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

by

Timothy R. McKinley

and

Steven J. Fleischman

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

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Weights and measures (metric)

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

Weights and measures (English)

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

Time and temperature

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

Physics and chemistry

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

General

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

Mathematics, statistics

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

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

By

Timothy R. McKinley
Alaska Department of Fish and Game, Division of Sport Fish, Soldotna

and

Steven J. Fleischman
Alaska Department of Fish and Game, Division of Sport Fish, Anchorage

Alaska Department of Fish and Game
Division of Sport Fish, Research and Technical Services
333 Raspberry Road, Anchorage, Alaska, 99518-1565

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Timothy R. McKinley,
Alaska Department of Fish and Game, Division of Sport Fish
43961 Kalifornsky Beach Rd., Ste B, Soldotna, AK 99669, USA

and

Steven J. Fleischman,
Alaska Department of Fish and Game, Division of Sport Fish
333 Raspberry Road, Anchorage, AK 99518, USA

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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 early-run Chinook salmon (*Oncorhynchus tshawytscha*) from 1986 to 2012. Bayesian statistical methods were employed, which assessed uncertainty in the presence of measurement error, serial correlation, and missing data. Results were robust to several alternate configurations of the model and data. A sustainable escapement goal of 3,800 to 8,500 fish is recommended for Kenai River early-run Chinook salmon, evaluated by multiplying DIDSON-based estimates of inriver abundance by 1.55 to account for undetected Chinook salmon passing the sonar site at river mile 9, 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. Annual runs of Kenai River early-run Chinook salmon are expected to remain below average in the near future.

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

INTRODUCTION

Two stocks (early- and late-run) of Chinook salmon (*Oncorhynchus tshawytscha*) return to the Kenai River (Figure 1) to spawn. A major inriver sport fishery occurs here and anglers can expend in excess of 300,000 days per year fishing for Kenai River Chinook salmon (Jennings et al. 2011). Chinook salmon bound for tributaries of the Kenai River (tributary spawners) enter the river from late April through early July while Chinook salmon that spawn in the Kenai River itself (mainstem spawners) enter the river from mid-June through mid-August (Burger et al. 1985; Bendock and Alexandersdottir 1992).

FISHERIES MANAGEMENT

Kenai River early-run Chinook salmon are harvested in 1) an inriver sport fishery, 2) a marine sport fishery along the eastern shore of Cook Inlet from Anchor Point to Cape Ninilchik, and 3) an educational gillnet fishery occurring near the river mouth.[1]

In 1988, the Alaska Board of Fisheries adopted management plans for the early and late runs (McBride et al. 1989). These plans defined the early run as fish entering the river prior to 1 July and the late run as fish entering the river after 30 June. In the original plan, the optimum spawning escapement for early-run Chinook salmon was set at 9,000 fish, with management directives centered around projected escapement levels of less than 5,300 fish, 5,300 to 9,000 fish, and greater than 9,000 fish (McBride et al. 1989). In 1999, the management plan was revised with a biological escapement goal (BEG; definition in Alaska Administrative Code 5 AAC 39.222 [f][3]) established as a range of 7,200 to 14,400 Chinook salmon. Prior to the 2005 season, the Alaska Department of Fish and Game (ADF&G) recommended a BEG of 4,000–9,000 early-run Chinook salmon, and the Alaska Board of Fisheries set an optimal escapement goal (definition in 5 ACC 39.222 [f][25]) of 5,300–9,000 for this stock. The *Kenai River and Kasilof River Early-Run King Salmon Management Plan* (5 AAC 57.160) contains mandates that the inriver sport fishery be managed to achieve the optimal escapement goal. In brief, the fishing season begins under restrictive regulations until it can be projected that the spawning escapement will exceed the lower bound of the optimal escapement goal.

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[1] Occasionally, small numbers of early-run fish are also caught during very early openings of the commercial eastside setnet fishery and in an ADF&G cost-recovery program.

A slot-limit regulation was enacted in 2002 in response to a declining number of ocean-age-5 early-run Chinook salmon. The original slot limit allowed retention of Chinook salmon with total length (TL) less than 40 inches or greater than 55 inches. The lower limit was changed to 44 inches in 2003, and then to 46 inches TL in 2008. The slot limit is in effect 1 January–30 June from the mouth of the Kenai River to the Soldotna Bridge, and 1 January–14 July from the Soldotna Bridge upstream to Skilak Lake.

Other sport fishing regulations for this stock, which are among the most restrictive in Alaska, are also detailed in the management plan, and include a daily bag and possession limit of one and a seasonal limit of two Chinook salmon, closed areas, and partial restrictions on fishing from guided boats.

STOCK ASSESSMENT HISTORY

A comprehensive stock assessment program was initiated in the mid-1980s to provide information for use in management of Kenai River Chinook salmon fisheries. Objectives of the stock assessment program are as follows: 1) model inriver run and fishery mortality to manage the fisheries inseason, and 2) develop brood tables for long-term stock assessment and escapement goal analyses. Inseason stock assessment makes use of creel surveys, harvest sampling, inriver gillnetting, and sonar estimates of inriver run size to drive the implementation of the management plan (McKinley and Fleischman 2010). A complete brood table reconstruction requires information or assumptions about 18 sets of quantities (Table 1).

Inriver run abundance has been estimated with sonar since 1987 and has undergone several modifications as sonar technology and knowledge of its limitations have improved (Fleischman and McKinley 2013). During the years 1987–1994, dual-beam sonar technology was employed at river mile 8.6 (herein referred to as RM 9) to estimate the abundance of 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). Capture–recapture experiments were attempted for Kenai River early- and late-run Chinook salmon from 1985 through 1990 (McKinley and Fleischman 2010).[2]

Research on Kenai River Chinook salmon continued in the 1990s. Split-beam sonar replaced dual-beam sonar in 1995 (Burwen et al. 1998). An inriver netting program used to collect age composition data was standardized in the years 1998–2000 with respect to drift location (just downstream of the RM 9 sonar site), timing (low tide), 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). Finally, tethered fish experiments (Burwen and Fleischman 1998; Burwen et al. 2003) found that, for side-looking sonar in the Kenai River, duration of the returning echo (echo length) was a better predictor of fish size than TS (a measure of echo loudness).

Investigations began to indicate that target strength and range alone were ineffective for distinguishing between Chinook salmon and sockeye salmon (*O. nerka*; Eggers 1994). Tethered fish and netting studies (Burwen et al. 1998) showed that many sockeye salmon exceeded the minimum TS threshold and migrated midriver, thus creating the potential for misclassifying

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[2] Annual estimates of escapement were generated for the early run in 1986 and 1987.

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 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 early- and late-run fisheries.

In 2002, three improvements were made to the sonar and netting programs. First, a 5-in mesh gillnet was added to the existing netting program, and drifted alternately with the existing 7.5-in 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 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 the standard deviation of split-beam sonar echo length 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).

In addition to split-beam sonar, ADF&G began testing dual-frequency identification sonar (DIDSON) in the Kenai River in 2002. 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. DIDSON discriminates between species based on size measurements from fish images. Studies using live tethered Chinook and sockeye salmon confirmed a high correlation between DIDSON fish image length and true fish length (Burwen et al. 2007, 2010), thereby providing improved species discrimination over split-beam sonar. Compared to the split-beam sonar, the wider field of view and improved image quality provided by the DIDSON allowed for improved identification of individual fish targets both near the face of the transducer and at far range, even during periods of high fish passage. DIDSON was first deployed side-by-side with split-beam sonar on the south bank of the river. Beginning in 2010 and continuing through 2012, 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 prep* a). In 2011, onsite experiments found substantial numbers of large Chinook salmon migrating "behind" the south-bank transducer (Miller et al. *In prep* b) between the transducer and the river shore), and these findings were confirmed in 2012[3] (Burwen et al. *In prep*). Tidally induced fluctuations of water level precluded counting these fish with conventional placement of transducers.

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[3] Before 2011, similar experiments conducted with DIDSON on the north bank had failed to detect fish migrating behind the transducer.

In the 2000s, genetic stock identification (GSI) technology (Adams et al. 1994) was implemented to aid in addressing 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 of a "mixture" of fish of unknown origin by comparing the genetically-coded information from the mixture 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 sport 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 genetic 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 genetic reporting groups.

In 2010, Bromaghin et al. (2010) developed an approach for modeling radiotelemetry, 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.

ADF&G modified the Bromaghin et al. (2010) model to utilize genetic stock identification (GSI) data, collected from the inriver netting program, and to accommodate harvest upstream of the marking event. Other model inputs include estimates of passage from tributary weirs (Funny, Russian, and Killey rivers, and Slikok Creek), estimates of inriver harvest from an onsite creel survey and the ADF&G statewide harvest survey (SWHS), and daily CPUE from the inriver netting project. Preliminary SSART model estimates (referred to in this report as CRGEN estimates, for genetic capture–recapture) have been produced for the years 2007–2012. More information on the SSART model is provided in Appendices C1–C2.

Tributary weir counts within the Kenai River drainage provide information for the SSART model and a measure of escapement. ADF&G has operated a weir primarily for sockeye salmon near the outlet of Lower Russian Lake since 1969 (Begich and Pawluk 2010); this weir also provides an escapement estimate for the small Russian River Chinook salmon genetic reporting group. Upstream migrating fish are physically controlled by a fish-trap gate; fish are counted by direct observation as they swim through the fish trap. Some fish are not counted at the weir because they spawn downstream of it. The weir is located approximately 3 mi upstream from the Russian River confluence with the Kenai River. A weir has been operated in Slikok Creek by ADF&G since 2008 to count Chinook salmon (Begich and Pawluk 2010). This weir provides escapement counts for the Slikok Creek portion of the Funny River–Slikok Creek genetic reporting group. The weir is located approximately 0.31 mi upstream from the Slikok Creek confluence with the Kenai River. Little to no spawning is known to occur downstream of the weir. Beginning in 2006, the United States Fish and Wildlife Service has operated a weir on the Funny River (Gates and Boersma 2011), the main component of the second largest genetic reporting group of early-run Chinook salmon. The weir is located approximately 0.75 mi upstream from the Funny River confluence with the Kenai River. Very little, if any, spawning is known to occur downstream of the weir. Beginning in 2012, a resistance-board weir and underwater video system was operated approximately 2 mi downstream from the confluence of Benjamin Creek with the Killey River. The weir provided an escapement estimate for part of the Benjamin Creek–Killey River genetic reporting group, the largest early run reporting group, for the SSART model. The weir was operational from early June until early August. The fraction of the Benjamin Creek–Killey River escapement that passed through the weir was estimated via radiotelemetry. Weirs on Quartz Creek and Grant Creek are planned for 2013. A weir on Quartz Creek was operated by ADF&G during the years 1982–1984 and provided escapement counts for migrating Chinook salmon. See Table 2 for annual early-run Chinook salmon passage for several Kenai River tributaries.

OBJECTIVES

ADF&G is currently transitioning to management of Kenai River Chinook salmon based on DIDSON/ARIS[4] assessment technology. Ultimately, this assessment will take place upstream of the current location, at a site where there is little or no tidal influence. Thus far, steps in this transition have included the commencement of DIDSON-based abundance estimates in 2010 (Miller et al. *In prep* a), discontinuation of TS-based estimates in 2011 (Miller et al. *In prep* b), and discontinuation of split-beam sonar in 2012 (Burwen et al. *In prep*). TS-based abundance estimates were not available during the years 2011–2012, so Kenai River Chinook salmon stocks were managed based on multiple indices of abundance. This report provides the foundation for the next step in the transition, which is management based on DIDSON estimates obtained at RM 9, beginning in 2013. Objectives of this 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 a 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 run reconstruction is directly assimilated into the spawner–recruit analysis and estimates of 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 escapement goal based on DIDSON estimates of inriver abundance at RM 9. Normally, such a recommendation would be timed to coincide with a regularly scheduled Alaska Board of Fisheries meeting and optimally, a new escapement goal would not be developed until transition to a new sonar site is complete. However, the recent need for inseason restrictions in response to an ongoing decline in abundance prompted an out-of-cycle escapement goal review.
3) Provide an updated summary of abundance, harvest, and age composition statistics for this stock for the years 1986–2012.

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[4] ARIS (Adaptive Resolution Imaging Sonar) is the next generation of multi-beam imaging sonar technology. It produces images comparable to or better than a DIDSON.

METHODS

DATA SOURCES

The state-space model requires the following input data: 1) estimates of annual harvest below (downstream of) and above (upstream of) the stock assessment at RM 9, 2) estimates of total run age composition, and 3) estimates of relative and absolute annual abundance, with CVs for the absolute measures. Sources of these data components are described in the following sections.

Annual Harvest

Annual harvests are summarized in Table 3.

Harvest below RM 9

Harvests in the eastside setnet (ESSN) fishery prior to 25 June were assumed to be Kenai River early-run Chinook salmon due to the timing and proximity of the harvest to the Kenai River mouth. Stock composition of fish harvested in the Cook Inlet marine recreational fishery is largely unknown, but the contribution of Kenai River Chinook salmon is thought to be small. Begich (2007) concluded that Kenai River early-run Chinook salmon comprised less than 10% of the marine recreational harvest; for this analysis we assumed 5%, with a CV of 1.0. Educational harvests were small and considered to be known with high precision; we assumed a CV of 0.10. The resulting estimates of sampling error for the marine recreational and educational harvests were squared, summed, and divided by the summed harvest estimates to obtain CVs for the total harvest below RM 9.

Harvest above RM 9

Sport harvests below the Soldotna Bridge were estimated with an onsite creel survey (Perschbacher 2012a, 2012b). Estimates of sport harvest upstream of Soldotna Bridge were obtained with the SWHS (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 harvest above RM 9.

Age Composition

Direct estimates of age composition (Table 3) were obtained from fish sampled at the RM-9 inriver gillnetting project (annual sample size n_y ranged from 82 to 1,453 fish).[5] We assumed that fish harvested in the Cook Inlet recreational fishery and the educational fishery, which annually comprises only 1–4% of the total run, had age composition similar to the inriver run (Table 1). Commercial ESSN and cost recovery fish harvested in the years 2005–2010 (Table 3: “Misc marine”) were assumed to have the same age composition as “Harvest below RM 9” fish reported by Fleischman and McKinley (2013: Table 2, page 27). Ages were assigned by counting scale annuli following Mosher (1969).

Measures of Abundance

DIDSON-based estimates of early-run Chinook salmon passage during 2010 through 2012 reported here are preliminary estimates from Miller et al. (*In prep* a) and Burwen et al. (*In prep*).

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[5] Age composition data were also collected from the onsite creel survey (Perschbacher 2012 a, 2012b), but they were not needed for the state-space model.

The DIDSON estimates are germane to all ages and sizes of Chinook salmon migrating upstream between the sonar transducers at the RM-9 site.

Traditional two-event capture–recapture estimates (CRTRA) of Kenai River early-run Chinook salmon inriver abundance were available for 1986–1987 (McKinley and Fleischman 2010). Preliminary estimates of inriver run were also available for 2007 through 2012 from genetic capture–recapture (CRGEN) experiments by fitting the SSART model to genetic allele frequency, radiotelemetry, harvest, and weir data (Appendices C1–C2).

Annual catch rates from the inriver test gillnet fishery (NCPUE; Perschbacher 2012a, 2012b) were obtained by summing daily catch rates from 16 May through 30 June. Because of a change in mesh size (only 7.5-inch mesh was used before 2002; 5.0-inch and 7.5-inch mesh were used thereafter), catch rates from 1998 through 2000 and from 2002 through 2012 were treated as separate indices (NCP75 and NCPUE, respectively). Net apportioned split-beam sonar estimates of Chinook salmon passage (NASB), and estimates based on ELSD during 2002 through 2009 were obtained from Miller et al. (*In prep* b). Annual catch rates (guided anglers only) from the inriver sport fishery (SCPUE; Perschbacher 2012a, 2012b) were obtained by summing daily estimates from 16 May through 30 June. For days during which CPUE was not measured, the mean of sampled days from the same time stratum was imputed.

There are fewer historical data available for Kenai River early-run Chinook salmon, compared to the late run (Fleischman and McKinley 2013). Because the commercial sockeye salmon fishery does not start until late June, no commercial fishery catch rates were available to index early-run Chinook salmon abundance. SCPUE was used for years 2002–2012 only; it did not provide a reliable index of abundance for the years 1986–2001 due to changes in regulations and frequent inseason management actions. For a long-term index of abundance that spanned the entire time period, we utilized annual estimates of late-run Chinook salmon abundance (Fleischman and McKinley 2013: Table 6, page 31), which exhibited positive relationships with early-run indices of abundance (Figure 2). Early- and late-run Kenai River Chinook salmon share freshwater and perhaps marine habitat as juveniles, and these commonalities are borne out in correlated annual abundance measures.

More details about annual measures of abundance are provided in Table 4; values of these measures are listed in Table 5.

STATE-SPACE MODEL

The state-space model integrates relevant information and estimates all parameters simultaneously, including historical abundance, stock productivity, and stock capacity. 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 incorporates six "index" measures (NCPUE, NASB, SCPUE, ELSD, N^LR, NCP75; defined in Table 4) to estimate the relative abundance of Chinook salmon across years. Information on absolute abundance is obtained from recent sonar (DIDSON) and capture-recapture (CR) estimates. DIDSON provides three annual estimates of a spatial subset of inriver abundance (fish migrating in the middle section of the river; see below); and CR (CRTLM and CRGEN) provides 8 annual estimates on the magnitude of total inriver abundance (see below). The measures of abundance have positive relationships with one another (Figure 2) and show common trends through time (Figure 3). In the RR sub-model, each index has a linear relationship through the origin with true (midriver, inriver, or total) abundance (Figure 4). Estimates of these relationships were used to scale the individual indices in Figure 3 (see Table 6 for parameter estimates). The RR sub-model synthesizes the multiple incomplete sources of information on relative and absolute abundance to produce annual estimates of inriver run abundance (labeled as IR with error bars in Figure 3).

The RM-9 sonar site is subject to tidal influence, and the sonar transducers were placed such that they remained submerged during the lowest tides. At high tide they were distant from shore and unable to sample the entire cross section of the river. Because of this constraint, some Chinook salmon were able to swim behind the transducers and go undetected by the sonar.[6] 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 redeployment of transducers to ensonify the entire width of river. For this reason, reconstruction of Chinook salmon historical abundance requires one or more unbiased estimates of Chinook salmon inriver run. The current analysis uses preliminary estimates from traditional and genetic capture–recapture methods (CRTRA, CRGEN) to provide these estimates of inriver run.

In the full state-space model, abundance of Kenai River early-run Chinook salmon is described by a Ricker (1975) spawner–recruit[7] (SR) function, which defines the number of fish expected to return (the "recruitment") from a given "escapement" (number of spawning fish). The Ricker SR relationship is the most common choice for modeling Pacific salmon stock dynamics in Alaska. In the model, productivity is allowed to vary among brood years, 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, and 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 produce the theoretical maximum recruitment (S_{MAX}).

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

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

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[6] The existence of Chinook salmon passing behind the transducers was investigated multiple times, but never confirmed until an additional DIDSON was deployed to sample behind the left-bank transducer in 2011 (Miller et al. *In prep* b).

[7] Often termed "stock–recruit" in the fisheries literature.

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

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

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 among cohorts to a specified extent. Age-at-maturity vectors[8] $\underline{\boldsymbol{p}}_y = (p_{y4}, p_{y5}, p_{y6}, p_{y7})$ from year y returning at ages 3–7 were drawn from a *Dirichlet* $(\gamma_3, \gamma_4, \gamma_5, \gamma_6, \gamma_7)$ distribution. The Dirichlet parameters can also be expressed in an alternate form where

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

is the (inverse) dispersion[9] 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 (recruitment) 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:

$$N_y = \sum_a N_{ya}. \tag{7}$$

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:

$$H_{By} = \mu_{By} N_y. \tag{8}$$

Inriver run IR at RM 9 was modeled as follows:

$$IR_y = N_y - H_{By}. \tag{9}$$

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[8] These age proportions are maturity and survival schedules for a given brood year (cohort) across calendar years. In contrast, Equation 19 describes age proportions in a given calendar year across brood years.

[9] A low value of D is reflective of a large amount of variability of age-at-maturity proportions $\underline{\boldsymbol{p}}$ among brood years, whereas a high value of D indicates more consistency in $\underline{\boldsymbol{p}}$ over time.

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 between the transducers 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:

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

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 (CRTRA 1986–1987 and CRGEN 2007–2012), direct estimates of midriver run (DIDSON 2010–2012), six indices of inriver run relative abundance (NCPUE, NASB, SCPUE, ELSD, N^LR, NCP75), and age composition estimates from the inriver netting project. Sampling distributions (likelihood functions) for the data follow.

Estimated midriver run of Chinook salmon from the DIDSON was modeled as follows:

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

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 CRTRA and CRGEN 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 (Table 3) was

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

where the $\{\varepsilon_{HBy}\}$ were normal $(0, \sigma^2_{HBy})$. Coefficients of variation $\{CV_{HBy}\}$ were assumed to be 43–100% (Table 3). State-space results are unlikely to be sensitive to choice of sampling error CV for small harvest quantities like H_{By} (Fleischman et al. *In press*; Fleischman and McKinley 2013).

Estimated annual harvest of Kenai River Chinook salmon above RM 9 (Table 3) 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 the inriver creel survey and the SWHS.

Six indices of abundance were available (Table 4). 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 proportionality relating true abundance to index I_i, X_y is the generic true abundance (midriver run MR for NCPUE, NCP75,[10] NASB, and ELSD; inriver run IR for SCPUE; and total run N for N^LR) and the $\{\varepsilon_{iy}\}$ are independently and normally distributed process errors with variance σ^2_{Ii}. Parameters q_i and σ^2_{Ii} were estimated from the data.

The model requires annual data on the age composition of the total run abundance. Because inriver run comprises more than 95% of total run, we used inriver run age composition as a surrogate for total run age composition.

The inriver netting project operated solely with 7.5-inch mesh nets until 2002, when 5.0-inch nets were added and twine type was changed. In order to account for the resulting change in probability of capture by age, we assumed that catches were subject to relative selectivity factors $\boldsymbol{\rho}\ (= \rho_3 - \rho_7)$. Based on net selectivity investigations conducted in 2001–2002 (Reimer 2003), we believe that catches from the combination of both mesh sizes are approximately representative of the population, therefore we set $\rho_3 - \rho_7$ to unity for 2002–2012. For the years 1986–2001, when only the 7.5-inch mesh was used, the vector $\boldsymbol{\rho}$ was a free parameter estimated from the data. Expected age proportion parameters θ_a were the normalized product of $q_{y,a}$ (actual proportions) and ρ_a (see Appendices A1–A2 for coding details):

$$\theta_{y,a} = \frac{N_{y,a}\rho_a}{\sum_a N_{y,a}\rho_a}. \tag{19}$$

The model requires multinomial age counts and assumes that age counts come from a simple random sample of the total run. This assumption cannot be met for real-world fisheries data, so we rescaled the age data with an "effective sample size" of $n_{Ey} = 100$. Surrogate scale-age counts x_{ya} were obtained that summed to n_{Ey} rather than n_y. Scale age counts x_{ya} (listed in Appendix A2) were modeled as multinomially distributed, with order parameter n_{Ey} and proportion parameters θ_a. We have found that key results from state-space analyses of Pacific salmon data are generally not sensitive to choice of n_{Ey} (e.g., Fleischman and McKinley 2013).

MODEL FITTING

Markov Chain Monte Carlo (MCMC) methods, which are well-suited for modeling complex population and sampling processes, were employed. The MCMC algorithms were implemented in OpenBUGS (Lunn et al. 2009), 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

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[10] Because NCP75 catch rate was based on 7.5-inch mesh only, we assumed that it was related to the abundance of age-5 to age-7 fish only.

possible with classical statistical methods. By properly specifying process variation, measurement error, and time-dependent linkage separately in the model, biases in the analysis can be reduced (Su and Peterman 2012).[11]

Bayesian statistical methods employ the language of probability to quantify uncertainty about model parameters. Knowledge existing about the parameters outside the framework of the current analysis is the "prior" probability distribution. The output of the Bayesian analysis is called the "posterior" probability distribution, which is a synthesis of the prior information and the information contained in the data. See Fleischman et al. (*In press*), as well as Ericksen and Fleischman (2006), Szarzi et al. (2007), Fleischman and Borba (2009), Fleischman and Evenson (2010), Fleischman et al. (2011), Hamazaki et al. (2012), and Fleischman and McKinley (2013) for similar applications of the methods used in this report.

Prior Distributions

Non-informative priors (chosen to have a minimal effect on the posterior) were used for most parameters. Initial recruitments 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 $\ln(\alpha)$ and β (Millar 2002), as well as for μ_{logR} and p_{MR}, and coefficients of proportionality q_i (log transformed). The initial model residual v_0 was given a normal prior with mean zero and variance $\sigma^2_W/(1-\phi^2)$. Annual harvest rates $\left\{\mu_{By} \text{ and } \mu_{Ay}\right\}$ were given beta (0.1,0.1) prior distributions. Diffuse conjugate inverse gamma priors were used for σ^2_W and σ^2_{logR}.

Diffuse conjugate inverse gamma priors were also used for σ^2_{Ii} (index uncertainty parameters), with one exception. The parameter σ^2_{I5}, which governs uncertainty of N^LR as an index of early run abundance, was given an informative inverse gamma (10,1) prior. This was an arbitrary choice intended to increase σ^2_{I5}, which reduces statistical confidence in N^LR as an index. This prior distribution provided an avenue to incorporate staff belief that the late-run estimates of abundance from Fleischman and McKinley (2013) were less reliable as an index of early run abundance than recent data (Figure 2) indicated.

Sampling from the Posterior Distribution

MCMC samples were drawn from the joint posterior probability distribution of all unknowns in the model. For results presented here, every third sample from a single Markov chain was written to disk. Of these, the first 5,000 samples were discarded, and 40,000 additional samples were used to estimate the marginal posterior medians, standard deviations, and percentiles. The diagnostic tools of OpenBUGS were used to assess mixing and convergence, and no major problems were encountered. Interval estimates were constructed from the percentiles of the posterior distribution.

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[11] It is not uncommon for Bayesian and traditional analyses to produce similar results. In that case, the benefit of the Bayesian analysis is that it confirms that uncertainty in the analysis does not invalidate the results.

REFERENCE POINTS, OPTIMAL YIELD, AND RECRUITMENT PROFILES

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

$$S_{MSY} \cong \frac{\ln(\alpha')}{\beta}\left[0.5 - 0.7\ln(\alpha')\right]. \tag{20}$$

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

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

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

$$U_{MSY} \cong \ln(\alpha')\left[0.5 - 0.7\ln(\alpha')\right], \tag{22}$$

escapement leading to maximum production

$$S_{MAXR} = \frac{1}{\beta}, \tag{23}$$

and equilibrium spawning abundance, where recruitment exactly replaces spawners:

$$S_{EQ} = \frac{\ln(\alpha')}{\beta}. \tag{24}$$

The quantity

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

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 10,000 by 100) 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 (Fleischman et al. *In press*).

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

The probability that a given spawning escapement S would produce average recruitments exceeding X% of maximum recruitment $MR = \alpha S_{MAXR} e^{-1}$ was obtained by calculating R at incremental values of S for each MCMC sample, then comparing R with X% of the value of MR

for that sample. The proportion of samples in which R exceeded X% of MR, plotted versus escapement, is an optimal recruitment probability profile (Fleischman et al. *In press*).

SENSITIVITY TO ASSUMPTIONS

Several alternate configurations of the analysis were conducted to test for robustness of the results (Table 7).

For alternate configurations 1a and 1b, strong informative priors were applied to p_{MR} with means of 0.80 and 0.50 and standard deviations of 0.03. These scenarios mimic the acquisition of external information about p_{MR}, such as the planned 2013 deployment of sonar at RM 14 designed to detect all Chinook salmon.

Alternate configuration 2 omitted data from the years 1986–2001, for which abundance data were sparse and estimates depended solely upon indices of relative abundance N^LR (1986–2001) and NCP75 (1998–2000 only), plus 2 annual CRTRA estimates of absolute abundance (1986–1987).

Alternate configuration 3 used a modified version of the base model that allowed for trending age at maturity (TAM). The TAM model was developed to produce forecasts of run size and age composition in 2013.[12] In the TAM model, the assumption of constant age at maturity was relaxed, by allowing expected age proportion parameters π_3–π_7 (Equation 5) to trend across brood years, as governed by a multivariate logistic (ML) function (Congdon 2003: page 99):

$$\pi_{ay} = \frac{\exp(\nu_{ay} + \rho_{ay} t)}{\sum_a \exp(\nu_{ay} + \rho_{ay} t)} . \tag{26}$$

Age at maturity of fish from individual brood year y was allowed to vary from the expected proportions following a Dirichlet $(\gamma_{3y}, \gamma_{4y}, \gamma_{5y}, \gamma_{6y}, \gamma_{7y})$ distribution, where

$$\gamma_{ay} = D\pi_{ay} \tag{27}$$

and inverse dispersion parameter D govern the degree that annual age at maturity departs from the ML model.

Alternate configuration 4 removed the informative prior on $\sigma_{N\text{^}LR}$, substituting a flat noninformative prior instead, in order to quantify the effect of the informative prior on the base model results.

Using a traditional spreadsheet version of the analysis, we assessed the effect of our assumption that marine recreational catches are composed of 5% Kenai River early-run fish by repeating the analysis under alternate assumptions of 0% and 10%.

Fleischman and McKinley (2013: Table 5, page 30) found that estimates from a state-space model of late-run Kenai River Chinook salmon data were only mildly sensitive to the assumption of linearity between true abundance and relative abundance indices, and that choice of effective sample size n_E did not affect key parameters. We did not repeat these tests for the early-run analysis.

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[12] Forecasts are not included in this report.

ESCAPEMENT GOAL REVIEW PROCESS

An interdivisional escapement goal review team[13] (review team) was convened to review the available data, plan and interpret analyses, and make an escapement goal recommendation. The escapement goal recommended in this report is the product of several collaborative meetings of the review team and other department staff. The escapement goal recommendation was reached by consensus.

RESULTS

HARVEST AND AGE COMPOSITION

Annual harvests of Kenai River early-run Chinook salmon ranged from 326 fish in 2012[14] to over 15,000 fish in 1988 (Table 3). Age composition of the inriver run was predominately age-5 (1.3) and age-6 (1.4) 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, HARVEST RATES, AGE AT MATURITY, AND FRACTION DETECTED BY SONAR

Abundance measures had positive relationships with one another (Figure 2) and show common trends through time (Figure 3). Reconstructed estimates of inriver run abundance (*IR*; black line with error bars in Figure 3) synthesized information from all abundance measures, generally passing through the center of the scaled individual measures. Inriver runs were relatively large during the years 1986–1988 and 2003–2007, 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 for the years 2002–2012, when direct estimates and multiple indices were available. Estimates were less precise before 2001, when the only indices available were late-run Kenai River Chinook salmon run abundance (N^*LR*) and three years of NCP75 (1998–2000), and when the only direct estimates were very imprecise (CRTRA; 1986–1987).

There is a great deal of uncertainty about escapement *S* in years without direct estimates of run abundance, with error CVs of up to 64% (Table 8; Figure 5a). Reconstructed total run abundance *N* (Figure 5c) and brood year recruitments *R* (Figure 5b) were more certain because they contain a harvest component, which was relatively well-estimated. Error CVs for *N* and *R* were 8–20% except for *R* at the beginning and end of the data series, when one or more age classes were missing (Table 8; Figures 5b and 5c). Harvest rates on Kenai River early-run Chinook salmon varied greatly (0.04 to 0.82 of total run abundance) and were profoundly affected by fishing regulations and inseason restrictions (Figure 5e).

Age at maturity did not vary much through the 1989 brood year, but has varied substantially since. Likewise, age composition from the post-1989 brood years has fluctuated from calendar year to calendar year (Figure 6).

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[13] The review team included four ADF&G staff from Soldotna and six from Anchorage (see Acknowledgments).

[14] Does not include sport harvest above the Soldotna Bridge, however that harvest was likely very small in 2012.

State-space model estimates of total run abundance by age class are tabulated in Appendix B1.

The fraction p_{MR} of Chinook salmon detectable by the sonar at the RM-9 site is also the ratio of midriver abundance MR to inriver abundance IR. The estimate of p_{MR} from the state-space model was 0.65 (90% CI = 0.57–0.74).

STOCK PRODUCTIVITY, CAPACITY, AND YIELD

The results from the state-space model 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 each one was estimated. Because of measurement error and other sources of uncertainty, Ricker SR relationships that could have plausibly generated the observed data are diverse (Figure 7: light lines), some deviating substantially from the "point estimate" of the Ricker relationship (Figure 7: heavy dashed line).

Compared to other Alaskan Chinook salmon stocks, productivity of Kenai River early-run Chinook salmon is moderately high ($\alpha = 6.3$), although note the wide 90% credibility interval (CI = 2.9–11.6; Table 6). Productivity of the stock has fluctuated over time, as evidenced by the high serial correlation ($\phi = 0.70$; 90% CI = 0.17–0.96; Table 6) in the spawner–recruit residuals (Figure 5d). There has been a persistent, although variable, decrease in productivity starting with the 2004 brood year (Figure 5d). Imprecise estimates of the productivity parameter α are typical of stocks with time-varying productivity and low or variable harvest rates (e.g., Fleischman et al. *In press*; Fleischman and McKinley 2013).

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 $S_{MAXR} = 1/\beta$, and uncertainty about equilibrium abundance S_{EQ} is reflected by variability in the values of S where the curves intersect the replacement line. S_{EQ} is estimated with reasonably high certainty (CI = 9,204–7,950), as is spawning escapement leading to maximum sustained yield S_{MSY} (CI = 3,368–5,956; Table 6). Posterior medians of S_{EQ} and S_{MSY} were 12,270 and 4,434, respectively (Table 6).

Given the wide diversity of plausible spawner–recruit relationships (SRRs; Figure 7), it is important to choose an escapement goal that is robust to this uncertainty, rather than one tailored to any single SRR (e.g., the point estimate). The optimal yield probability profiles in Figure 8 were generated by tallying, across plausible SRRs, 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 4,400 spawning Chinook salmon (Figure 8), can be used to quantify the yield performance of prospective escapement goals, taking into consideration the uncertainty about the true abundance, productivity, and capacity of the stock.

Expected sustained yield (number of fish over and above that necessary to replace the number of spawners, averaged over the brood years 1986–2008) is also maximized near an escapement of 4,400 spawners (Figure 9). Under reduced levels of productivity experienced during recent (2004–2008) brood years, expected yield is reduced to about one half of the historical average (Figure 9).

Expected recruitment (number of fish returning from a single annual escapement event, as specified by the Ricker relationship, averaged over the 1986–2008 brood years) is maximized near S_{MAXR} = 6,362 spawners (Figure 10). Under 2004–2008 productivity levels, expected recruitment is reduced by about 25% from the historical average (Figure 10).

DISCUSSION

SENSITIVITY ANALYSES

The fraction p_{MR} of Chinook salmon migrating midriver between the transducers at RM 9 is a key quantity. The inverse of p_{MR} (p_{MR}^{-1} = 1.55; 90% CI = 1.36–1.76) can be applied as a correction factor to expand DIDSON-based estimates of midriver run to the full river cross section. Although the estimate of p_{MR} is fairly precise (CV = 0.08; Table 6), it is based solely on comparisons of DIDSON with CRGEN and CRTRA embedded in the state-space model and may be biased (page 18). ADF&G is anticipating that a direct, improved estimate of p_{MR} may be available after the 2013 season, conditional on the ability to successfully deploy sonar at RM 14. By applying informative prior distributions to p_{MR}, alternate configurations 1a (prior mean 0.80) and 1b (mean 0.50) simulate the availability of strong external information about p_{MR} from such an experiment.

As expected, p_{MR} prior means of 0.80 and 0.50 resulted in posterior medians of 0.77 and 0.54, respectively, compared to 0.65 for the base model (Table 7, configurations 1a and 1b).[15] However, there was also an effect on S_{MSY} in the opposite direction (S_{MSY} posterior medians 4,051 and 4,697 respectively). In configuration 1a (Table 7), the higher value of p_{MR} would require more fish counted by the DIDSON at RM 9, which would produce management advice favoring less fishing. However the lower value of S_{MSY} would favor more fishing, offsetting the effect of the higher p_{MR}. In configuration 1b, the lower value of p_{MR} would favor less fishing and the higher value of S_{MSY} would favor more fishing. Therefore, as a rule, discordant differences in p_{MR} and S_{MSY} partially offset one another with respect to their influence on fishery management. In alternate configuration 1, the relative changes in the expansion factor p_{MR}^{-1} were about 17% and the changes in S_{MSY} were about 8%. Because the differences are offsetting, this means that the net effect of any new information about p_{MR} on fishery management is reduced by approximately one half.

Alternate configuration 2 omitted data from 1986 to 2001, which were more sparse and perhaps less reliable than data that followed (Table 4, Table 5). Configuration 2 reduced the time span of the analysis to only 11 years (2002–2012), and the number of complete brood years to 4 (2002–2005).[16] Although this modification reduced the estimates of α and β, the estimates of S_{MSY} and p_{MR} were almost identical to those from the base analysis (Table 7, configuration 2). The short and long datasets were thus roughly in agreement with respect to escapement goal considerations. Analyses of Kenai River late-run Chinook salmon data were also consistent between short and long datasets (Fleischman and McKinley 2013).

Alternate configuration 3, designed to accommodate a trend in age at maturity (the TAM model), affected several model parameters (Table 7). The point estimate of α (reflecting average

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[15] In the Bayesian framework, the posterior distribution is a weighted compromise between the data and the prior distribution. Because p_{MR} was estimated with precision CV = 0.08 by the data in the base model, the informative prior (CV = 0.05) moves the estimates of p_{MR} most of the way toward the prior mean.

[16] The age-structured state-space model is also able to extract information from the incomplete (2006–2009) brood years (Fleischman et al. *In press*).

productivity) was reduced from 6.3 to 4.8 and the estimate of AR(1) productivity coefficient ϕ increased slightly from 0.70 to 0.77, indicating a stronger recent decline in productivity. However the differences in S_{MSY} and p_{MR} between the base and TAM models were negligible (Table 7).

Differing assumptions about the stock composition of Cook Inlet recreational harvests (0% and 10% Kenai River origin, versus 5% for the base analysis) affected the point estimate of S_{MSY} by less than 0.5% (not shown).

REMAINING UNCERTAINTIES

Only a single long-term index (N^LR) was available to reconstruct early-run abundance before 2002, and unlike the other indices, it was not based on direct observations of early-run fish. The early-run results therefore depend on assuming that the relationship between early- and late-run abundance has not undergone a large change. The N^LR index missed a possible increase in early-run abundance in 1999 that was reflected in the short term NCP75 index (Figure 3) and was corroborated by exceptionally high catch rates in the 1999 inriver sport fishery (Reimer et al. 2002). To hedge against over-stating confidence in N^LR as an index, we set an informative prior on the $\sigma_{N\hat{}LR}$ parameter that governs the amount of error in the relationship between N^LR and true early-run abundance (see Prior Distributions, page 12). The effect of the informative prior was to increase the point estimate of $\sigma_{N\hat{}LR}$ from 0.09 to 0.25 (Table 7: configuration 4 and base model, respectively). As expected, by decreasing the certainty with which N^LR reflects true historical abundance, there was a slight increase in the imprecision of the estimate of S_{MSY} (from CV = 0.16 to CV = 0.17; not shown). However, effects on the point estimates of S_{MSY} and p_{MR} were negligible (Table 7).

Uncertainty about the number of spawning fish required to produce optimal yield (S_{MSY}) is well assessed in the current analysis, for example through the use of optimal yield profiles (Figure 8) and expected yield plots (Figure 9). The effect of observation uncertainty introduced by p_{MR}, the fraction of fish detected at the RM-9 sonar site, is less well assessed. Until the sonar site is moved, p_{MR} plays a role equally as important as S_{MSY} in determining how many fish must be observed by the RM-9 DIDSON in order to meet the escapement goal. Because the state-space model estimate of p_{MR} is relatively small (0.65, compared to 0.78 for the late run; Fleischman and McKinley 2013), the expansion factor to account for imperfect detection is relatively large (1.55 early run versus 1.28 late run). Currently, our knowledge of p_{MR} is based solely on the state-space model, which relies heavily on information from DIDSON and CRGEN estimates during the years 2010–2012 (average DIDSON/CRGEN ratio 0.62, from quantities in Table 5). Because capture–recapture experiments can be subject to bias, there is uncertainty about p_{MR} beyond what is assessed by the model (CV = 0.08, CI = 0.57–0.74). On the other hand, CRGEN estimates are less likely to be biased for the early run than the late run, because a substantial fraction of early-run fish is directly observed at the weirs. Also, the early-run CRGEN estimates are more precise (annual CVs = 0.11–0.21; Table 5) than the corresponding late-run estimates (CVs = 0.15–0.23; Fleischman and McKinley 2013). Furthermore, the results of alternate model configurations 1a and 1b suggest that the results of the current analysis are somewhat robust to bias in p_{MR} due to partially offsetting effects on S_{MSY}. Although 2013 data from an experimental upriver sonar site may alter our perspective on p_{MR} and its associated expansion factor, the net effect on fishery management is not likely to be extreme. Finally, except for an indirect role in future versions of the run reconstruction, p_{MR} will become irrelevant upon moving the sonar site.

The early run is composed primarily of tributary-spawning fish, but it is defined as fish that pass RM 9 before 1 July. Recent genetic data suggest that this temporal cutoff provides imperfect separation of tributary and mainstem spawning fish, and that substantial numbers of mainstem spawners arrive in late June (Appendices D1–D2). Because mainstem spawners outnumber tributary spawners, there is the potential for early-arriving mainstem spawners to influence the spawner–recruit analysis of early-run fish. It is possible that the current definition of the early run could be improved upon with the help of a careful analysis of genetic stock composition data. We did not attempt to address this issue in the current analysis.

SUMMARY AND CONCLUSIONS

Similar to Kenai River late-run Chinook salmon (Fleischman and McKinley 2013), productivity of early-run Chinook salmon is moderately high on average, but it has fluctuated over time (Figure 5d). A recent decline in productivity has resulted in runs that are probably the smallest in several decades (Figure 5c).

Unlike the late run, for which recent escapements were the smallest in decades, the smallest escapements of early-run fish probably occurred during the late 1980s and mid-1990s. During many of these years, escapements were probably below S_{MSY} and harvest rates above U_{MSY} (Figures 5a and 5d). These years were counterbalanced by many years of moderate to high escapements and very low harvest rates (1990–1992, 1998, and 2000–2012; Figures 5a and 5d). The stock has been lightly harvested since 1999.

Management of the early-run fishery has been variable, resulting in large contrasts in historical harvest rates and escapements (Figure 5). The varied harvest history of the early-run stock has enhanced our ability to quantify productivity and capacity and to identify escapements leading to optimal yield. Because 1) only a single abundance index was available before 2002, 2) CRTRA estimates were very imprecise, and 3) inriver harvest rates were sometimes high, model-based estimates of the small escapements during the late 1980s and mid-1990s were very imprecise (Table 8). However, the imprecise estimates of S had relatively little impact on our ability to estimate the production relationship because there was sufficient precision to identify those escapements as small, and they resulted in relatively large yields (Figure 7). This information, combined with recent large escapements that did not replace themselves (Figure 7), supplied good information about escapements leading to optimal yields (Figure 8).

Key results of the analysis (estimates of S_{MSY} and p_{MR}, which are most relevant to the escapement goal) were robust to several alternate model and data configurations (Table 7).

ESCAPEMENT GOAL RECOMMENDATION

Information about the range of escapements that will lead to optimal yields is summarized in the optimal yield profile (OYP). Yield reaches a maximum at S_{MSY}. The steeper the limbs of the OYP, and the greater the maximum probability, the better the information about sustained yield at different levels of escapement. Compared to other Alaska Chinook salmon stocks that have been analyzed in a similar manner, the OYP for Kenai River early-run Chinook salmon (Figure 8) has very good information content (Figure 11).

Because the early-run stock is harvested primarily by recreational fisheries (marine and inriver), run size is an important consideration because of its effect on catch rates. Run size (calendar year abundance) is directly tied to recruitment (brood year return), which reaches a maximum *MAXR* at $S_{MAXR} = 1/\beta$. Information about the range of escapements that lead to optimal recruitment is summarized in an optimal recruitment profile. Optimal recruitment profiles and OYPs are overlain in Figure 12 for probabilities of achieving 70%, 80%, and 90% of *MSY* or *MAXR*, respectively. These probabilities, which are maximized near 4,400 spawning Chinook salmon for yield and 6,400 for recruitment, can be used to quantify the yield and recruitment performance of prospective escapement goals, taking into consideration the uncertainty about the true abundance, productivity, and capacity of the stock.

Based on the foregoing analysis, the Alaska Department of Fish and Game recommends a sustainable escapement goal (SEG; definition in 5 ACC 39.222 [f][36]) of 3,800–8,500 Kenai River early-run Chinook salmon.

The recommended goal brackets both S_{MSY} and S_{MAXR}. At the lower bound of the recommended range there is a very high (>94%) probability of achieving near-optimal yields (70%, 80%, or 90% of MSY). At the upper end of the range, the probability of optimal yields is much reduced (34%, 17%, and 6% probability of achieving 70, 80, 90% of *MSY*, respectively), however there is high (99%, 95%, and 77%) probability of achieving near-optimal recruitment (70%, 80%, or 90% of *MAXR*, respectively). At the center of the range (6,150), there is an 86% probability of achieving 80% of optimal yield *and* recruitment.

The recommended goal is based on actual numbers of spawning fish, so it must be evaluated by accounting for undetected Chinook salmon passing the RM-9 sonar site. This is accomplished by multiplying DIDSON-based estimates of midriver passage by a correction factor to expand the estimates to reflect Chinook salmon passage in the entire cross-section of the river. We recommend a correction factor of 1.55, which is obtained from the state-space model as the inverse of p_{MR} (point estimate 0.65), the fraction of Chinook salmon detected by sonar at RM 9. Projections of harvest and release mortality[17] above RM 9 must be subtracted from expanded DIDSON inriver passage estimates to project escapement during the fishing season.

The recommended interim escapement goal has the following attributes:

The new goal represents a significant change from the status quo. Because the stock assessment for Kenai River Chinook salmon has changed from split-beam sonar to DIDSON, the old and new goals are based on different currencies and are not comparable. Even though the numerical value of the recommended goal is similar to the existing SEG, the net effect of the new goal may be a substantial change in potential management actions. This effect is difficult to quantify, but can be seen by comparing recent model-derived estimates of annual escapement with the recommended goal (Figure 13). During the most recent four years (2009–2012), when the use of bait was only rarely permitted and restrictions were frequent, annual escapements were 1,400–4,600 fish above the recommended goal. Hypothetically, had this goal been in place during those years, the number and severity of fishery restrictions probably would have been reduced.

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[17] Release mortality is obtained by multiplying creel survey estimates of number of fish released by 0.064 (Bendock and Alexandersdottir 1992).

The new goal is higher than yield considerations alone would dictate. Assuming perfect knowledge of the spawner–recruit relationship (α = 6.3, β = 0.00016) an escapement goal range of 2,871 to 6,464 spawners would provide expected yields of at least 90% of *MSY*. According to Eggers (1993), an escapement goal range of 3,547 (0.8 × $S\hat{}_{MSY}$ point estimate) to 7,094 (1.6 × $S\hat{}_{MSY}$) would provide robust yield performance. Accounting for uncertainty in our knowledge of α, β, and S_{MSY} , a goal of 2,800–6,000 spawners would provide greater than 90% probability of achieving 80% of MSY.[18] The escapement goal review team recommended a goal that was higher than the aforementioned ranges in order to be precautionary and provide an extra margin of safety for the stock in the face of remaining uncertainties (page 18). These uncertainties include sparse pre-2002 data in the early-run reconstruction (one indirect long-term abundance index, two imprecise annual estimates of inriver run), the possible unwanted influence of early-arriving mainstem spawners on the current analysis, and the possible influence of the harvest of tributary spawners in July on this analysis. The large correction for undetected fish required at the RM-9 sonar site also contributes uncertainty to the results. Better information about this quantity will probably be available shortly, after the 2013 season.

The new goal will protect the Kenai River early-run Chinook salmon stock from overfishing. Because DIDSON–based assessment represents a large advancement over previous methods, the ability to detect a small run and manage appropriately has been greatly improved. After transition of sonar assessment operations upriver to a site with fewer detection issues, assessment will be further enhanced. By combining accurate assessment with an escapement goal based on comprehensive, up-to-date knowledge of stock dynamics, we will continue to prevent overfishing of the stock.

The new goal will benefit fisheries that harvest Kenai River early run Chinook salmon. The new goal will reduce the potential for unnecessary fishery restrictions. Better assessment capabilities facilitate the timely transfer of accurate information to fishery managers during the season. The recommended goal brackets the escapements that provide near-optimal yield and recruitment (Figure 12).

It is important to note that goal setting involves trade-offs. As explained above, elevating the goal slightly provides a safety factor in favor of higher escapements, however it may also reduce harvest opportunity during future periods of low abundance. Expected yield (Figure 9) and probability of optimal yield (Figure 8) may also be reduced. Because recruitment (and run size) is maximized at larger numbers of spawning fish than is yield, these sacrifices are partially offset by increased recruitment (Figure 10), and higher probability of optimal recruitment (Figure 12). However any further increase in the goal beyond what is recommended would result in additional sacrifices of yield *and* recruitment (Figure 12).

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[18] There is no accepted algorithm for selecting an escapement goal with an OYP. The stated range of 2,800–6,000 is one example of a goal based on yield probabilities.

Small runs are expected for the near future. Results of the run reconstruction and spawner–recruit analysis suggest that the Kenai River early-run stock has been undergoing a decline in productivity. The 2012 total run (5,387 was the smallest on record (Figure 14), representing more than a four-fold decline from peak abundance in 2004 (23,460 fish; Table 8). Similar declines have been documented for other Chinook salmon stocks statewide (ADF&G Chinook Salmon Research Team 2013). Thus far, there is little evidence that the decline will soon be reversed. Based on the current analysis of historical data, escapements of 3,800–8,500 Kenai River early-run Chinook salmon can provide yields averaging approximately 9,000 fish (Figure 9; 80% CI = 2,000–18,000). However this expectation of yield performance is based on "average" stock dynamics across brood years 1986 to 2008. During the five most recent brood years (2004–2008), productivity residuals have been negative (Figure 5d), averaging −0.30 (natural logarithm) units, which is equivalent to a 26% decline in productivity ($1-e^{-0.30}$). Figure 9 also shows revised yield expectations, should the reduced productivity of recent brood years continue into the future. Under this scenario, expected yield would be approximately 5,000 for escapements in the goal range, a more than 40% reduction in yield from average conditions.[19]

The new goal is consistent with previous practice, with respect to escapement goal selection. In Figure 11, optimal yield profiles from seven other recently-reviewed Chinook salmon stocks are reproduced and rescaled for comparison with the Kenai River early-run OYP, and probabilities of achieving 90% of *MSY* are plotted versus the lower bound[20] of the escapement goal for each stock. These lower-bound probabilities range from 43% to 100% for the seven stocks.[21] The Kenai River early-run stock has a 94% probability of achieving optimal yield at the lower bound of the recommended goal. Although the Kenai River early-run goal is higher than would be indicated purely by yield considerations, it is within the range (ranked 3 of 8, after Kuskokwim and Anchor rivers stocks) of probabilities achieved by other recent Chinook salmon goals. Optimal recruitment was a factor considered in setting an escapement goal for Kuskokwim River Chinook salmon (Hamazaki et al. 2012).

The new goal is transferable. The goal is expressed in the "currency" of actual fish, accounting for imperfect detection at the RM-9 site. Although the goal will be subject to review and revision (see below), it will not require reformulation after the planned transition to an upriver sonar site is complete. Supplementary analyses indicate that data collected in 2013 will probably not result in drastic changes to management of the fishery (Sensitivity Analyses, alternate configurations 1a and 1b).

The escapement goal for Kenai River early-run Chinook salmon will need to be periodically reviewed. All escapement goals in the state of Alaska are subject to trienniel review. This goal

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[19] Under a modified version of the state-space model developed for forecasting, yield expectations are reduced even further. The modified "TAM" model accommodates a trend in age at maturity. Yield projections from the TAM model are not shown in this report.

[20] Given that large runs are not expected in the near future, the lower bound of the goal is currently more relevant than the upper bound for Kenai River early-run Chinook salmon.

[21] The divergent risk probabilities in Figure 11 are a consequence of the differing sets of considerations that are relevant to each individual stock. Some of these considerations include status quo (i.e., current goal), type of fishery (commercial, sport, subsistence), recent history of the stock (declining or increasing), fishing power (ability to harvest large runs), and accuracy and timeliness of inseason assessment. In all cases, including Kenai River early-run Chinook salmon, the recommended goal represents a compromise between these competing considerations, one that was arrived at after careful and protracted deliberation by the escapement goal review team.

will merit attention for the following reasons: 1) Sonar assessment methodology remains in transition. Until this transition is complete, there will be uncertainty about the absolute magnitude of inriver abundance. 2) DIDSON and CRGEN estimates remain preliminary at the time of preparation of this report. Although we do not anticipate major changes in these estimates, they are subject to revision until published. 3) The recruitment from recent small escapements has yet to be assessed. As the 2007–2009 cohorts complete their return, a more comprehensive understanding of productivity and age at maturity will emerge for this stock. Finally, 4) further investigation of the Chinook salmon stock composition during late June and early July is needed to assess the potential influence of mainstem-spawning fish on early run stock assessment.

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TABLES

Table 1.–Quantities required for brood year reconstruction of Kenai River early-run Chinook salmon.

Quantities	How obtained [a]	Details
Cook Inlet marine sport harvest	E	Fraction (5%) of SWHS estimate of harvest prior to 25 June.
Age composition of Cook Inlet marine sport harvest	I	Assumed equal to age composition of inriver run.
Commercial eastside setnet (ESSN) and cost-recovery harvest	E	Fish sales receipts: all harvest before 25 June assumed to originate from Kenai River early run.
Age composition of commercial ESSN harvest	E	Collection of age and sex samples at processors and buying stations.
Educational harvest	E	Reported directly to ADF&G.
Age composition of educational harvest	I	Assumed equal to age composition of inriver run.
Inriver run	E	Sonar; capture–recapture experiments at RM 9.
Age composition of inriver run	E	Netting project at RM 9.
Total run	D	Inriver run plus harvests before the sonar.
Age composition of total run	D	Age composition of inriver run plus age composition of harvests before the sonar.
Sport catch and harvest below Soldotna Bridge	E	Onsite creel survey.
Age composition of sport harvest below Soldotna Bridge	E	Age samples collected in onsite creel survey.
Sport catch and harvest above Soldotna Bridge	E	SWHS (mail survey).
Age composition of sport harvest above the Soldotna Bridge	I	Assumed equal to age composition of sport harvest below Soldotna Bridge.
Catch-and-release mortalities	I	Fraction (6%) of released fish estimated from creel survey.
Age composition of catch-and-release mortalities	I	Assumed equal to age composition of inriver run.
Escapement	D	Subtraction of all known inriver mortalities above RM 9 from the inriver run.
Age composition of the escapement	D	Subtraction of all known inriver mortalities (by age) from the inriver run (by age).

[a] E = estimated directly; I = imputed from other quantities; D = derived from other quantities.

Table 2.–Counts of annual early-run Chinook salmon passage for Kenai River tributary weirs, 1979–2012.

Year	Russian River	Quartz Creek	Slikok Creek	Funny River	Killey River[a]
1979	279				
1980	186				
1981	30				
1982	68	337			
1983	52	351			
1984	270	497			
1985	189				
1986	52				
1987	12				
1988	117				
1989	177				
1990	34				
1991	16				
1992	15				
1993	76				
1994	69				
1995	41				
1996	47				
1997	40				
1998	144				
1999	171				
2000	40				
2001	68				
2002	155				
2003	638				
2004	394				
2005	133				
2006	36			2,779	
2007	88			2,075	
2008	110		59	1,246	
2009	227		70	1,114	
2010	164		28	1,187	
2011	52		44	990	
2012	43		27	879	1,631

[a] Killey River weir was installed and operated approximately 20 RM upstream of the confluence with the Kenai River.

Table 3.–Estimated harvest below and above river mile 9 (RM 9), and age composition of inriver run at RM 9 for Kenai River early-run Chinook salmon, 1986–2012.

	Harvest and other mortality									Age composition proportions of inriver run at RM 9				
	Below RM 9					Above RM 9								
Year	Cook Inlet marine recr[a]	Misc marine[b,c,d]	Educ	Total	CV	Sport	Hook rel. mort.	Total	CV	3	4	5	6	7
1986	144	0		144	1.00	8,156	242	8,398	0.06	0.00	0.15	0.42	0.35	0.08
1987	181	0		181	1.00	13,557	306	13,863	0.07	0.00	0.02	0.38	0.57	0.03
1988	212	0		212	1.00	15,209	340	15,549	0.05	0.00	0.02	0.16	0.71	0.11
1989	193	0	73	266	0.73	8,394	149	8,543	0.06	0.00	0.04	0.15	0.71	0.09
1990	235	0	40	275	0.85	1,807	378	2,185	0.12	0.00	0.07	0.27	0.60	0.06
1991	241	0	2	243	0.99	1,945	152	2,097	0.11	0.00	0.07	0.22	0.65	0.05
1992	300	0	73	373	0.80	2,241	236	2,477	0.09	0.00	0.08	0.28	0.58	0.05
1993	407	0	118	525	0.78	9,342	286	9,628	0.05	0.00	0.04	0.28	0.64	0.04
1994	343	0	56	399	0.86	8,171	285	8,456	0.05	0.00	0.04	0.20	0.71	0.05
1995	412	0	37	449	0.92	10,217	357	10,574	0.05	0.00	0.05	0.20	0.70	0.05
1996	235	0	14	249	0.94	6,623	287	6,910	0.06	0.00	0.08	0.29	0.61	0.02
1997	282	0	141	423	0.67	6,429	349	6,778	0.10	0.00	0.04	0.35	0.60	0.01
1998	289	0	122	411	0.70	1,170	254	1,424	0.14	0.00	0.19	0.37	0.41	0.03
1999	245	0	114	359	0.68	8,129	261	8,390	0.06	0.00	0.08	0.54	0.38	0.00
2000	239	0	124	363	0.66	1,818	185	2,003	0.12	0.00	0.09	0.44	0.47	0.01
2001	184	0	198	382	0.48	2,399	204	2,603	0.10	0.00	0.17	0.28	0.53	0.02
2002	168	0	64	232	0.73	899	78	977	0.15	0.04	0.16	0.37	0.40	0.04
2003	202	0	46	248	0.81	2,839	389	3,228	0.16	0.01	0.31	0.20	0.47	0.01
2004	194	0	89	283	0.69	3,386	257	3,643	0.11	0.01	0.15	0.33	0.47	0.04
2005	187	341	76	604	0.31	3,810	253	4,063	0.10	0.01	0.12	0.30	0.53	0.04
2006	252	0	75	327	0.77	4,693	205	4,898	0.09	0.01	0.31	0.19	0.46	0.04
2007	201	41	16	258	0.78	3,493	220	3,713	0.14	0.00	0.26	0.28	0.43	0.03
2008	107	102	40	249	0.43	3,500	123	3,623	0.07	0.00	0.14	0.42	0.42	0.02
2009	71	16	49	136	0.52	1,466	97	1,563	0.12	0.03	0.15	0.24	0.56	0.02
2010	88	48	32	168	0.52	1,337	90	1,427	0.10	0.07	0.25	0.47	0.20	0.00
2011	110	0	42	152	0.72	1,337	92	1,429	0.14	0.02	0.26	0.31	0.41	0.01
2012	89	0	14	103	0.86	316	10	326	0.29	0.05	0.09	0.36	0.48	0.01

[a] Cook Inlet marine recreational harvest; assumes 5% of harvest is of Kenai-origin fish.

[b] For 2005, number reflects eastside setnet catch before 25 June.

[c] For 2007–2010, numbers reflect ADF&G cost recovery catch before 25 June.

[d] Some of these fish may originate from either the Kasilof River or the Kenai River late run.

Table 4.–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 distributions 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, NCP75	Perschbacher 2012 a-b	2002–2012, 1998-2000	Catch rate of king salmon from gillnets drifted inriver at the sonar site.	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 a-b	2002–2012	Mean daily catch rate of Chinook salmon from inriver sport fishery, from creel survey interviews.	Independent of sonar. Sensitive to changes in regulations and fishing conditions.
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
State space model estimates of late run abundance	N^LR	Fleischman and McKinley 2013	1986-2012	Late run total annual abundance as estimated using a state-space model similar to the one described in this report.	Provides inference for 1986-2001. Assumes stable relationship between early- and late runs.
Genetic capture–recapture estimates	CRGEN	Appendix C	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. Possibly subject to bias; methods currently under development.

Table 5.–Values of annual abundance measures used to reconstruct historical run size, Kenai River early-run Chinook salmon, 1986–2012.

Year	NCPUE	NASB	SCPUE	N^LR	ELSD	NCP75	DIDSON[a]	CR[a]
1986				78,120				27,080 (0.36)
1987				82,190				25,643 (0.23)
1988				72,940				
1989				44,800				
1990				38,550				
1991				44,000				
1992				51,800				
1993				62,130				
1994				60,140				
1995				55,660				
1996				52,900				
1997				51,640				
1998				52,310		1.5		
1999				52,840		2.2		
2000				52,110		1.1		
2001				60,700				
2002	2.0	6,132	0.019	66,400	5,210			
2003	5.6	12,657	0.049	97,690	13,147			
2004	3.8	17,998	0.060	99,690	13,633			
2005	3.8	12,334	0.070	96,970	13,686			
2006	2.8	7,449	0.048	74,310	13,071			
2007	2.6	4,516	0.049	60,100	8,716			13,010 (0.18)
2008	2.0	4,822	0.040	51,010	6,560			8,636 (0.11)
2009	1.2	2,834	0.021	36,890	4,428			10,580 (0.21)
2010	1.3	2,644	0.026	30,050			5,376 (0.18)	8,347 (0.14)
2011	1.7	4,041	0.027	35,780			6,515 (0.04)	9,267 (0.16)
2012	0.8	1,668		28,550			3,339 (0.05)	6,513 (0.13)

Note: Abbreviations defined in Table 4. Coefficient of variation listed in parentheses.

[a] DIDSON and recent CR (2007-2012) estimates are preliminary and subject to revision until published.

Table 6.–Parameter estimates for state-space model fitted to Kenai River early-run 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
$\ln(\alpha)$	1.84	1.07	2.45	0.25
α	6.3	2.9	11.6	0.73
β	0.000157	0.000108	0.000216	0.21
ϕ	0.70	0.17	0.96	0.38
σ_W	0.30	0.18	0.49	0.31
S_{MAXR}	6,362	4,634	9,240	0.21
S_{EQ}	12,270	9,204	17,950	0.21
S_{MSY}	4,434	3,368	5,956	0.17
U_{MSY}	0.71	0.53	0.84	0.14
D	38	25	60	0.28
π_3	0.03	0.02	0.04	0.31
π_4	0.21	0.17	0.25	0.11
π_5	0.31	0.27	0.35	0.08
π_6	0.41	0.36	0.45	0.07
π_7	0.04	0.03	0.06	0.23
p_{MR}	0.65	0.57	0.74	0.08
p_{MR}^{-1}	1.55	1.36	1.76	0.08
q_{NCPUE}	2.7E-04	2.3E-04	3.2E-04	0.10
q_{NASB}	0.70	0.57	0.86	0.13
q_{SCPUE}	2.8E-06	2.3E-06	3.4E-06	0.12
q_{ELSD}	0.95	0.79	1.14	0.11
$q_{N\hat{}LR}$	4.2	3.7	4.8	0.08
q_{NCP75}	1.7E-04	1.3E-04	2.4E-04	0.19
σ_{NCPUE}	0.22	0.14	0.34	0.28
σ_{NASB}	0.32	0.21	0.51	0.28
σ_{SCPUE}	0.26	0.16	0.44	0.33
σ_{ELSD}	0.15	0.05	0.32	0.51
$\sigma_{N\hat{}LR}$	0.25	0.21	0.30	0.11
σ_{NCP75}	0.22	0.14	0.34	0.28
ρ_3	0.004	0.000	0.025	1.31
ρ_4	0.094	0.068	0.132	0.20
ρ_5	0.269	0.213	0.334	0.14
ρ_6	0.404	0.333	0.479	0.11
ρ_7	0.215	0.139	0.328	0.26

Table 7.–Posterior medians of key quantities from base and alternate configurations of state-space model of the abundance of Kenai River early-run Chinook salmon.

		Alternative model and data configurations				
		1a [a]	1b [b]	2 [c]	3 [d]	4 [e]
	Base Model	*pMR = 0.8*	*pMR = 0.5*	2002–2012 Data only	TAM	Flat prior on $\sigma_{N^{\wedge}LR}$
α	6.3	6.3	5.9	**1.93**	**4.8**	6.4
β	1.6E-04	1.7E-04	1.5E-04	**7.8E-05**	1.5E-04	1.6E-04
σ_w	0.30	0.33	0.29	**0.46**	**0.40**	**0.36**
ϕ	0.70	0.73	0.67	**0.23**	**0.77**	0.69
S_{EQ}	12,270	**11,300**	**12,820**	**10,580**	11,900	12,540
S_{MSY}	4,434	**4,051**	**4,697**	4,436	4,373	4,441
D	38	38	38	34	**63**	**54**
p_{MR}	0.65	**0.77**	**0.54**	0.66	0.66	0.66

Note: Noteworthy differences are in bold.

[a] Informative prior with mean 0.8 on p_{MR}.

[b] Informative prior with mean 0.5 on p_{MR}.

[c] 1986–2001 data omitted.

[d] Trending age-at-maturity model

[e] Non-informative prior on $\sigma_{N^{\wedge}LR}$

Table 8.–Parameter estimates for state-space model fitted to Kenai River early-run 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				22,160 (0.75)
1980				11,500 (0.30)
1981				25,100 (0.18)
1982				29,500 (0.12)
1983				14,130 (0.15)
1984				9,292 (0.19)
1985				10,790 (0.18)
1986	20,310 (0.15)	20,100 (0.16)	11,670 (0.27)	10,490 (0.17)
1987	22,020 (0.14)	21,750 (0.14)	7,774 (0.40)	13,430 (0.14)
1988	20,110 (0.11)	19,800 (0.11)	4,295 (0.47)	15,350 (0.14)
1989	12,640 (0.14)	12,290 (0.15)	3,734 (0.46)	12,910 (0.13)
1990	10,210 (0.20)	9,842 (0.21)	7,637 (0.27)	10,460 (0.16)
1991	11,000 (0.18)	10,620 (0.18)	8,500 (0.23)	11,300 (0.16)
1992	12,430 (0.17)	11,930 (0.18)	9,444 (0.23)	10,220 (0.16)
1993	13,230 (0.14)	12,490 (0.14)	2,766 (0.58)	9,925 (0.16)
1994	13,700 (0.14)	13,160 (0.15)	4,691 (0.40)	16,000 (0.14)
1995	13,430 (0.11)	12,890 (0.11)	2,359 (0.50)	12,330 (0.16)
1996	10,240 (0.19)	9,764 (0.20)	2,687 (0.64)	11,290 (0.18)
1997	11,660 (0.15)	11,140 (0.16)	4,371 (0.39)	19,960 (0.14)
1998	12,440 (0.16)	11,930 (0.17)	10,480 (0.19)	18,670 (0.14)
1999	13,920 (0.13)	13,480 (0.14)	5,103 (0.35)	26,620 (0.12)
2000	11,240 (0.17)	10,790 (0.18)	8,764 (0.22)	19,730 (0.12)
2001	14,450 (0.17)	14,020 (0.18)	11,400 (0.22)	13,180 (0.12)
2002	11,280 (0.17)	10,860 (0.18)	9,866 (0.19)	14,520 (0.11)
2003	20,770 (0.12)	20,450 (0.13)	16,960 (0.16)	11,770 (0.10)
2004	23,800 (0.12)	23,460 (0.12)	19,850 (0.14)	5,419 (0.13)
2005	21,450 (0.11)	20,810 (0.11)	16,650 (0.14)	9,047 (0.10)
2006	18,580 (0.11)	18,180 (0.11)	13,270 (0.16)	8,318 (0.11)
2007	13,950 (0.09)	13,630 (0.10)	9,856 (0.14)	8,949 (0.19)
2008	10,490 (0.08)	10,210 (0.08)	6,570 (0.14)	7,282 (0.38)
2009	7,903 (0.10)	7,741 (0.10)	6,163 (0.14)	9,238 (0.47)
2010	8,021 (0.09)	7,830 (0.09)	6,393 (0.11)	
2011	10,070 (0.08)	9,895 (0.08)	8,448 (0.10)	
2012	5,605 (0.09)	5,387 (0.08)	5,044 (0.09)	

FIGURES

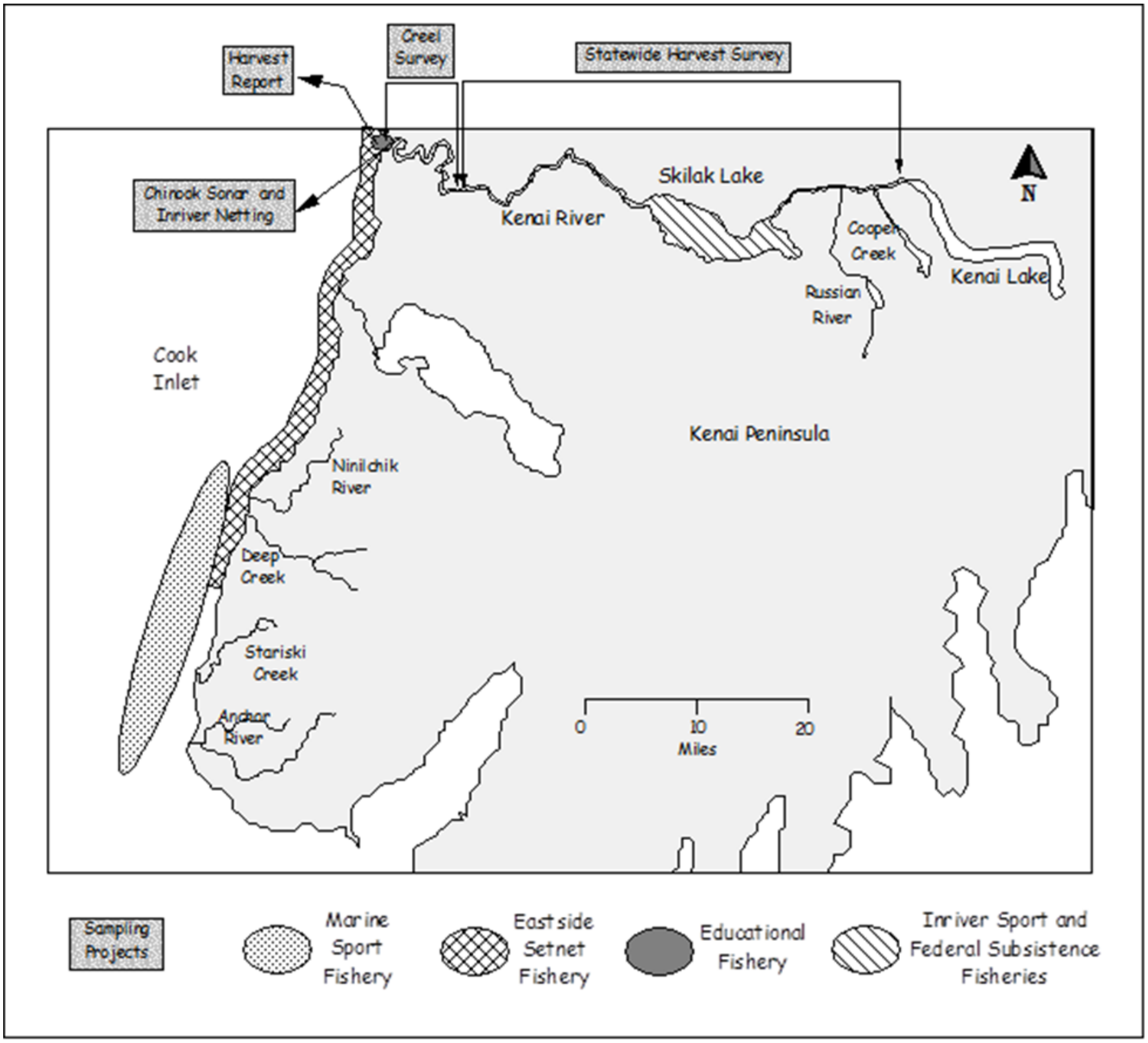


Figure 1.–Kenai River drainage, and fisheries and sampling programs for Kenai River early-run Chinook salmon.

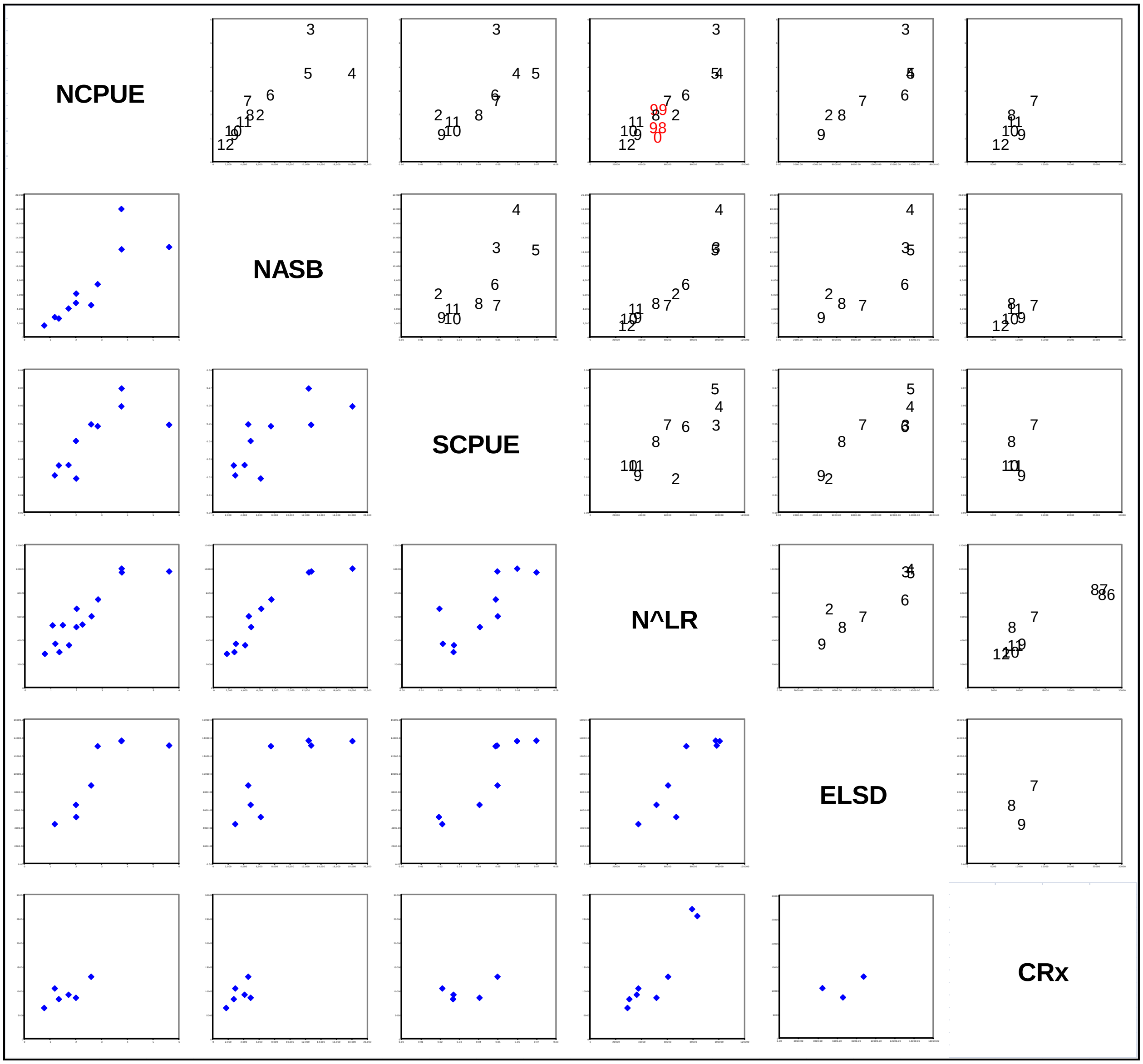


Figure 2.–Scatter plot matrix of key abundance measures for Kenai River early-run Chinook salmon, 1986–2012. Acronyms are defined in Table 4. CRx includes CRTRA and CRGEN. NCPUE includes NCP75 for 1998–2000, plotted in red font.

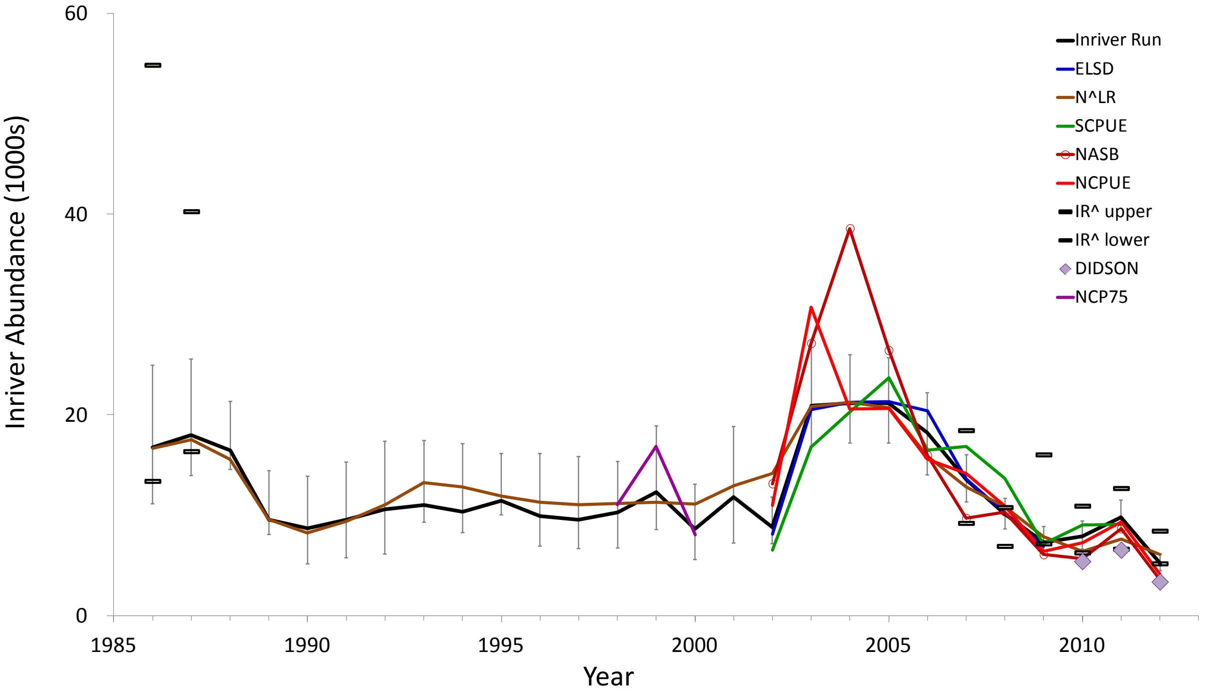


Figure 3.–Intermediate results from the run reconstruction component of the state-space model for Kenai River early-run Chinook salmon, illustrating how inriver run abundance (black line with error bars) was reconstructed from six measures of relative abundance: inriver gillnet catch rate (NCPUE, NCP75), split-beam sonar salmon abundance apportioned by Chinook salmon fraction in test gillnets (NASB), catch rate in the lower-river sport fishery (SCPUE), late-run Chinook salmon abundance (N^LR), and split-beam sonar estimates of Chinook salmon passage based on echo-length standard deviation (ELSD); plus estimates (IR^) of inriver abundance (capture–recapture estimates CRTRA and CRGEN) and estimates of midriver run from imaging sonar (DIDSON point estimates, 2010–2012). For plotting, relative abundance measures were converted to number of inriver Chinook salmon based on the relationships in Figure 4. Values of inriver run plotted here differ from state-space model estimates, which are subject to the additional influence of the spawner–recruit and age-at-maturity relationships.

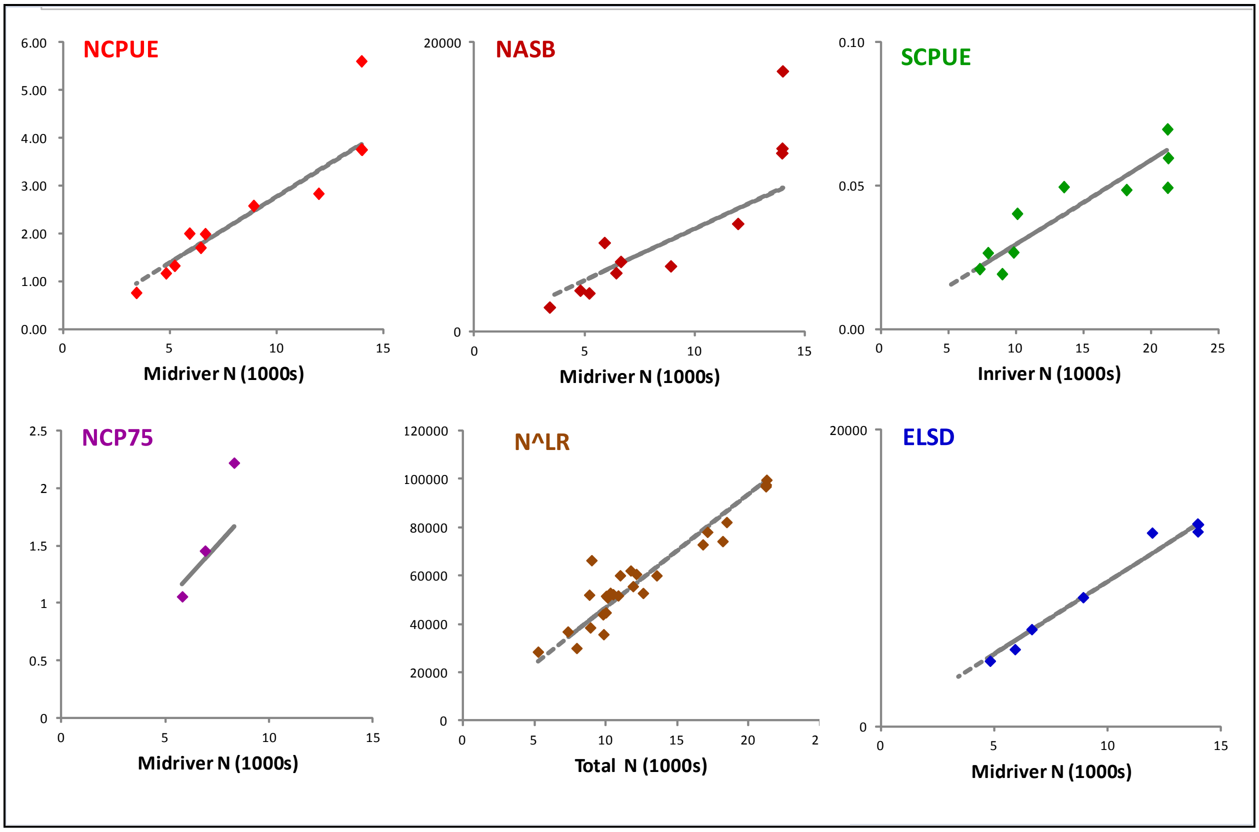


Figure 4.–Linear relationships between abundance measures and model-based point estimates of abundance, from state-space model of Kenai River Chinook salmon early-run data, 1986–2012. Slopes q and error standard deviations σ of these relationships are listed in Table 6.

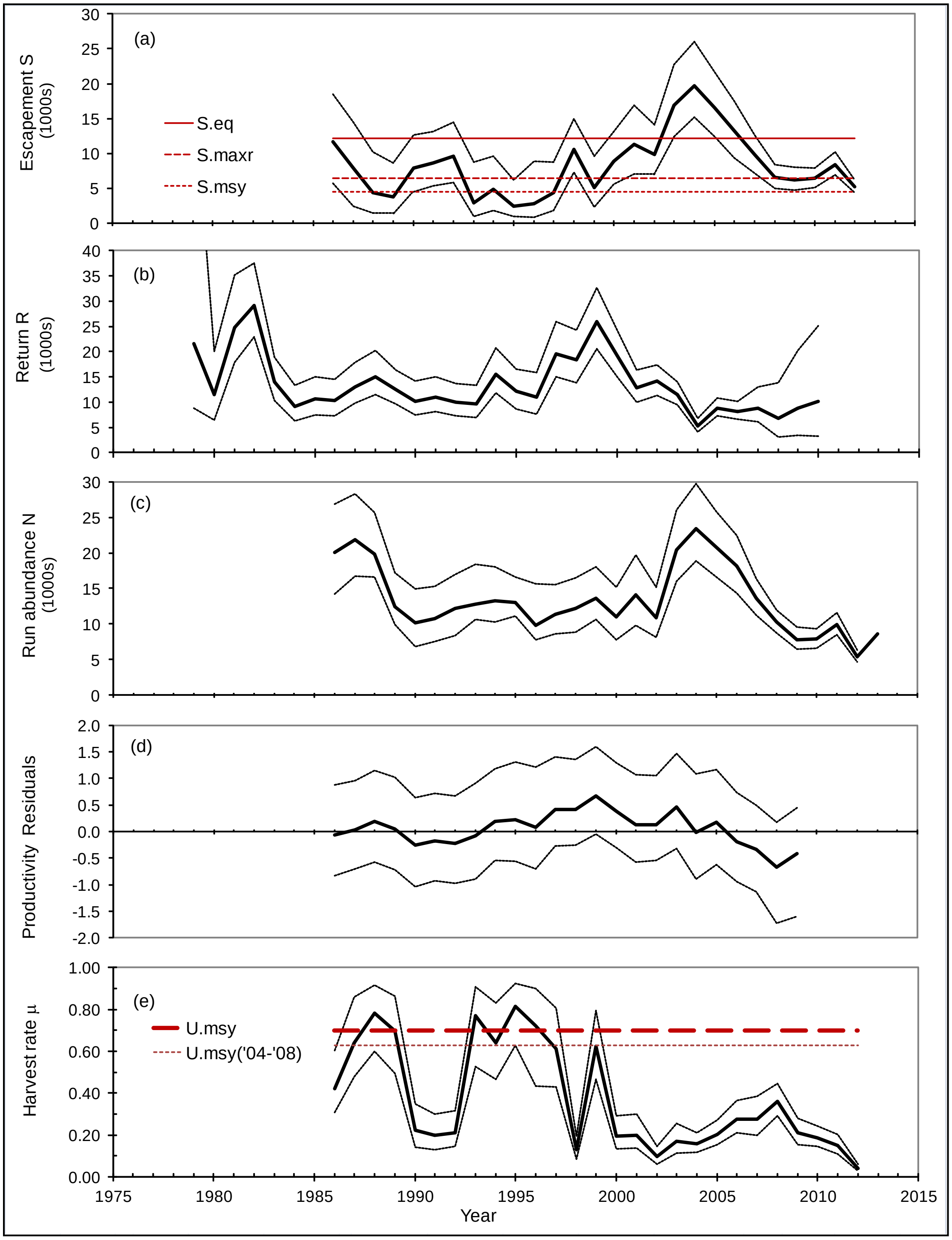
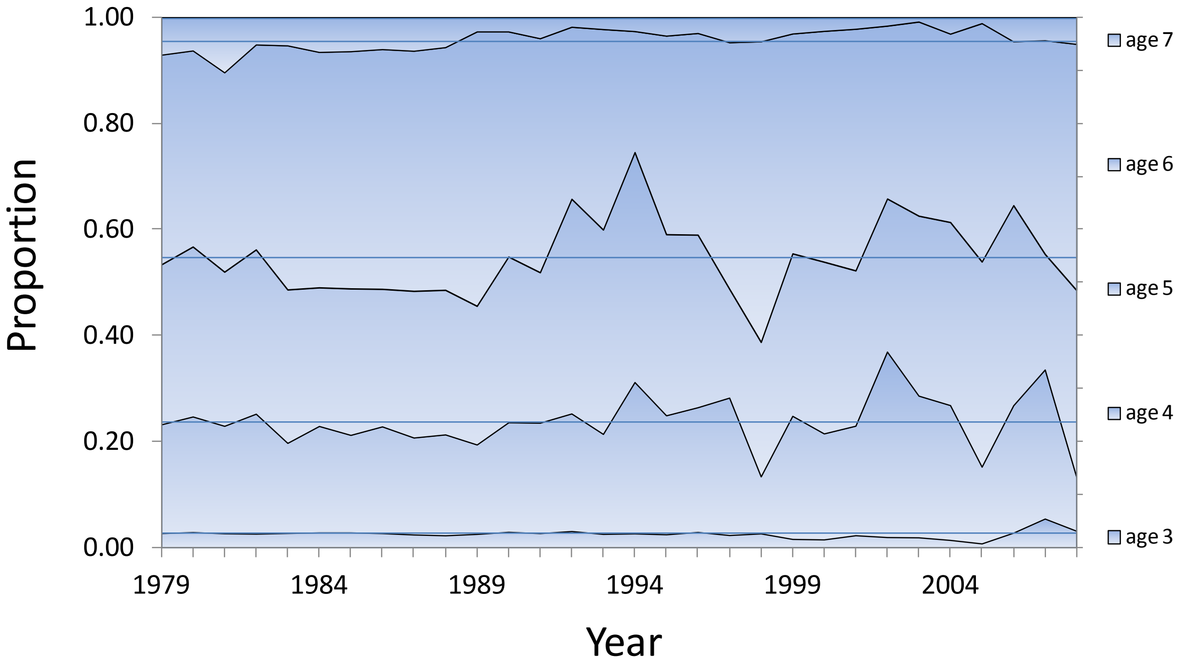


Figure 5.–Point estimates (posterior medians; solid lines) and 95% credibility intervals (lighter dashed lines) of (a) spawning escapement, (b) recruitment by brood year, (c) run abundance, (d) productivity residuals and (e) harvest rate from a state-space model of Kenai River early-run Chinook salmon, 1986–2012. Posterior medians of $S_{EQ,}$ S_{MAXR}, S_{MSY}, and U_{MSY} are plotted as horizontal reference lines in (a) and (e). U_{MSY} for recent brood years (2004–2008) is also plotted in (e).



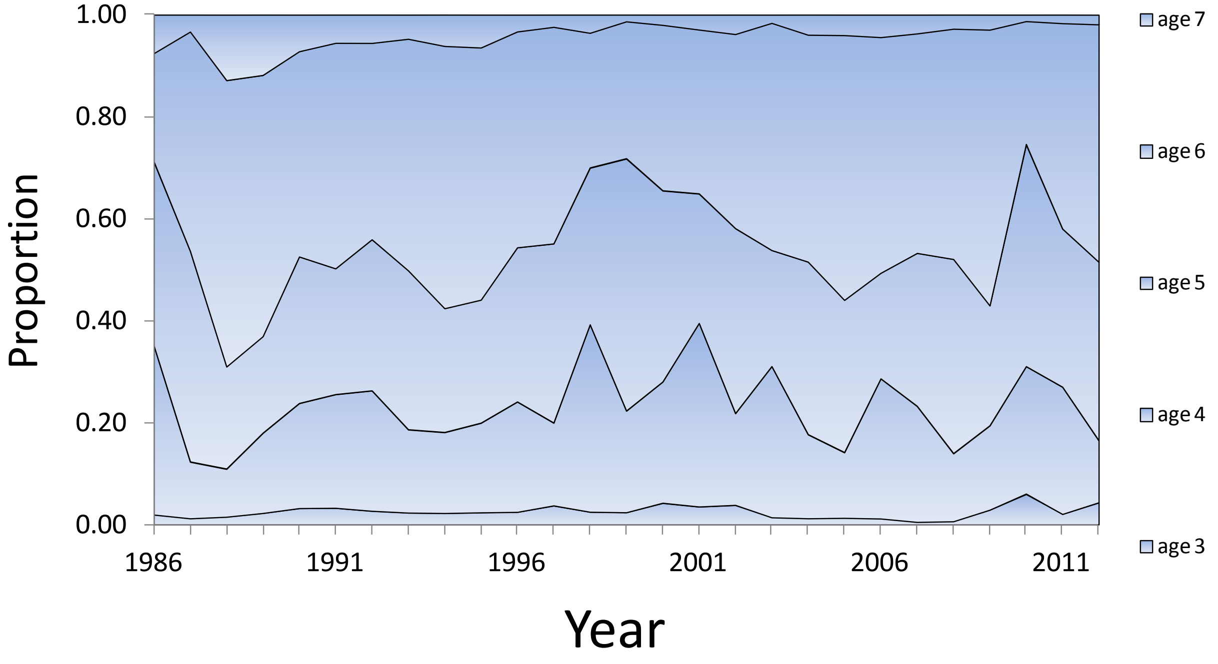


Figure 6.–Area graphs of age-at-maturity proportions by brood year (top), and age composition proportions by calendar year (bottom) from age-structured state-space model fit to Kenai River early-run Chinook salmon data. Distances between the solid lines are posterior medians of proportions. Horizontal lines in top figure are posterior medians of age-at-maturity central tendency proportions π_a.

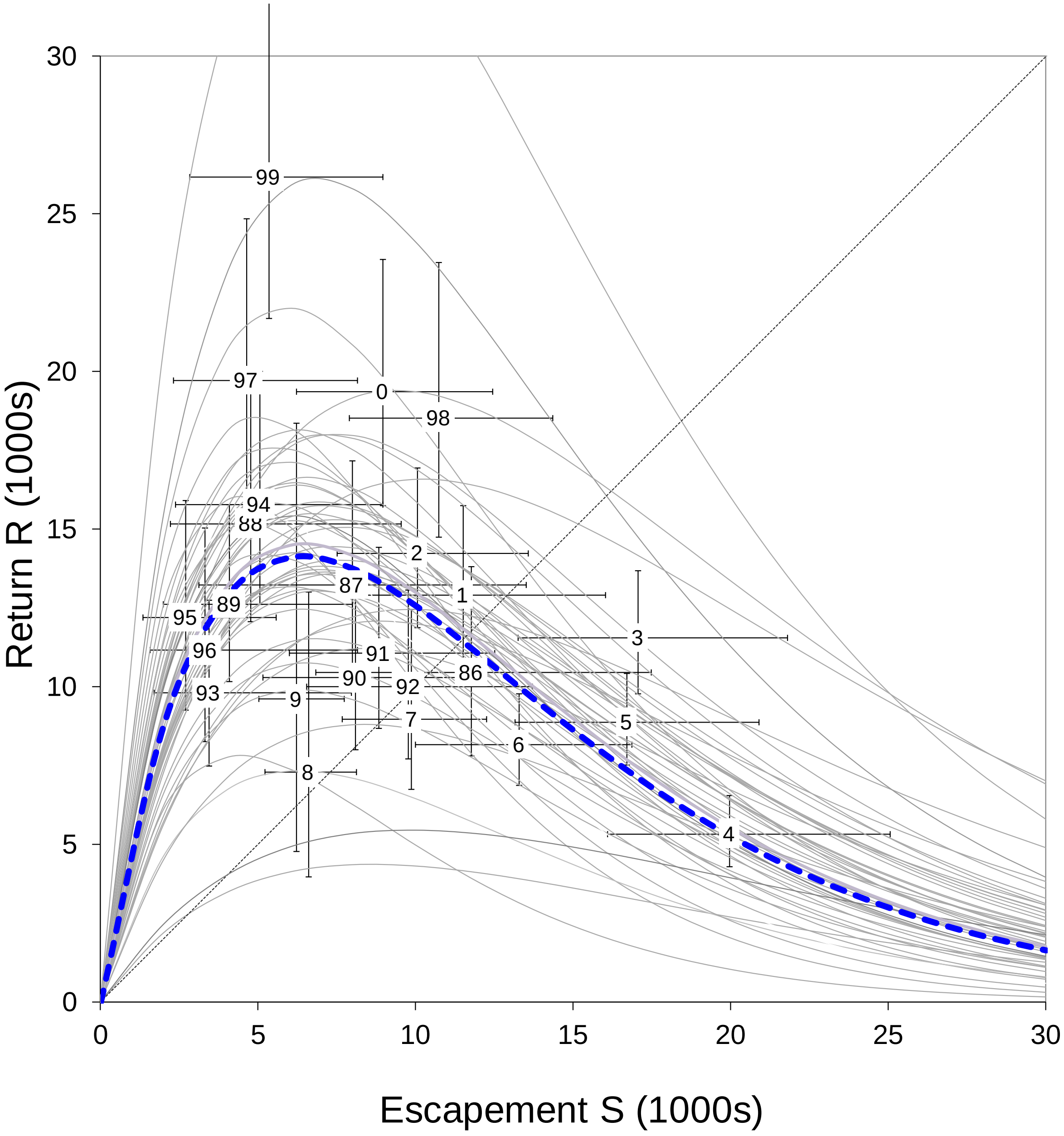


Figure 7.–Plausible spawner–recruitment relationships for Kenai River early-run Chinook salmon as derived from an age-structured state-space model fitted to abundance, harvest, and age data for 1986–2012. Posterior medians of *R* and *S* are plotted as brood year labels; error bars bracket 90% credibility 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*).

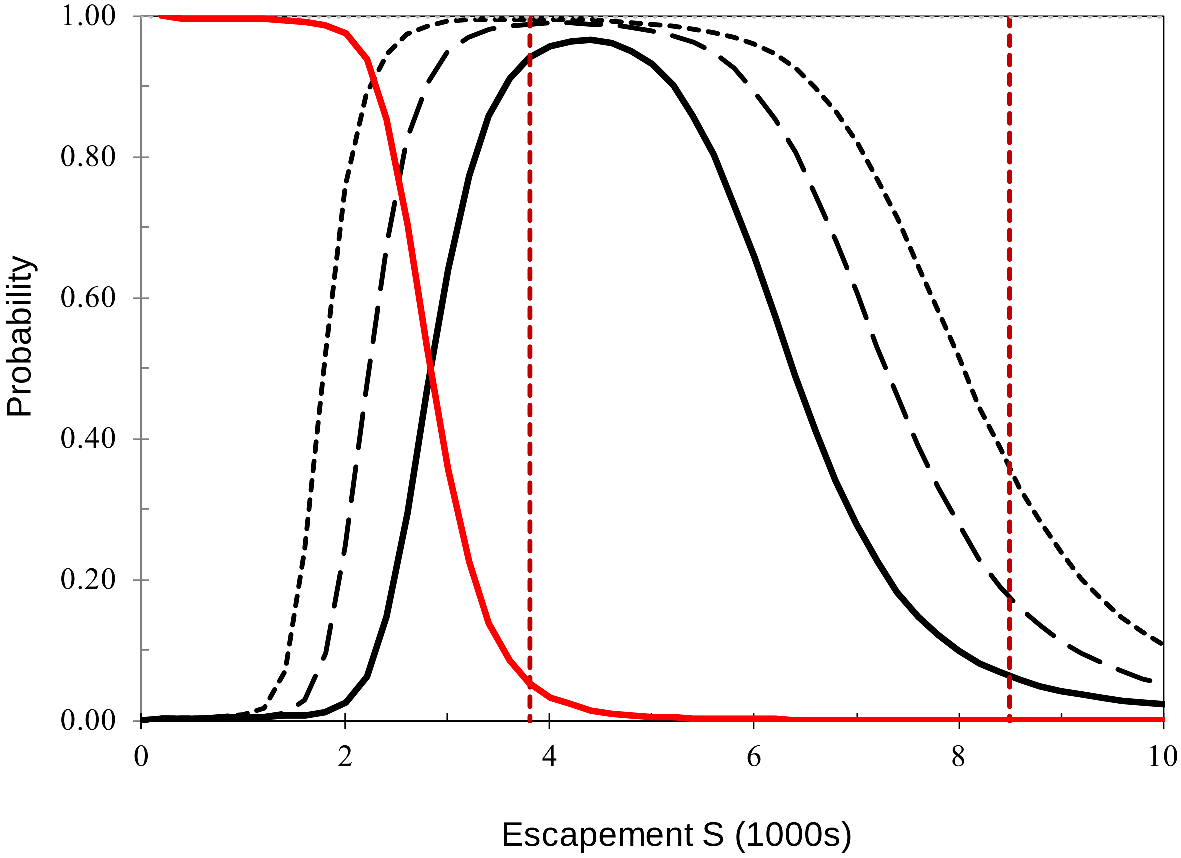


Figure 8.–Optimal yield profiles (OYPs) and overfishing profile (OFP) for Kenai River early-run Chinook salmon. OYPs (black dome-shaped profiles) show probability that a specified spawning abundance will achieve 70% (short dashes), 80% (long dashes), and 90% (solid line) of maximum sustained yield MSY. OFP (solid red declining line) is the probability that reducing the escapement to a specified spawning abundance will result in less than 90% of MSY. Vertical dashed red lines show recommended escapement goal range.

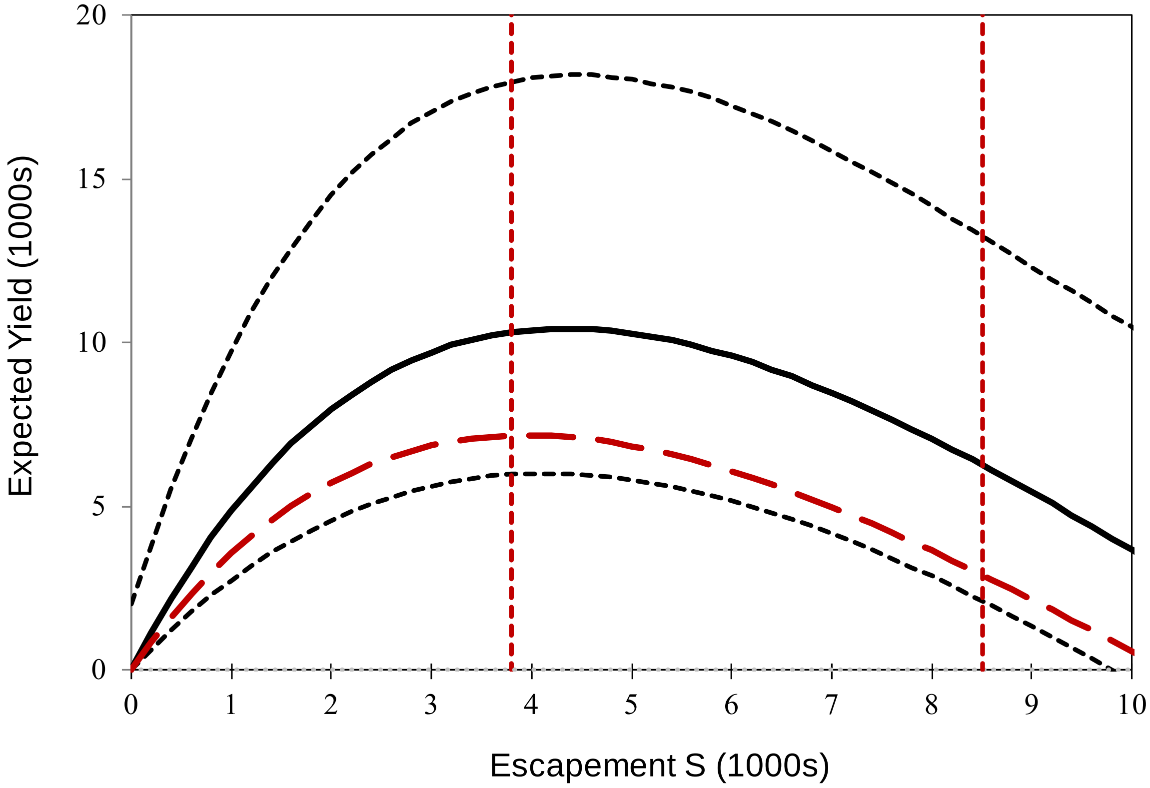


Figure 9.–Expected sustained yield (solid black line), and 80% interval (short dashed black lines) versus spawning escapement for Kenai River early-run Chinook salmon, assuming average productivity for brood years 1979–2008. Red vertical lines bracket recommended escapement goal range. Expected sustained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

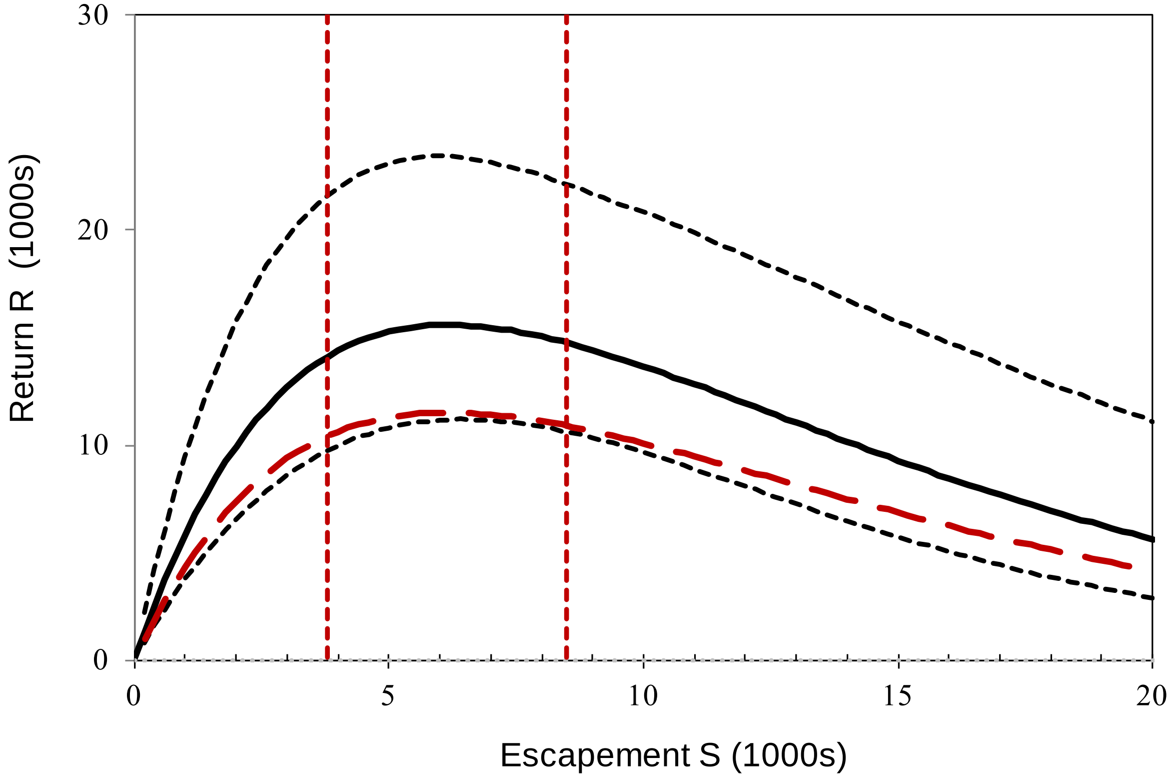


Figure 10.–Posterior median of expected recruitment (solid line), and 80% interval (dashed lines) as a function of spawning escapement for Kenai River early-run Chinook salmon. Model assumes average productivity for brood years 1979–2008. Expected recruitment under recent, reduced productivity (brood years 2004–2008) is also shown (long dashed red line). Vertical red lines bracket the recommended escapement goal range.

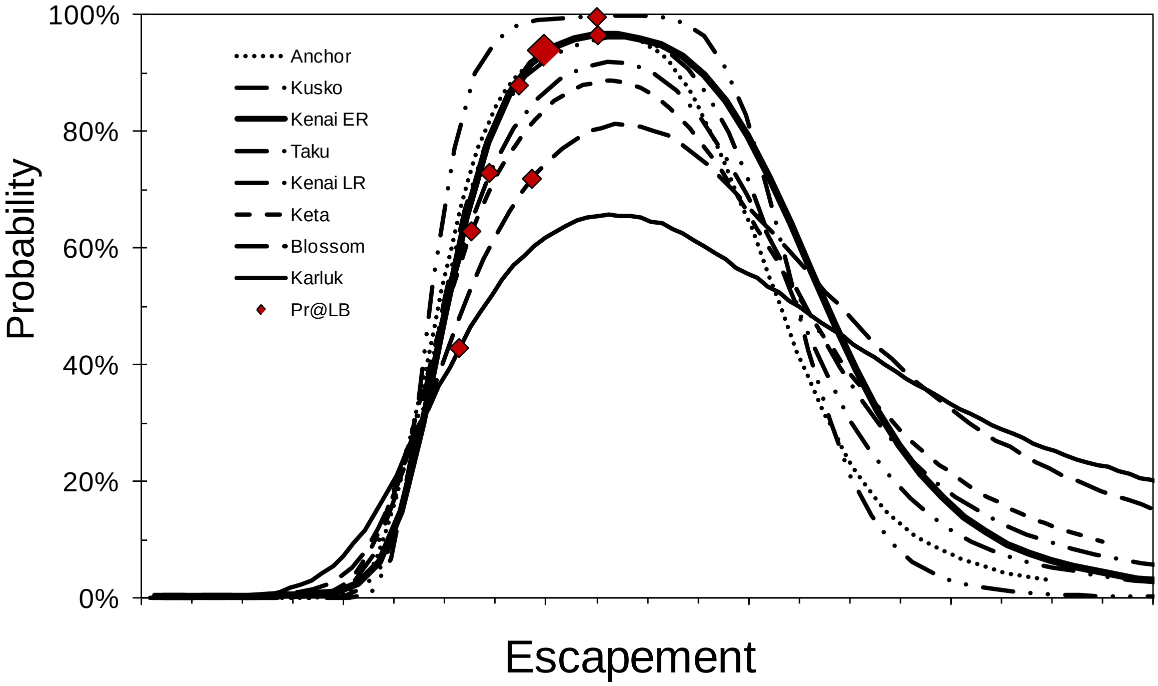


Figure 11.–Optimal yield profiles (OYPs; probability of achieving 90% of MSY) from similar state-space analyses of Chinook salmon data from Anchor River (Szarzi et al. 2007), Blossom River (Fleischman et al. 2011), Karluk River (Fleischman et al. *In press*), late-run Kenai River (Fleischman and McKinley 2013), Keta River (Fleischman et al. 2011), Kuskokwim River (Hamazaki et al. 2012), and Taku River (McPherson et al. 2010). The 90% OYP for Kenai River early-run Chinook salmon from Figure 8 is in bold. Symbols represent probability of 90% yield at the lower bound of the escapement goal. Horizontal axis scales were adjusted to align profiles and facilitate comparisons.

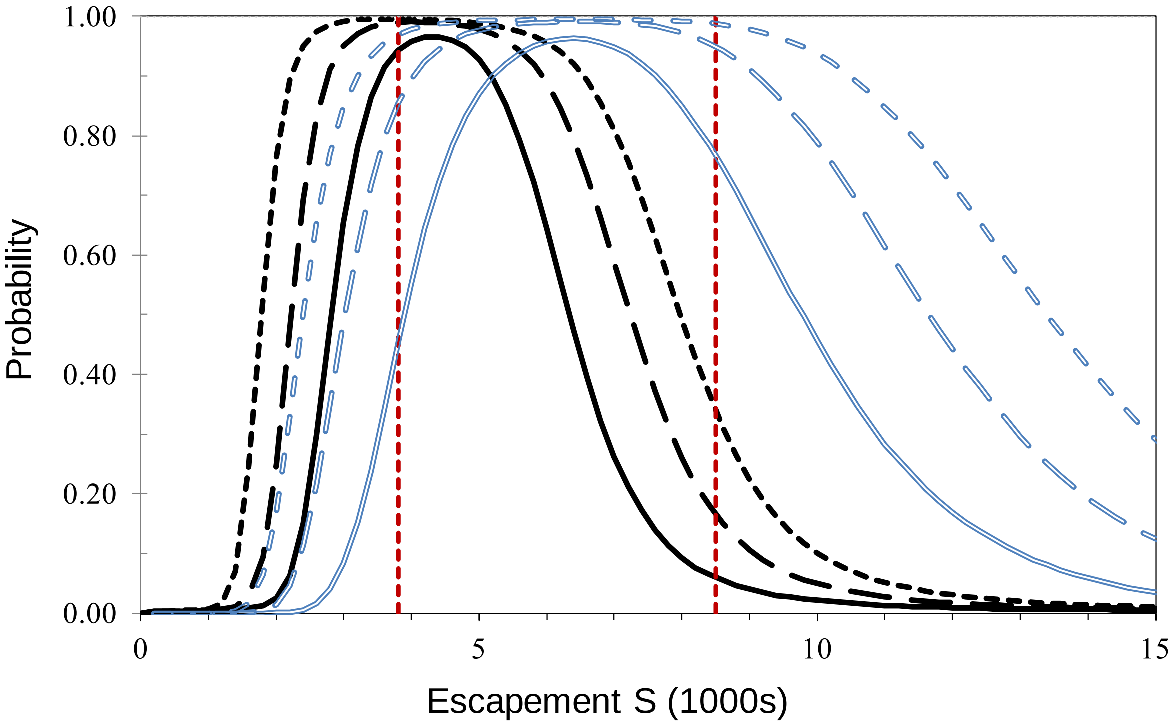


Figure 12.–Optimal yield profiles (OYPs; dark solid or dashed lines from Figure 8) and optimal recruitment profiles (lighter lines) for Kenai River early-run Chinook salmon, based on a state-space model fitted to 1986–2012 data. Vertical lines show recommended escapement goal range.

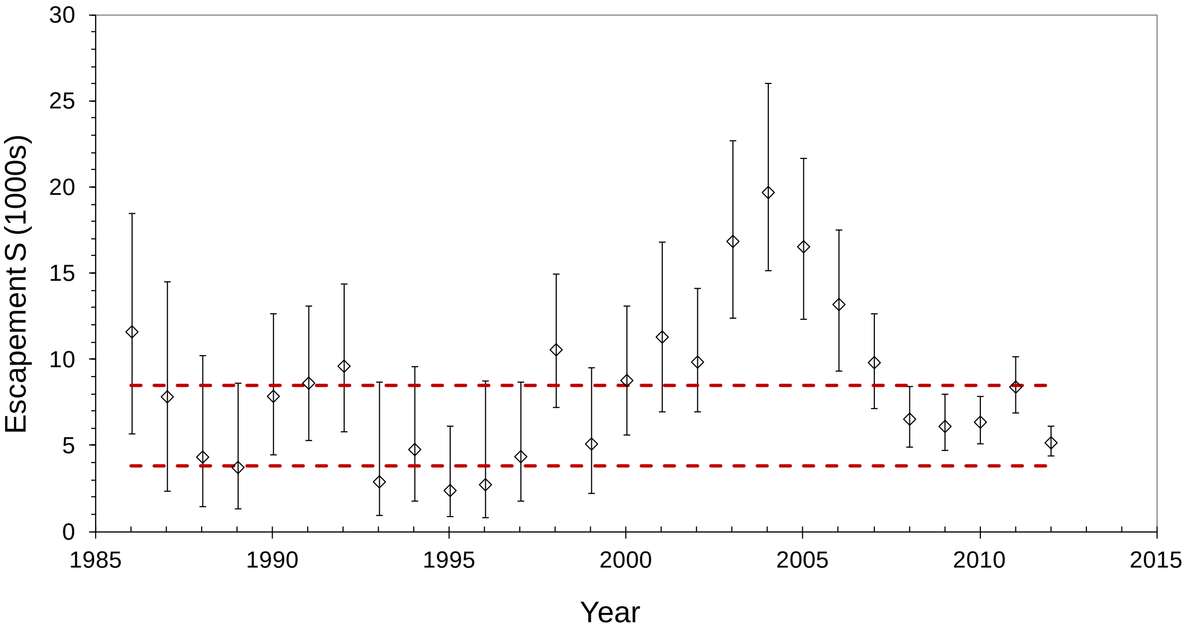


Figure 13.–Historical estimates of escapement and 95% credibility intervals obtained by fitting a state-space model to Kenai River early-run Chinook salmon data, 1986–2012. Horizontal dotted lines bracket the recommended escapement goal range.

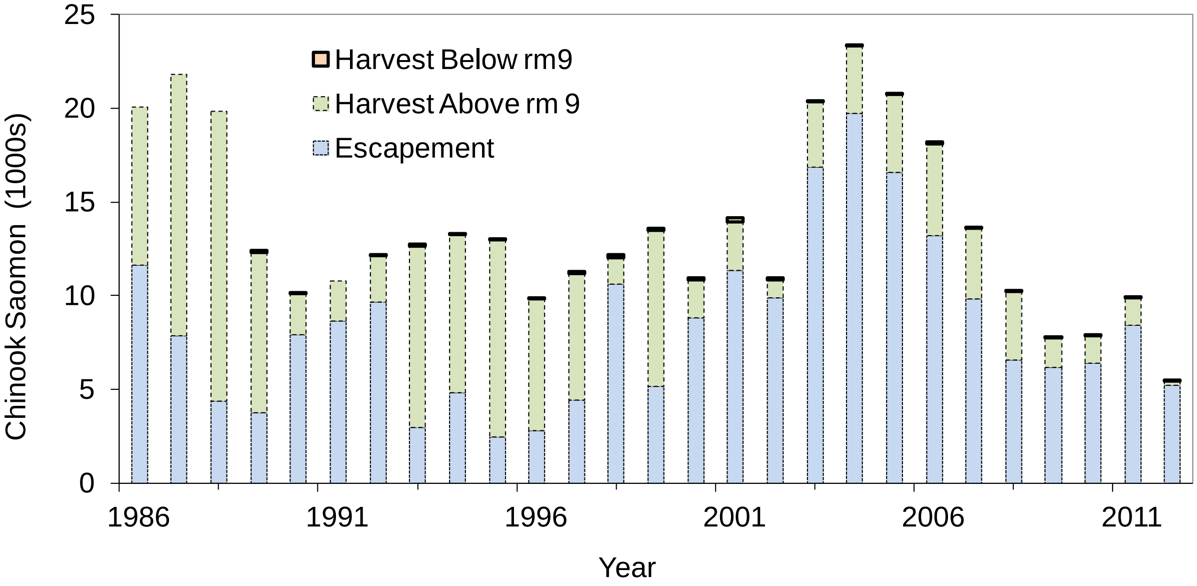


Figure 14.–Posterior medians of spawning escapement (bottom, blue bars, dotted outline), harvest above RM 9 (middle, green bars, dashed outline) and harvest below RM 9 (top, orange bars, solid outline) from 1986 to 2012 obtained from fitting a state-space model to Kenai River early-run Chinook salmon data.

APPENDIX A: OPENBUGS CODE AND DATA

Appendix A1.–OpenBUGS model code for state-space model of Kenai River early-run 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 MATURITY SCHEDULES, ONE PER BROOD YEAR
 D.scale ~ dunif(0,1)
 D.sum <- 1 / (D.scale * D.scale)  #D.sum is D in text of report
 pi[1] ~ dbeta(1,1)
 pi.2p ~ dbeta(1,1)
 pi.3p ~ dbeta(1,1)
 pi.4p ~ dbeta(1,1)
 pi[2] <- pi.2p * (1 - pi[1])
 pi[3] <- pi.3p * (1 - pi[1] - pi[2])
 pi[4] <- pi.4p * (1 - pi[1] - pi[2] - pi[3])
 pi[5] <- 1 - pi[1] - pi[2] - pi[3] - pi[4]
for (a in 1:A) {
```

-continued-

Appendix A1.–Part 2 of 4.

```
  gamma[a] <- D.sum * pi[a]
  for (y in 1:Y+A-1) {
      g[y,a] ~ dgamma(gamma[a],0.5)
      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=Y IS THE BROOD YEAR OF THE YOUNGEST FISH IN YEAR Y (lower left cell, forecast year)
# ASSIGN PRODUCT OF P AND R TO ALL CELLS IN N MATRIX (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]
            }
        }

# APPLY SELECTIVE CATCHES BY ONE AND TWO MESH TEST FISHERIES
    select.raw[1] ~ dnorm(1,1.0E-2)I(0,)
    select.raw[2] ~ dnorm(1,1.0E-2)I(0,)
    select.raw[3] ~ dnorm(1,1.0E-2)I(0,)
    select.raw[4] ~ dnorm(1,1.0E-2)I(0,)
    select.raw[5] <- 1
    select.two[1] <- 1
    select.two[2] <- 1
    select.two[3] <- 1
    select.two[4] <- 1
    select.two[5] <- 1
    for (t in 1:Y) {
      for (a in 1:A) {
        adj.one[t,a] <- N.ta[t,a] * select.one[a]
        adj.two[t,a] <- N.ta[t,a] * select.two[a]
        } }
    for (a in 1:A) { select.one[a] <- select.raw[a] / sum(select.raw[]) }

# OBSERVE AGE COMPOSITION
    for (t in 1:Y) {
      N[t] <- sum(N.ta[t,1:A])
      n[t] <- sum(x[t,])
      for (a in 1:A) {
        q[t, a] <- N.ta[t,a] / N[t]
        q1[t,a] <- adj.one[t,a] / sum(adj.one[t,])
        q2[t,a] <- adj.two[t,a] / sum(adj.two[t,])
        }
      }
for (t in 1:16) {
  x[t, 1:A] ~ dmulti(q1[t, ], n[t])
  }
for (t in 17:28) {
  x[t, 1:A] ~ dmulti(q2[t, ], n[t])
  }

p.MR ~ dnorm(0.5,1.0E-4)I(0.01,0.99)  # proportion migrating midriver,
p.MR.inv <- 1 / p.MR
```

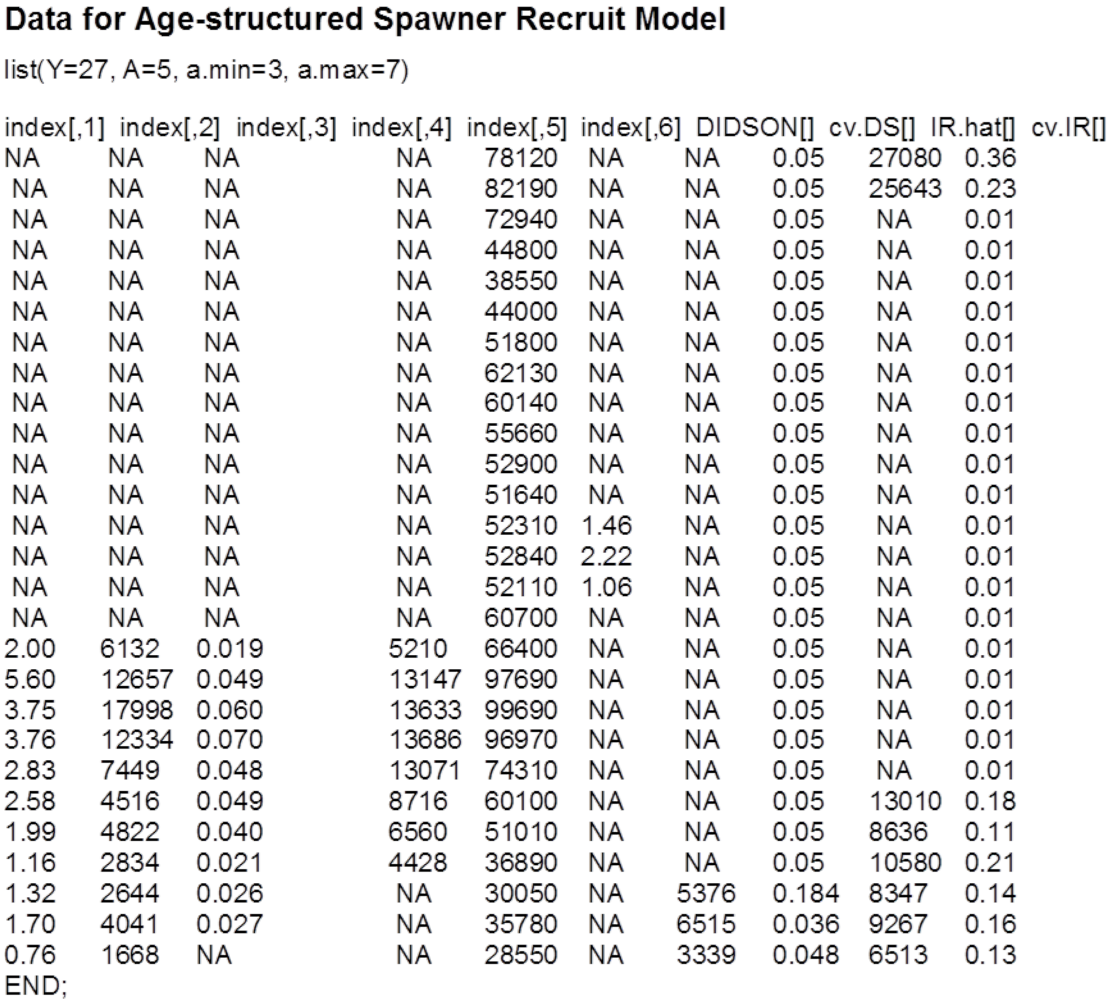
-continued-

```
for (y in 1:Y) {
 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)

 #FOR SOME YEARS, OBSERVE DIRECT ESTIMATE OF IR
 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])

 #DIDSON DETECTS FRACTION P.MR OF IR
 Midriver.Run[y] <- p.MR * 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])
 }

 tau.i[1] ~ dgamma(0.001,0.001)
 tau.i[2] ~ dgamma(0.001,0.001)
 tau.i[3] ~ dgamma(0.001,0.001)
 tau.i[4] ~ dgamma(0.001,0.001)
 tau.i[5] ~ dgamma(10,1)   # INFORMATIVE PRIOR, SIGMA 0.3
 tau.i[6] <- tau.i[1]
 for(i in 1:5) {
  log.q[i] ~ dnorm(0,1.0E-4)
  r.i[i] <- 1.0
  sigma.i[i] <- 1 / sqrt(tau.i[i])
  q.i[i] <- exp(log.q[i])    # q.i is theta in text of report
  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(Midriver.Run[y],r.i[4]))
  log.qiNri[y,5] <- log(q.i[5] * pow(N[y],r.i[5]))
  log.qiNri[y,6] <- log(q.i[6] * pow(N.old[y],r.i[6]))
  N.old[y] <- sum(N.ta[y,3:5])
  }
```

Appendix A1.–Part 4 of 4.

```
# CALCULATE SUSTAINED YIELD AT REGULAR INTERVALS OF S;
# FIND PROBABILITY S* WILL PROVIDE YIELDS WITHIN X% OF ;
R.msy <- S.msy * exp(lnalpha - beta * S.msy)*exp(sigma.red*sigma.red/2)
MSY <- R.msy - S.msy
  for (i in 1:) {                    #LOOP TO FIND Pr(SY>XX%MSY)
    S.star[i] <- 200*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)
 FOR 2004-2008
  lnalpha.recent    <- mean(lnalpha.y[27:31])
}
```

Appendix A2.–WinBUGS data objects for state-space model of Kenai River early-run Chinook salmon data, 1986–2012. Abundance indices are NCPUE, NASB, SCPUE, N^LR, ELSD, and NCP75.

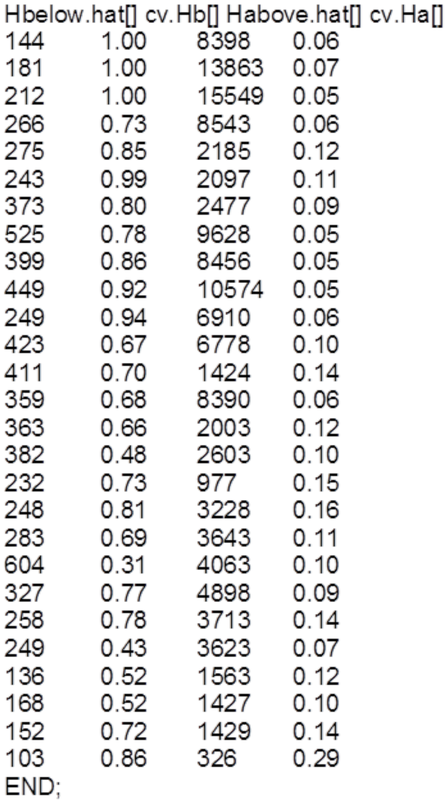


Data for Age-structured Spawner Recruit Model

```
list(Y=27, A=5, a.min=3, a.max=7)

index[,1] index[,2] index[,3] index[,4] index[,5] index[,6] DIDSON[] cv.DS[] IR.hat[] cv.IR[]
NA       NA      NA                NA      78120  NA      NA      0.05     27080  0.36
 NA      NA      NA                NA      82190  NA      NA      0.05     25643  0.23
 NA      NA      NA                NA      72940  NA      NA      0.05      NA    0.01
 NA      NA      NA                NA      44800  NA      NA      0.05      NA    0.01
 NA      NA      NA                NA      38550  NA      NA      0.05      NA    0.01
 NA      NA      NA                NA      44000  NA      NA      0.05      NA    0.01
 NA      NA      NA                NA      51800  NA      NA      0.05      NA    0.01
 NA      NA      NA                NA      62130  NA      NA      0.05      NA    0.01
 NA      NA      NA                NA      60140  NA      NA      0.05      NA    0.01
 NA      NA      NA                NA      55660  NA      NA      0.05      NA    0.01
 NA      NA      NA                NA      52900  NA      NA      0.05      NA    0.01
 NA      NA      NA                NA      51640  NA      NA      0.05      NA    0.01
 NA      NA      NA                NA      52310  1.46    NA      0.05      NA    0.01
 NA      NA      NA                NA      52840  2.22    NA      0.05      NA    0.01
 NA      NA      NA                NA      52110  1.06    NA      0.05      NA    0.01
 NA      NA      NA                NA      60700  NA      NA      0.05      NA    0.01
2.00     6132    0.019            5210     66400  NA      NA      0.05      NA    0.01
5.60     12657   0.049            13147    97690  NA      NA      0.05      NA    0.01
3.75     17998   0.060            13633    99690  NA      NA      0.05      NA    0.01
3.76     12334   0.070            13686    96970  NA      NA      0.05      NA    0.01
2.83     7449    0.048            13071    74310  NA      NA      0.05      NA    0.01
2.58     4516    0.049            8716     60100  NA      NA      0.05     13010  0.18
1.99     4822    0.040            6560     51010  NA      NA      0.05     8636   0.11
1.16     2834    0.021            4428     36890  NA      NA      0.05     10580  0.21
1.32     2644    0.026             NA      30050  NA      5376    0.184    8347   0.14
1.70     4041    0.027             NA      35780  NA      6515    0.036    9267   0.16
0.76     1668    NA                NA      28550  NA      3339    0.048    6513   0.13
END;
```

-continued-

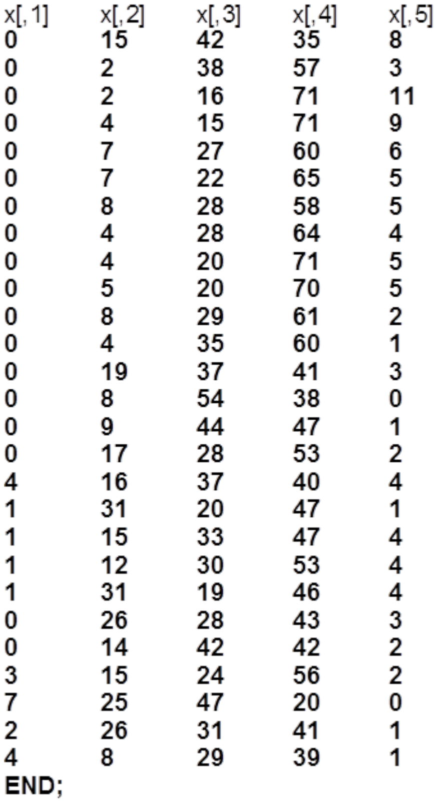
Appendix A2.–Part 2 of 3; estimates of harvest.



```
Hbelow.hat[] cv.Hb[] Habove.hat[] cv.Ha[]
144     1.00    8398    0.06
181     1.00    13863   0.07
212     1.00    15549   0.05
266     0.73    8543    0.06
275     0.85    2185    0.12
243     0.99    2097    0.11
373     0.80    2477    0.09
525     0.78    9628    0.05
399     0.86    8456    0.05
449     0.92    10574   0.05
249     0.94    6910    0.06
423     0.67    6778    0.10
411     0.70    1424    0.14
359     0.68    8390    0.06
363     0.66    2003    0.12
382     0.48    2603    0.10
232     0.73    977     0.15
248     0.81    3228    0.16
283     0.69    3643    0.11
604     0.31    4063    0.10
327     0.77    4898    0.09
258     0.78    3713    0.14
249     0.43    3623    0.07
136     0.52    1563    0.12
168     0.52    1427    0.10
152     0.72    1429    0.14
103     0.86    326     0.29
END;
```

-continued-

Appendix A2.–Part 3 of 3; multinomial age counts summing to effective sample size of 100.



```
x[,1]   x[,2]   x[,3]   x[,4]   x[,5]
0       15      42      35      8
0       2       38      57      3
0       2       16      71      11
0       4       15      71      9
0       7       27      60      6
0       7       22      65      5
0       8       28      58      5
0       4       28      64      4
0       4       20      71      5
0       5       20      70      5
0       8       29      61      2
0       4       35      60      1
0       19      37      41      3
0       8       54      38      0
0       9       44      47      1
0       17      28      53      2
4       16      37      40      4
1       31      20      47      1
1       15      33      47      4
1       12      30      53      4
1       31      19      46      4
0       26      28      43      3
0       14      42      42      2
3       15      24      56      2
7       25      47      20      0
2       26      31      41      1
4       8       29      39      1
END;
```

APPENDIX B: TOTAL RUN ABUNDANCE BY AGE CLASS

Appendix B1.–Total run abundance by age class obtained from fitting a state-space model to Kenai River early-run Chinook salmon data, 1986–2012.

Year	Age 3 (CV)	Age 4 (CV)	Age 5 (CV)	Age 6 (CV)	Age 7 (CV)
1986	404 (1.08)	6,690 (0.26)	7,281 (0.23)	4,272 (0.26)	1,540 (0.49)
1987	280 (1.11)	2,424 (0.38)	9,098 (0.20)	9,443 (0.20)	733 (0.59)
1988	322 (1.11)	1,889 (0.39)	4,076 (0.25)	11,330 (0.17)	2,612 (0.39)
1989	294 (1.07)	1,986 (0.35)	2,413 (0.27)	6,483 (0.20)	1,510 (0.43)
1990	338 (1.08)	2,113 (0.33)	2,972 (0.28)	4,144 (0.26)	744 (0.50)
1991	364 (1.06)	2,430 (0.32)	2,702 (0.27)	4,826 (0.23)	606 (0.51)
1992	337 (1.06)	2,903 (0.31)	3,656 (0.25)	4,738 (0.23)	688 (0.52)
1993	316 (1.07)	2,143 (0.34)	4,127 (0.23)	5,989 (0.21)	628 (0.53)
1994	312 (1.07)	2,139 (0.34)	3,299 (0.25)	6,953 (0.20)	838 (0.50)
1995	324 (1.07)	2,311 (0.31)	3,199 (0.23)	6,516 (0.17)	856 (0.49)
1996	262 (1.07)	2,235 (0.33)	3,142 (0.27)	4,373 (0.24)	343 (0.65)
1997	438 (1.06)	1,859 (0.35)	4,055 (0.23)	4,878 (0.21)	278 (0.73)
1998	316 (1.06)	4,532 (0.26)	3,775 (0.23)	3,226 (0.23)	440 (0.58)
1999	341 (1.07)	2,746 (0.30)	6,834 (0.19)	3,698 (0.22)	184 (0.90)
2000	485 (1.05)	2,643 (0.33)	4,156 (0.23)	3,587 (0.23)	223 (0.72)
2001	516 (1.06)	5,149 (0.26)	3,639 (0.27)	4,578 (0.24)	420 (0.64)
2002	435 (0.48)	1,995 (0.26)	4,028 (0.20)	4,216 (0.20)	424 (0.45)
2003	306 (0.72)	6,091 (0.19)	4,691 (0.21)	9,143 (0.16)	335 (0.65)
2004	307 (0.73)	3,880 (0.23)	8,008 (0.17)	10,510 (0.16)	937 (0.44)
2005	289 (0.72)	2,681 (0.25)	6,265 (0.18)	10,840 (0.14)	845 (0.44)
2006	229 (0.73)	5,006 (0.19)	3,787 (0.20)	8,422 (0.15)	809 (0.43)
2007	080 (1.02)	3,099 (0.19)	4,106 (0.17)	5,872 (0.14)	506 (0.48)
2008	073 (1.02)	1,364 (0.23)	3,914 (0.14)	4,626 (0.13)	286 (0.53)
2009	233 (0.51)	1,291 (0.22)	1,844 (0.19)	4,225 (0.14)	232 (0.53)
2010	484 (0.36)	1,965 (0.18)	3,434 (0.14)	1,899 (0.18)	101 (0.82)
2011	213 (0.60)	2,477 (0.18)	3,087 (0.16)	3,998 (0.14)	168 (0.64)
2012	240 (0.42)	0,656 (0.26)	1,901 (0.15)	2,519 (0.12)	103 (0.63)

APPENDIX C: GENETIC CAPTURE–RECAPTURE ESTIMATES OF INRIVER RUN

Appendix C1.–Genetic capture–recapture (CRGEN) estimates of inriver run.

CRGEN estimates were generated by fitting a "Stock Specific Abundance and Run Timing" (SSART) statistical model to Kenai River Chinook salmon data. The SSART model is based on the work of Bromaghin et al. (2010), who developed a likelihood framework for joint estimation of salmon abundance and migratory timing using radio-telemetric data. ADF&G modified the work of Bromaghin et al. (2010) to accommodate the use of GSI allele frequency data and data from the harvest after the first event, and by adopting a Bayesian framework for model fitting.

The SSART model (Appendix C2) was used to create a matrix of relative abundance by stock and by time period, where the stocks are the following genetic reporting groups: Killey River–Benjamin Creek, Funny River–Slikok Creek, Mainstem Kenai River, Quartz Creek–Crescent Creek, Russian River, and Grant Creek. Information about stock composition was provided by 1) genetic stock identification (GSI) methods applied to fish sampled with inriver gillnets, and 2) radiotelemetry. Information about relative abundance across (15-day) time periods was provided by catch rates at the RM-9 inriver test gillnetting program. The matrix of relative abundance was anchored by independent estimates of escapement for Funny River and Slikok Creek, and Russian River reporting groups,[22] thereby permitting estimation of absolute abundance for the entire inriver run. Harvest by stock was accounted for by sampling GSI information from fish encountered in the lower river creel survey and a supplemental sampling program, and weighting by creel and mail survey estimates of harvest by time strata. Timing of each stock past the RM-9 capture site was assumed to be bell-shaped.[23]

Unlike traditional mark–recapture experiments, which must assume that behavior of marked fish is unaffected by handling, the SSART model experiment utilizes GSI information as the primary "mark." Because GSI data are derived solely from tissue samples collected at time of capture, fish behavior after the time of sampling has no bearing on the estimates.

Radiotransmitters were applied to a subsample of captured fish, and their spawning destinations were determined by radio-telemetry methodology. Telemetry provides known stock identification for a subset of GSI-sampled fish, which strengthens the GSI information and improves the precision of abundance estimates.

The SSART capture–recapture model not only provides estimates of abundance of Kenai River Chinook salmon stocks but also their run timing, which is valuable for management purposes. Model structure is hierarchical among years with respect to total abundance, stock composition, and run-timing parameters.

Like the state-space model described in the main body of this report, the SSART model is implemented in OpenBUGS (Lunn et al. 2009), which provides the flexibility to combine information from multiple data sources.

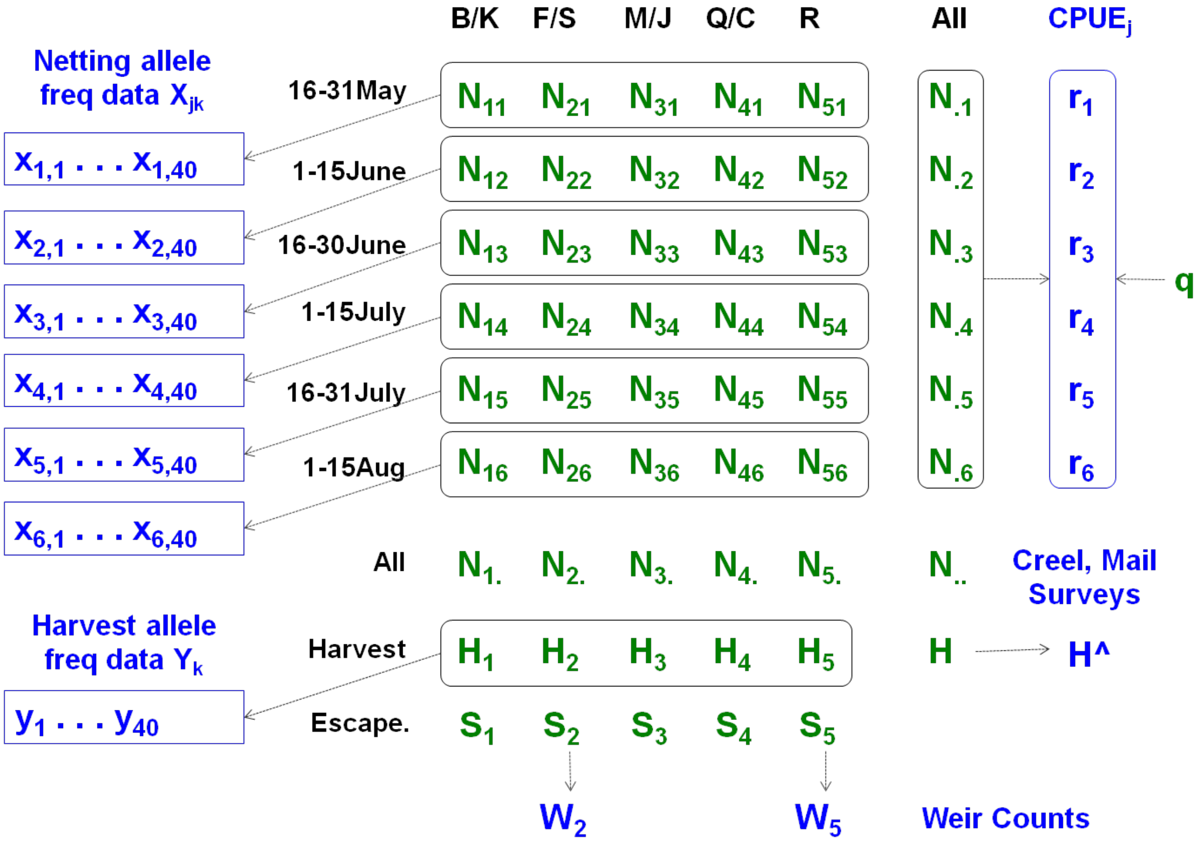
Preliminary estimates of inriver abundance of early-run Chinook salmon during the years 2007–2012 are reported in Table 2. Because the model itself continues to undergo development, and because more years of data will be added, these estimates will change. A report detailing SSART model methods and results is planned for publication in 2014.

---

[22] The Benjamin and Killey rivers reporting group was also used in 2012.

[23] Expectation of run timing was based on the normal probability density function.

Appendix C2.–Flowchart of annual quantities (parameters N, H, and S in green; data x, y, r, H, and W in blue) from a stock-specific abundance and run timing (SSART) model. By fitting the SSART model to 2007–2012 Kenai River Chinook salmon data, CRGEN estimates of inriver run abundance by stock and time period are obtained. Two revisions to the model have occurred since this figure was produced: a sixth reporting group (Grant Creek) was added to the model, and the number of alleles was reduced from 40 to 38.



APPENDIX D: GENETIC ESTIMATES OF INRIVER RUN TIMING, KENAI RIVER CHINOOK SALMON

McKinley[24] quantified the overlap in the run timing of tributary and mainstem spawning Kenai River Chinook salmon during the years 2003–2007. Chinook salmon in spawning condition were sampled in 10 different mainstem areas and tributaries of the Kenai River to develop a genetic baseline database. Additionally, mixture samples for tributary versus mainstem run-timing estimates were collected via an existing netting program as they entered the lower Kenai River. Based on the lower river mixture sampling, most of the Chinook salmon that enter the Kenai River prior to the middle of June are of tributary origin; depending on the year, after the second or third week in June, mainstem fish become more predominant (Appendix D2). Few tributary spawning Chinook salmon enter the Kenai River in July. Results from the lower river sport fishery mixture sampling demonstrate that 1) most of the harvest in May and June is of tributary-bound fish, and 2) nearly all of the harvest in July is of mainstem-bound fish. The middle river sport fishery mixture sampling results indicate that 1) most of the harvest in June is of tributary-bound fish, 2) the harvest in the first two weeks of July is nearly an equal mix of tributary- and mainstem-bound fish, and 3) nearly all of the harvest in the last two weeks in July is of mainstem-bound fish.

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[24] T. McKinley, 2011, unpublished Alaska Sustainable Salmon Fund Project Completion Report, AKSSF Project Number 45143(700), located at ADF&G Soldotna, AK.

Appendix D2.–Proportion of tributary-spawning Kenai River Chinook salmon by weekly time period in the lower Kenai River netting program, 2003–2007.