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]
    }
  n[t] <- sum(x[t,1:A])
  x[t,1:A] ~ dmulti(q[t,],n[t])
  }

# INRIVER PASSAGE ESTIMATED, AS WELL AS HARVESTS BELOW AND ABOVE BORDER
 p.MR ~ dnorm(0.5,1.0E-4)I(0.01,0.99)  # proportion migrating midriver,

for (y in 1:Y) {
  p.MR.y[y] <- p.MR
  mu.Hbelow[y] ~ dbeta(0.1,0.1)
  H.below[y] <- mu.Hbelow[y] * N[y]
  log.Hb[y] <- log(H.below[y])
  tau.log.Hb[y] <- 1 / log(cv.Hb[y]*cv.Hb[y] + 1)
  Hbelow.hat[y] ~ dlnorm(log.Hb[y],tau.log.Hb[y])
  Inriver.Run[y] <- max(N[y] - H.below[y], 1)

  log.IR[y] <- log(Inriver.Run[y])
  tau.log.IR[y] <- 1 / log(cv.IR[y]*cv.IR[y] + 1)
  IR.hat[y] ~ dlnorm(log.IR[y],tau.log.IR[y])
```

-continued-

```
  #DIDSON detects fraction p.MR of total migrants
  Midriver.Run[y] <- p.MR.y[y] * Inriver.Run[y]
  log.MR[y] <- log(Midriver.Run[y])
  tau.log.DS[y] <- 1 / log(cv.DS[y]*cv.DS[y] + 1)
  DIDSON[y] ~ dlnorm(log.MR[y],tau.log.DS[y])

  mu.Habove[y] ~ dbeta(0.1,0.1)
  H.above[y] <- mu.Habove[y] * Inriver.Run[y]
  log.Ha[y] <- log(H.above[y])
  tau.log.Ha[y] <- 1 / log(cv.Ha[y]*cv.Ha[y] + 1)
  Habove.hat[y] ~ dlnorm(log.Ha[y],tau.log.Ha[y])
  mu[y] <- (H.below[y] + H.above[y]) / N[y]
  S[y] <- max(Inriver.Run[y] - H.above[y], 1)
  log.S[y] <- log(S[y])
  }

  for(i in 1:5) {
   log.q[i] ~ dnorm(0,1.0E-4)
   tau.i[i] ~ dgamma(0.001,0.001)
   r.i[i] <- 1.0
   sigma.i[i] <- 1 / sqrt(tau.i[i])
   q.i[i] <- exp(log.q[i])
   for (y in 1:Y) {
    index[y,i] ~ dlnorm(log.qiNri[y,i],tau.i[i])
    }
   }
  for (y in 1:Y) {
   log.qiNri[y,1] <- log(q.i[1] * pow(Midriver.Run[y],r.i[1]))
   log.qiNri[y,2] <- log(q.i[2] * pow(Midriver.Run[y],r.i[2]))
   log.qiNri[y,3] <- log(q.i[3] * pow(Inriver.Run[y],r.i[3]))
   log.qiNri[y,4] <- log(q.i[4] * pow(N[y],r.i[4]))
   log.qiNri[y,5] <- log(q.i[5] * pow(Midriver.Run[y],r.i[5]))
   }

# CALCULATE SUSTAINED YIELD AT REGULAR INTERVALS OF S;
# FIND PROBABILITY S* WILL PROVIDE YIELDS WITHIN X% OF MSC;
R.msy <- S.msy * exp(lnalpha - beta * S.msy)*exp(sigma.red*sigma.red/2)
MSY <- R.msy - S.msy
 for (i in 1:50) {                 #LOOP TO FIND Pr(SY>XX%MSY)
   S.star[i] <- 800*i
   R.star[i] <- min(S.star[i] * exp(lnalpha.c - beta * S.star[i]),1.0E6)
   R.recent[i] <- min(S.star[i] * exp(lnalpha.c.recent - beta * S.star[i]),1.0E6)
   SY[i] <- R.star[i] - S.star[i]
   SY.recent[i] <- R.recent[i] - S.star[i]
   I90[i] <- step(SY[i] - 0.9 * MSY)
   I80[i] <- step(SY[i] - 0.8 * MSY)
   I70[i] <- step(SY[i] - 0.7 * MSY)
   }
# MEAN lna FOR 2004-2008
 lnalpha.recent    <- mean(lnalpha.y[26:30])
 lnalpha.c.recent <- mean(lnalpha.y[26:30]) + (sigma.white * sigma.white / 2 / (1-phi*phi) )
}
```

Appendix A2.–WinBUGS data objects for state-space model of Kenai River Chinook salmon data, 1986–2012.

Data for Age-structured Spawner Recruit Model

list(Y=**28**, A=**4**, a.min=**4**, a.max=**7)**

```
index[,1]   index[,2]   index[,3]   index[,4]   index[,5]
 NA     NA    0.110 2028    NA
 NA     NA    0.099 1720    NA
 NA     NA    0.115 1385    NA
 NA     NA    0.066 977     NA
 NA     NA    0.055 749     NA
 NA     NA    0.058 974     NA
 NA     NA    0.073 1033    NA
 NA     NA    0.102 1428    NA
 NA     NA    0.080 1586    NA
 NA     NA    0.065 1862    NA
 NA     NA    0.042 1472    NA
 NA     NA    0.050 1034    NA
 NA     NA    0.066 1400    NA
 NA     NA    0.078 1206    NA
 NA     NA    0.072 1099    NA
 NA     NA    0.100 1181    NA
12.74 41813 0.106 1383   33508
16.88 62635 0.176 2041   57101
14.18 75050 0.129 2253   43542
13.81 85590 0.127 1607   48275
17.58 52482 0.091 1134   37692
10.42 29457 0.073 1436   28914
12.17 36011 0.060 808    24589
5.38  17722 0.074 762    15655
3.03  12501 0.039 834     NA
5.14  18765 0.068 956     NA
2.98  13896 NA    NA      NA
NA    NA    NA    NA      NA
END;
```

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Hbelow.hat[]	cv.Hb[]	IR.hat[]	cv.IR[]	DIDSON[]	cv.DS[]	Habove.hat[]	cv.Ha[]
16083	0.10	NA	0.01	NA	0.03	10188	0.05
20305	0.10	NA	0.01	NA	0.03	13223	0.06
12538	0.10	NA	0.01	NA	0.03	19871	0.05
8888	0.10	NA	0.01	NA	0.03	9779	0.06
5173	0.10	NA	0.01	NA	0.03	6966	0.07
5725	0.10	NA	0.01	NA	0.03	7919	0.05
10473	0.10	NA	0.01	NA	0.03	7790	0.06
13413	0.10	NA	0.01	NA	0.03	18253	0.04
13434	0.10	NA	0.01	NA	0.03	18409	0.04
11565	0.10	NA	0.01	NA	0.03	13081	0.05
10686	0.10	39356	0.14	NA	0.03	8449	0.06
11565	0.10	39080	0.14	NA	0.03	13325	0.06
5884	0.10	NA	0.01	NA	0.03	8110	0.07
9742	0.10	NA	0.01	NA	0.03	13107	0.08
5100	0.10	NA	0.01	NA	0.03	14890	0.05
7649	0.10	NA	0.01	NA	0.03	15969	0.07
9894	0.10	NA	0.01	NA	0.03	11343	0.07
13464	0.10	NA	0.01	NA	0.03	17923	0.09
21271	0.10	NA	0.01	NA	0.03	16007	0.07
21135	0.10	NA	0.01	NA	0.03	17194	0.08
13156	0.10	NA	0.01	NA	0.03	13320	0.08
13419	0.10	39600	0.16	NA	0.03	10360	0.07
8761	0.10	52530	0.14	NA	0.03	10498	0.08
7279	0.10	45480	0.20	NA	0.03	8530	0.07
6994	0.10	18830	0.17	19000	0.07	7026	0.06
8775	0.10	31110	0.18	21036	0.02	7373	0.07
727	0.10	NA	0.01	21914	0.03	196	0.06
1	0.10	NA	0.01	NA	0.03	1	0.06

END;

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x[,1]	x[,2]	x[,3]	x[,4]
14	43	39	4
4	29	65	1
3	5	76	15
11	14	63	12
14	16	64	5
10	18	67	6
8	18	71	3
9	15	70	6
7	12	75	5
23	23	48	6
10	34	54	1
6	24	66	2
16	15	65	3
14	22	59	4
5	32	60	2
15	19	63	3
20	21	54	3
32	20	46	1
16	28	53	1
10	19	66	4
28	15	46	9
24	28	40	7
9	21	60	7
33	11	49	4
21	34	32	5
31	20	44	2
10	40	44	4
0	0	0	0

END;

APPENDIX B: GENETIC STOCK IDENTIFICATION OF CHINOOK SALMON HARVESTED IN THE EASTSIDE SETNET FISHERY IN 2010–2011

Appendix B1.–Genetic stock identification of Chinook salmon harvested in the eastside setnet fishery in 2010–2011.

MEMORANDUM State of Alaska

Department of Fish and Game

Division of Commercial Fisheries

TO: Jeff Regnart
Division of Commercial Fisheries
Director

And

Charles Swanton
Sport Fish Division
Director

DATE: November 30, 2012

THROUGH: William Templin
Fisheries Scientist I

PHONE NO: 267-2290

FROM: Andrew Barclay
Fishery Biologist III

SUBJECT: ESSN Chinook salmon MSA

From 2010 to 2012 genetic tissue samples were collected opportunistically from Chinook salmon harvested in the Upper Cook Inlet (UCI) Upper Subdistrict set gillnet fishery, commonly referred to as the East Side Set Net (ESSN) fishery. Tissue samples were collected from Chinook salmon during regular openings at receiving sites and occasionally from a fish processor the following day. The sampling goal for each fishing period was to sample as many Chinook salmon as possible during each tide from all areas of the ESSN fishery. Because there was only one dedicated person to collect these samples, some areas of the ESSN fishery could not be sampled during each tide. Additionally, some areas were targeted for sampling because they were expected to have larger Chinook salmon harvests, while some areas with lower harvests were not sampled. A total of 885, 1281, and 185 Chinook salmon genetic tissue samples were collected in 2010, 2011, and 2012, respectively.

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In 2012 the ESSN fishery was closed for much of the season to protect Chinook salmon returning to the Kenai River. In the fall of 2012, the Gene Conservation Laboratory was directed to proceed with analysis of the collected samples to determine the stock composition the ESSN during the three years. Based on discussions with biologists and biometricians from both Commercial Fisheries and Sport Fish divisions, the 2012 samples were excluded from the analysis because of the low sample size and restricted fishing periods from which they originated. The GCL generally does not release estimates that might have management or allocation implications until data are collected over a minimum of three years. However, due to the public interest in this question, the GCL has analyzed the 2010 and 2011 collections and the results are provided in this memo. These estimates should be viewed as preliminary until data from a more structured study plan from additional years are analyzed.

The current genetic baseline for UCI Chinook salmon contains a total of 66 individual collections representing 32 populations which have been analyzed for 40 single nucleotide polymorphism loci (Table 1; Figure 1)[ed. note: see Appendices B2 and B4]. This baseline contains the same set of loci and collections as the baseline reported in Barclay et al. (2012) with the exception of two additional Kenai River populations (Grant Creek and Lower Kenai River mainstem). The updated baseline was used in the analysis of the ESSN fishery samples; however, Slikok Creek (Kenai River) was removed from the baseline because it is a very small population and it is genetically similar to Crooked Creek (Kasilof River). Initial tests of the baseline (which included Slikok Creek) for mixed-stock analysis (MSA) indicated that a large portion of Crooked Creek fish misallocated to Slikok Creek. Once Slikok Creek was excluded, MSA tests of the baseline indicated that adequate genetic differentiation existed among all the reporting groups and that they could be used with high confidence (at least 90% correct allocations in 100% proof tests; see methods in Barclay et al. 2010). These reporting groups include: 1) all UCI Chinook population North and West of the Kenai River; *NorthwestCI*, 2) Kenai River tributary populations (excluding Juneau Creek); *KenaiTrib*, 3) Kenai River mainstem populations including Juneau Creek; *KenaiMainstem*, 4) the Kasilof River mainstem population; *KasilofMainstem*, and 5) Anchor River, Ninilchik River, Deep Creek, and Crooked Creek; *CoastalSKenaiPen* (Table 1; Figure 1). Although Juneau Creek is a tributary of the Kenai River it was included in the Kenai River mainstem reporting group because it is genetically similar to Kenai River mainstem populations.

For the 2010 and 2011 collections, tissues were subsampled in proportion to the harvest within statistical areas of the Upper Subdistrict (Ninilchik, Cohoe, South K. Beach, North K. Beach, South Salamatof, and North Salamatof), with a goal of 400 individuals per year. Some tissue samples in 2010 and 2011 were collected at processors which received deliveries from multiple statistical areas. Because the specific statistical area of these samples was not identified, these samples were excluded from analysis. A total of 376 and 347 samples were selected for analysis from 2010 and 2011, respectively. Several samples from 2010 (3) and 2011 (5) were excluded from the analysis because they failed to genotype at more than 20% of loci screened (see methods in Barclay et al. 2012). These individuals were removed because the inclusion of individuals with poor quality DNA might introduce genotyping error and reduce the accuracy of the MSA. The final number of successfully analyzed samples was 373 and 342 samples in 2010 and 2011, respectively.

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The MSA program BAYES was used to estimate the proportions of the 5 reporting groups (stocks; Figure 1) contributing to each fishery sample. The analysis employed a similar the BAYES protocol reported in Barclay et al. (2010) for baseline evaluation tests, except that each fishery sample was analyzed for 5 chains with 40,000 iterations per chain. Estimates and 90% credibility intervals for each fishery sample were tabulated from the combined set of the second half of each chain (100,000 iterations).

The stock composition estimates for 2010 and 2011 were similar. In both years the Kenai River mainstem reporting group had the greatest contribution followed by the Kasilof River mainstem reporting group. The combined contribution of all other reporting groups in both years did not exceed 2.4% (Table 2; Figure 2) [ed. note: see Appendices B3 and B5].

Please let me know if you have any questions regarding this analysis.

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Appendix B2.–[ed. note: this is Table 1 from memorandum in Appendix B1] Tissue collections of Chinook salmon collected throughout Upper Cook Inlet including the year sampled, number of samples collected (N), the number of individuals analyzed from each collection included in the baseline and their assigned reporting group for the analysis of the East Side Set Net fishery collections. Unique population numbers represent all the analyzed collections that contribute to a single population.

Pop. No.	Reporting group	Location	Year collected	N	Analyzed
1	NorthwestCI	Straight Creek	2010	105	95
2		Chuitna River	2008	20	20
2			2009	122	122
3		Coal Creek	2009	42	42
3			2010	35	35
4		Middle Fork Chulitna River	2009	72	72
4			2010	97	97
5		Stephan Lake weir	2008	19	19
5		Prairie Creek	1995	52	52
5			2008	98	98
6		Chunilna Creek	2009	50	50
7		Montana Creek	2008	33	33
7			2009	155	155
7			2010	30	30
8		Deception Creek	2009	122	100
8		Willow Creek	2005	74	74
9		Moose Creek	1995	51	51
9		Deshka River weir	2005	200	200
10		Talachulitna River	1995	58	58
10			2008	74	72
10			2010	48	48
11		Sunflower Creek	2009	53	53
12		Little Susitna River	2009	3	3
12			2010	122	122
13		Moose Creek	1995	20	20
13			2008	33	33
13			2009	22	22
14		Ship Creek	2009	311	311
15		Chickaloon River	2008	2	2
15			2010	66	65

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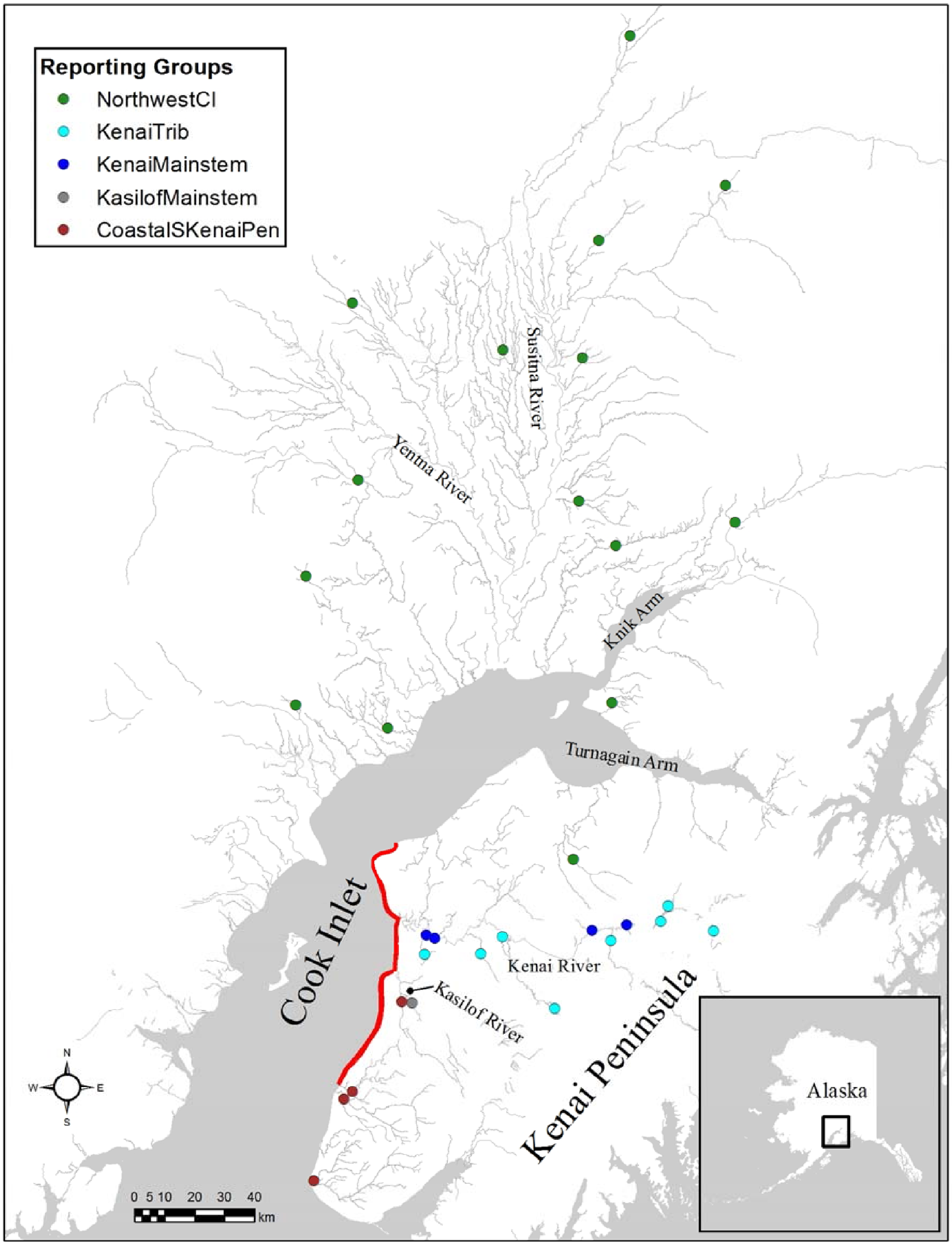
Pop. No.	Reporting group	Location	Year collected	N	Analyzed
16	KenaiTrib	Grant Creek	2011	23	23
16			2012	32	32
17		Quartz Creek	2006	35	34
17			2008	34	34
17			2009	41	41
17		Dave's Creek	2007	8	8
17			2008	5	5
18		Crescent Creek	2006	165	165
19		Russian River	2005	24	24
19			2006	16	16
19			2007	84	83
19			2008	91	91
20		Benjamin Creek	2005	56	56
20			2006	150	150
21		Killey River	2005	68	68
21			2006	190	190
22		Funny River	2005	37	37
22			2006	183	183
23		Slikok Creek	2004	48	48
23			2005	100	95
23			2008	58	57
24	KenaiMainstem	Juneau Creek	2005	32	32
24			2006	100	91
24			2007	24	24
25		Upper Kenai River mainstem	2009	200	200
26		Middle Kenai River mainstem	2003	80	80
26			2004	39	39
26			2006	183	183
27		Lower Kenai River mainstem	2011	90	80
28	KasilofMainstem	Lower Kasilof River mainstem	2005	144	49
28		Middle Kasilof River mainstem	2005	273	273
29	CoastalSKenaiPen	Crooked Creek	1992	95	95
29			2005	212	212
30		Ninilchik River weir	2006	190	162
31		Deep Creek	2009	100	100
32		Anchor River weir	2006	200	200

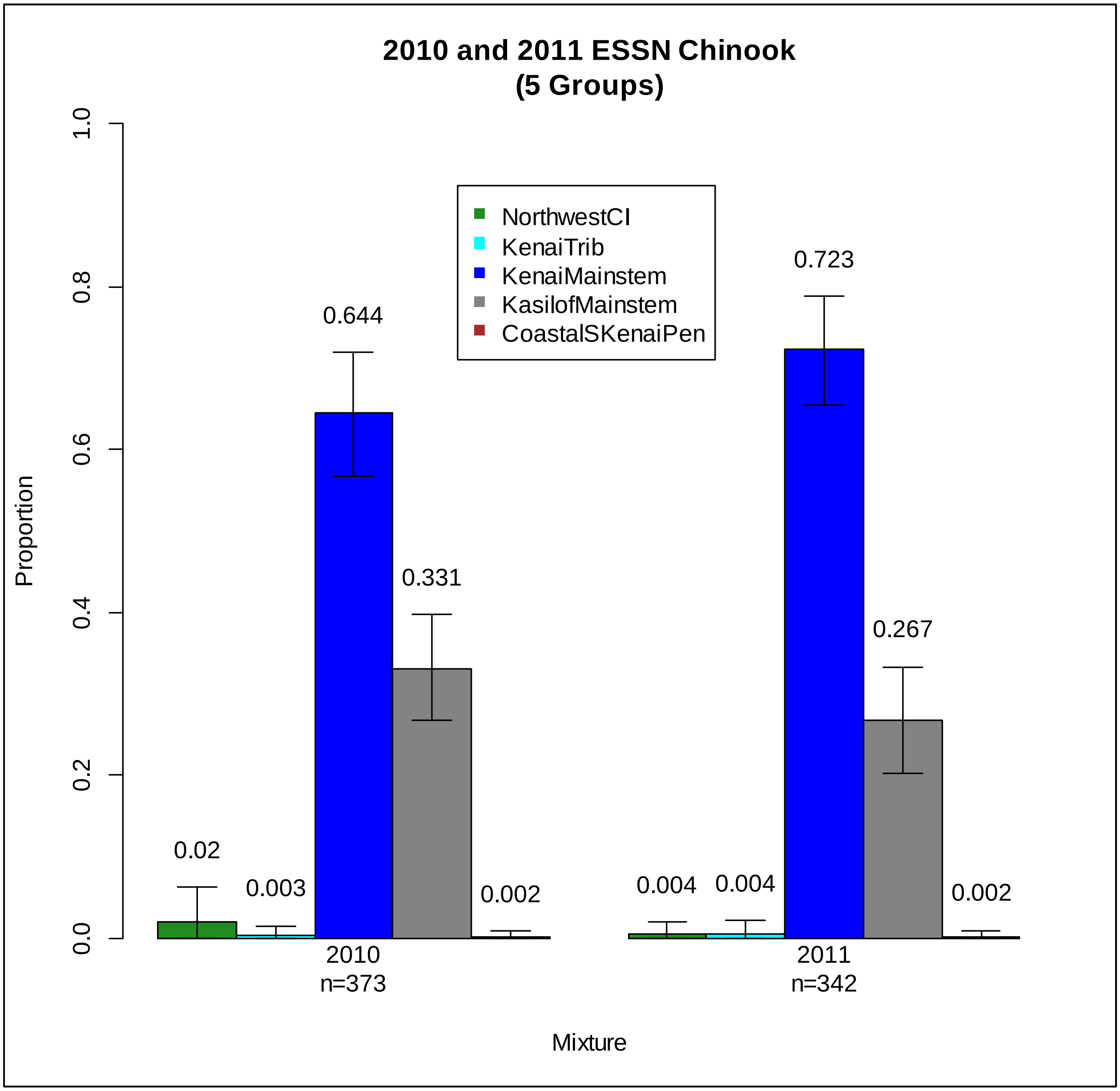
Appendix B3.–[ed. note: this is Table 2 from memorandum in Appendix B1] Stock proportion estimates, standard deviation (SD), sample size (n), and lower (5%) and upper (95%) bounds of the 90% credibility interval for mixtures of Chinook salmon harvested in the east side set net fishery in 2010 and 2011.

	2010 (n= 373)				2011 (n=342)			
Reporting Group	Mean	SD	5%	95%	Mean	SD	5%	95%
NorthwestCI	0.020	0.022	0.000	0.063	0.004	0.007	0.000	0.019
KenaiTrib	0.003	0.006	0.000	0.015	0.004	0.008	0.000	0.021
KenaiMainstem	0.644	0.046	0.566	0.719	0.723	0.041	0.654	0.788
KasilofMainstem	0.331	0.040	0.267	0.398	0.267	0.040	0.203	0.333
CoastalSKenaiPen	0.002	0.004	0.000	0.009	0.002	0.004	0.000	0.009

Appendix B4.–[ed. note: this is Figure 1 from memorandum in Appendix B1] Sampling locations (dots) for Chinook salmon used to compile a genetic baseline for Upper Cook Inlet. East Side Set Net fishery area is highlighted in red. Colors for each reporting group are indicated in the legend.



Appendix B5.–[ed. note: this is Figure 2 from memorandum in Appendix B1] Stock proportion estimates for Chinook salmon harvested in the East Side Set Net (ESSN) fishery of Upper Cook Inlet in 2010 and 2011. Numbers above the bars are the mean estimates, n is the sample size of the fishery sample for each year, and whiskers indicate the upper and lower bounds of the 90% credibility interval.



APPENDIX C: TOTAL RUN ABUNDANCE BY AGE CLASS

Appendix C1.–Total run abundance by age class obtained from fitting a state-space model to Kenai River late-run Chinook salmon data, 1986–2012.

Year	Age 4 (CV)	Age 5 (CV)	Age 6 (CV)	Age 7 (CV)
1986	12,030 (0.24)	32,000 (0.18)	31,300 (0.18)	3,133 (0.45)
1987	4,544 (0.33)	22,050 (0.19)	53,810 (0.14)	1,538 (0.57)
1988	3,807 (0.35)	6,062 (0.29)	54,210 (0.15)	9,481 (0.27)
1989	5,419 (0.27)	7,043 (0.24)	26,710 (0.16)	5,228 (0.29)
1990	5,848 (0.25)	6,908 (0.23)	23,020 (0.16)	1,897 (0.39)
1991	5,391 (0.27)	8,693 (0.22)	27,010 (0.16)	2,291 (0.37)
1992	5,518 (0.29)	10,390 (0.22)	34,580 (0.15)	1,732 (0.45)
1993	6,384 (0.28)	11,240 (0.23)	42,760 (0.15)	3,503 (0.37)
1994	5,463 (0.29)	8,612 (0.24)	43,420 (0.15)	3,103 (0.39)
1995	11,910 (0.21)	12,310 (0.20)	27,460 (0.16)	3,327 (0.37)
1996	5,686 (0.25)	15,310 (0.16)	26,270 (0.12)	1,060 (0.56)
1997	4,203 (0.29)	11,490 (0.18)	32,090 (0.11)	1,402 (0.48)
1998	8,127 (0.24)	8,638 (0.23)	32,500 (0.15)	1,940 (0.45)
1999	8,141 (0.24)	11,990 (0.20)	30,620 (0.15)	2,324 (0.41)
2000	4,274 (0.32)	15,350 (0.19)	30,260 (0.16)	1,436 (0.51)
2001	9,645 (0.24)	12,000 (0.22)	37,580 (0.16)	2,117 (0.46)
2002	13,820 (0.20)	14,880 (0.19)	35,610 (0.13)	2,398 (0.44)
2003	29,530 (0.18)	21,390 (0.20)	46,480 (0.14)	1,921 (0.58)
2004	14,990 (0.23)	28,850 (0.17)	56,010 (0.13)	2,106 (0.57)
2005	9,205 (0.27)	18,080 (0.20)	65,740 (0.12)	4,169 (0.41)
2006	17,540 (0.19)	11,970 (0.22)	38,570 (0.14)	6,709 (0.30)
2007	11,270 (0.19)	16,230 (0.16)	26,940 (0.13)	4,104 (0.33)
2008	4,437 (0.27)	10,620 (0.19)	33,940 (0.11)	3,469 (0.33)
2009	10,570 (0.17)	4,976 (0.24)	20,950 (0.13)	1,954 (0.41)
2010	6,274 (0.20)	10,330 (0.15)	12,220 (0.14)	1,758 (0.37)
2011	10,380 (0.17)	7,401 (0.19)	17,990 (0.12)	0,969 (0.50)
2012	3,474 (0.26)	10,810 (0.15)	13,930 (0.14)	1,275 (0.41)

APPENDIX D: RETURN AND YIELD AT INCREMENTAL LEVELS OF ESCAPEMENT

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Appendix D1.–Posterior medians of return (used to produce Figure 12) and sustained yield (used to produce Figure 11) for escapements from 2,000 to 50,000 spawning fish, obtained from fitting a state-space model to Kenai River late-run Chinook salmon data, 1986–2012.

Escapement S	Return R	Sustained Yield SY
2000	10,720	8,480
4000	20,070	15,630
6000	28,070	21,560
8000	34,920	26,400
10000	40,890	30,220
12000	45,820	33,180
14000	49,940	35,320
16000	53,150	36,750
18000	55,790	37,470
20000	57,820	37,630
22000	59,240	37,260
24000	60,280	36,400
26000	60,930	35,190
28000	61,370	33,610
30000	61,210	31,760
32000	61,030	29,690
34000	60,600	27,380
36000	59,980	24,920
38000	59,220	22,290
40000	58,380	19,540
42000	57,490	16,690
44000	56,450	13,710
46000	55,210	10,650
48000	53,970	7,492
50000	52,660	4,236