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Prioritization of Naturally Produced Snake River Spring/Summer Chinook Salmon (*Oncorhynchus tshawytscha*) and Summer Steelhead (*O. mykiss*) Populations Based on Population Trends

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September 2002 - August 2004

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Abstract

We prioritized naturally produced Snake River spring/summer Chinook salmon and summer steelhead populations in order of risk level using a decision analysis of population trend. Population trend is based on both the growth rate of population size and the variability in population sizes over time. We applied the Diffusion Approximation (DA) model to time series data on run size indices. Estimates of the DA model parameters reflect not only population trend but also various risk metrics. We expressed uncertainty in the DA model parameters as Bayesian posterior distributions of those parameters. Status of 29 Chinook salmon populations and five steelhead populations was assessed. Big Sheep Creek Chinook salmon population in Imnaha sub-basin is extinct. With pre- and post-1980 data being used, all Chinook salmon and steelhead populations were at risk. With only post-1980 data being used, (*i*) Upper Mainstem Grande Ronde River Chinook salmon, Tucannon River Chinook salmon, and Tucannon steelhead were at serious risk; (*ii*) Alturas Lake Creek Chinook salmon, East Fork Salmon River Chinook salmon spring run, Catherine Creek Chinook salmon, and Upper Grande Ronde steelhead were at moderate risk.

Introduction

Snake River spring/summer Chinook salmon (*Oncorhynchus tshawytscha*) return to natal rivers from March to October, and Snake River summer steelhead (*O. mykiss*) return from late June to October. Adult Chinook salmon are classified into two groups of spring and summer runs. Typically, spring Chinook salmon are defined as run that passes Bonneville Dam (Columbia river km 235.075; river mile 146.1) before 31 May, and summer Chinook salmon after 31 May. Further definition of spring, summer and fall Chinook salmon is possible using molecular genetic markers (Myers et al. 1998; Brannon et al. 2004; Narum et al. 2004). Up-river summer steelhead are also classified into two groups of A-run and B-run. A-run steelhead are predominantly age 1-ocean fish (age x.1) while B-run steelhead are larger, predominated by age 2-ocean fish (age x.2). Their stock structure is also better described genetically (Brannon et al. 2004).

Since 1957, in-river commercial fishery area has been divided into non-Indian and treaty-Indian parties (WDFW & ODFW 2002). Non-Indian commercial fishery is limited to Zones 1-5, which is from the Columbia River mouth to Bonneville Dam, whereas Tribal commercial fishery is to Zone 6, from Bonneville Dam to McNary Dam (Columbia river km 469.828; river mile 292). Non-Indian commercial fishermen can catch Chinook salmon but are not allowed to catch steelhead. Tribal commercial fishermen can catch any species. Sports fisheries are allowed in all zones, but sports anglers cannot retain captured wild fish as identified by the absence of an adipose clip.

The National Marine Fisheries Service (NMFS) defines an evolutionarily significant unit (ESU) as a distinct collection of fish populations that are sufficiently reproductively isolated from other populations. The Snake River spring/summer Chinook salmon ESU includes current runs to the Tucannon River, the Grande Ronde River system, the Imnaha River and the Salmon River (Matthew and Waples 1991) but excludes run to the Clearwater River drainage (Fig. 1, Table 1). The Snake River steelhead ESU includes runs to the Grande Ronde River system, the Imnaha River drainage, the Clearwater River drainage, the South Fork Salmon River, the smaller mainstem tributaries before the confluence of the mainstem, the Middle Fork salmon production sites, the Lemhi and Pahsimeroi valley production areas, and upper Salmon River tributaries (West Coast Salmon BRT 2003) (Fig. 2, Table 1). Though resident *O.*

mykiss (rainbow trout) are present in the Snake River basin, the level of reproductive isolation between co-occuring resident and anadromous forms varies within the Columbia River Basin (West Coast Salmon BRT 2003; Narum et al. 2004). We analyze data of only the anadromous form in this paper.

Snake River spring/summer Chinook salmon and steelhead have suffered from a severe decline in population size. Fish return sizes, particularly from 1980-2000, were less than 1% of those from about 1955-1970 (Hyun and Talbot 2004). The NMFS listed the ESU of these fish as 'threatened' on April 22, 1992 and August 18, 1997 respectively under the Endangered Species Act. However, adult returns of both Chinook salmon and steelhead from 2001-2003 significantly increased (NMFS BRT draft report 2003).

Salmonid population viability status is determined by four factors: population abundance, population growth rate, population spatial structure, and diversity (McElhany et al. 2000). Since it is difficult to address a complete viability analysis because information and long term data for these four factors are rarely available, we focus our analysis of viability on population growth for Snake River spring/summer Chinook salmon and steelhead.

We used time series data on abundance indices for Snake River spring/summer Chinook salmon and steelhead, and focused on calculation of risk metrics for individual populations and the ESUs. Where data of times series abundance are available, the Diffusion Approximation (DA) model (also called the Wiener-Drift process model) is a useful tool for the calculation of risk metrics (Dennis et al. 1991). One of the DA model's merits lies in its generic function where well-known risk metrics are functions of the DA model's parameters (Dennis et al. 1991). Those well-known risk metrics include population growth rate, extinction probability, probability that the recent population size declines by a certain proportion, and time to extinction, etc.

Another merit of the DA model is its ability to cover the population growth rate (λ) calculated from other variables and methods. Some traditional variables and methods in fisheries include 'recruits per spawner' (R/S), '8-year geometric means of the spawner-to-spawner ratio,' 'smolt-to-adult ratios' (SARs), 'the ordinary regression model of the logarithm of abundance against time,' and 'residuals from a stock/recruit relationship.' For example, estimate of λ derived from the logarithm of R/S can be different from that calculated with parameters from the DA model for a short data series, but theory on stochastic population processes states that they are eventually equal for a ‘long term’ data series (Caswell 2001). Further, SARs leave out the adult-to-smolt portion of the life cycle, and estimate of λ from SARs is not a measure of the integration of survivorship and fecundity over the entire life cycle (Holmes 2004b). Holmes (2004b) has a detailed discussion about the limitation of those traditional variables and methods.

We find that it is not appropriate to directly apply the DA model to time series data of abundance index such as redd counts. Though estimates of the DA model parameters from data of actual abundance are acceptable, those from data of abundance index are highly inaccurate (largely biased and poorly precise). Holmes and Fagan (2002) and Holmes (2004a) developed new estimators of the DA model parameters that can be used for abundance index data. Even with data corrupted due to non-process errors that are from density-dependent feedback, observation, and sampling errors, the new estimators lead to a significant improvement in the accuracy. In this paper, we refer to these as Dennis-Holmes (D-H) estimators.

As mentioned above, well-known risk metrics can be calculated with the DA model parameters. Thus, a risk metric calculated from the DA model parameters is obviously correlated to any other risk metric calculated from the DA model parameters. For example, if the population growth rate calculated from the DA model parameters is good or bad, the other risk metrics calculated from the DA model parameters will be good or bad accordingly. Because of this obvious correlation, it is inefficient to calculate all risk metrics. That is, any quantity that incorporates estimates of the DA model parameters covers those well-know risk metrics.

We use Bayesian methods to express uncertainty in the DA parameters. Further, to prioritize populations at risk, we used a decision analysis about population trend, considering both the growth rate of a population size, and the variability in population sizes over time. A decision analysis is a formal tool in making a decision about hypotheses of interest. The prioritization of populations at risk would benefit managers who have to apply a safety net or recovery action to populations.

Methods

Data

We collected annual abundance index data from the NMFS Technical Review Team (TRT) (T. Cooney, NMFS, OR), the U.S. v. Oregon Technical Advisory Committee (TAC) (H. Yuen, US Fish & Wildlife Service, WA), the Nez Perce Tribal Fisheries Department (R. Orme, ID), Idaho Department of Fish and Game (IDFG) (S. Kiefer), and Oregon Department of Fish and Wildlife (ODFW) (B. Knox). Data of five kinds of abundance index are available: expanded redd counts (Exp.RC), redd counts (RC), redds per kilometer (RPKm), redds per mile (RPM), and total live counts (TLC) (Table 1).

We followed population structure defined by the TRT. The TRT defined 31 spring/summer Chinook salmon populations and 25 steelhead populations, based on genetics, spawning distribution, life history, morphology, demographic structure, and habitat. Those populations are listed in Table 1.

When escapement index data were available but harvest information was missing, we calculated harvest index using exploitation rate. Exploitation rate is defined as a ratio of catch to run where run is the sum of catch and escapement (i.e., exploitation rate = catch/run = catch/[catch+escapement]). Fig. 3 compares exploitation rates for spring/summer Chinook salmon and steelhead populations from the TRT dataset with those for spring/summer Chinook salmon ESU and A-run steelhead from the TAC. There is a minor variation in exploitation rate between individual populations, but a strong similarity between the TRT and TAC datasets (Fig. 3). The minor variation in exploitation rate between Chinook salmon populations is mainly due to a difference in run timing between spring and summer runs (Fig. 3 (a)). Usually exploitation rate for summer Chinook salmon run is lower than for spring run. When exploitation rate was missing from a year in a dataset for a spring Chinook salmon population, a lumped spring and summer Chinook salmon population and an A-run steelhead population, we applied the mean value of available exploitation rates from the year for the other populations of the same species. When exploitation rate was missing from a year in a dataset for a summer Chinook salmon population, we applied the minimum value of available exploitation rate values from the year for the other populations. Once we know exploitation rate and escapement index for a population at a year, we can calculate unknown catch index for the population at the year with the following equation.

$$(1) \qquad \text{catch} = \frac{(\text{exploitationrate}) \times \text{escapement}}{1\text{- (exploitation rate)}}$$

In eq. 1, catch unit becomes the same as escapement unit so eq. 1 holds regardless of different escapement indices.

To know the proportion of naturally produced fish out of run to a spawning area, local managers check the presence of adipose fin of a spawner. A fish whose adipose fin is missing is from a hatchery. The TRT dataset provides information of annual proportion of naturally produced fish for ESU and populations. Finally, we calculate return size index, *I* of naturally origin fish at a year as follows:

$$(2) \qquad I = [\text{escapement} + \text{catch}] \times (\text{fraction of naturally origin fish})$$

Return size index at return year for ESU and populations are shown in Figs. 4 and 5.

Time periods analyzed

In population trend assessment, the range of data time series as well as appropriate analysis methods is important as results will differ. We assessed the status of ESUs and populations over two time series: (1) the entire time series of available data, and (2) time series after 1980.

To address an issue concerning whether the current population viability is comparable to those from the healthy time, we must use the entire time series. To assess whether the current population viability is at extinction risk, recent data series should be used because salmonid longevity is typically five or six years, and thus population sizes from 10 or more years ago are less correlated to the current population size.

We have three reasons for choosing the post-1980 data series for our models: (*i*) since 1975 when the last dam was built in the Snake River, the Snake River ecosystem has been less perturbed compared to the pre-1975 period when several dams had been built, (*ii*) it is reported that ocean regime shift occurred in 1979, (*iii*) and D-H estimators of the DA model parameters are not appropriate for data series shorter than 20 years.

Diffusion Approximation model (the Wiener-Drift process model)

The DA model is based on a stochastic exponential growth model (eq. 3). A standard form of the stochastic exponential growth model is as follows: N_t = $N_0 \cdot \exp(m \cdot t + e_t)$, where $e_t \sim N(0, s^2 \cdot t)$. N_t is the population size at time *t*, *m* is the slope of the population trend over time (i.e., the population growth rate), e_t is time-dependent error term, and s^2 represents variability in population sizes over time. e_t is assumed to follow a normal probability distribution where its mean and variance are zero and '$s^2 \cdot t$'. Thus, the stochastic exponential growth model has two parameters: m and s^2. The actual abundance *N* is proportional to its index I (i.e., N_t = constant $\cdot I_t$), so we could express the standard form with the abundance index without information loss because the constant was cancelled out in both sides of the equation. That is,

(3) $$I_t = I_0 \cdot \exp\left(m \cdot t + e_t\right), \text{ where } e_t \sim N(0, s^2 \cdot t)$$

However, the stochastic exponential growth model should not be directly applied to time series data of populations with short longevity because the model's time step is discrete and its population state is autocorrelated resulting in inaccurate estimates of two parameters.

It is shown that the approximate normal distribution of log(I_t) is identical to the distribution of a Wiener process with drift (Goel and Richter-Dyn 1974; Ricciardi 1977; Karlin and Taylor 1981). The DA model is a simple type of continuous-time, continuous-state, Markov stochastic process known as a diffusion process (Lande and

Orzack 1988). A detailed derivation of the DA model is described in Dennis et al. (1991).

In practice, the DA model is transformed into an ordinary regression model that does not have an intercept term (Dennis et al. 1991; eq. 4):

$$(4) \qquad \underset{\sim}{Y} = m \cdot \underset{\sim}{D} + \underset{\sim}{e}$$

Vector $\underset{\sim}{D}$ has elements of $\left(\sqrt{t_1}, \sqrt{t_2}, \cdots, \sqrt{t_q}\right)$, where $t_i = t_i - t_{i-1}$, and $i = 1, \cdots, q$. Vector $\underset{\sim}{Y}$ has elements of $\left(y_1, y_2, \cdots, y_q\right)$, where $y_i = \dfrac{\log\left(N_i / N_{i-1}\right)}{\sqrt{t_i}}$. Error term vector $\underset{\sim}{e}$ has elements of $\left(e_1, e_2, \cdots, e_q\right)$, where $e_i \sim N(0, s^2)$. When data of fish abundance N_i are not available, the data absence is not problematic because we deal with ratios of those in neighboring years (i.e., N_i / N_{i-1}). By the assumption that the actual abundance is proportional to the abundance index (i.e., $N_i = \text{constant} \cdot I_i$), the response variable is as follows: $y_i = \dfrac{\log\left(I_i / I_{i-1}\right)}{\sqrt{t_i}}$.

The DA model has the property that $\log\left(I_t / I_0\right)$ is distributed normally with mean mt and variance $s^2 t$ (Dennis et al 1991). This DA model has several merits: (1) the model is not an empirical model but a mechanistic model, (2) the time increment of the model is not discrete but continuous, (3) the response variable values over time are independent, normal, and stationary (Graybill 1976, Riciardi 1977), (4) the normal distribution is valid not only for large observations but also for small, and (5) estimation of the model parameters is less sensitive to missing data than the stochastic exponential growth model.

Dennis-Holmes' estimator of two parameters

Well-known risk metrics are functions of two parameters, m and s^2 in the DA model (Dennis et al. 1991). These risk metrics include the long-term rate of population change (often called λ), extinction probability, probability that the recent population size declines by a certain proportion, and time to extinction. Because various risk metrics are calculated with those two parameters, an important issue is to accurately estimate those parameters rather than to calculate those various risk metrics.

However, our historical data of abundance indices have considerable observational or sampling error, and data measurement methods have not been consistent over time. As a result, directly fitting our data of abundance indices to the DA model (eq. 4) led to very inaccurate estimates of m and s^2.

We used the D-H estimators of m and s^2 because these estimators significantly improve the accuracy in estimates of m and s^2 (Holmes and Fagan 2002; Holmes 2004a). Eqs. 5 and 6 show D-H estimators of m and s^2.

(5) $$\hat{m} = \text{mean}\left[\log\left(\frac{\sum_{i=0}^{L-1} I_{t+1+i}}{\sum_{i=0}^{L-1} I_{t+i}}\right), t = 1,2,3,...\right]$$

(6) $$\hat{s}^2 = \text{slope of var}\left[\log\left(\frac{\sum_{i=0}^{L-1} I_{t+t+i}}{\sum_{i=0}^{L-1} I_{t+i}}\right), t = 1,2,3,...\right] \text{against } t\text{, where } t = 1 \sim 4$$

L is the number of counts summed together, and we used 4 for L following Holmes and Fagan (2002) (i.e., L = 4). Note that $\hat{s}^2$ and $\hat{m}$ are dimensionless because the abundance index unit is canceled out in the numerator and denominator in eqs. 5 and 6. This dimensionless characteristic enables direct comparison of population status.

The estimated distributions of the parameter estimates are as follows (Dennis et al. 1991; Holmes and Fagan 2002; Holmes 2004a).

(7) $$\hat{s}^2 \mid s^2 \sim Gamma\left(\text{shape} = \frac{df}{2}, \text{scale} = \frac{2 \cdot s^2}{df}\right)$$

where $df \approx 0.333 + 0.212n - 0.387L$. df is degrees of freedom, and n is the length (number of years) of the data series.

(8) $$\hat{m} \mid m, s^2 \sim N\left(m, \frac{s^2}{n-L}\right)$$

The conditional distribution of $\hat{m}$ given s^2 is normal (eq. 8), but the marginal distribution of $\hat{m}$ is t-distribution (Dennis et al. 1991; Gelman et al. 1995; McClure et al. 2003) (eq. 9).

(9) $$\hat{m} \mid m \sim t_{df}\left(m, \frac{\hat{s}^2}{n-L}\right)$$

Eq. 9 means that, in a common notation, $\dfrac{\hat{m}-m}{\sqrt{\hat{s}^2/(n-L)}} \sim t_{df}$

Uncertainty in parameters

We applied Bayesian techniques to express uncertainty in the DA parameters m and s^2. In calculating the joint posterior density of m and s^2, we used $\hat{m}$ and $\hat{s}^2$ as data. This idea of treating $\hat{m}$ and $\hat{s}^2$ as data is also found in Holmes (2004a). First we identify the likelihood function of m and s^2.

(10) $$L(m, s^2 \mid \hat{m}, \hat{s}^2)$$

$$= p(\hat{m}, \hat{s}^2 \mid m, s^2) \qquad \because \text{definition}$$

$$= p(\hat{s}^2 \mid s^2) \cdot p(\hat{m} \mid m, s^2) \qquad \because \text{conditionally independence}$$

$$= Gamma(\hat{s}^2 \mid s^2) \cdot N(\hat{m} \mid m, s^2) \quad \because \text{ from eqs. 7 and 8}$$

where *Gamma*(x|y) and *N*(x|y) represent the gamma and normal density of *x* given *y*. We show mathematical forms of these densities in Appendix A. That is, $L(m, s^2 \mid \hat{m}, \hat{s}^2)$ = $Gamma(\hat{s}^2 \mid s^2) \cdot N(\hat{m} \mid m, s^2)$

For a joint prior density of m and s^2, we considered an uninformative prior because we had little knowledge about them. What we know about m and s^2 is that m is a location parameter and s^2 is a scale parameter. Assuming prior independence of location and scale parameters, we applied the standard uninformative prior (Gelman et al. 1995). That is,

(11) $p(m, s^2) \propto \dfrac{1}{s^2}$ where the domain of s^2 is $(0, +\infty)$.

Finally the joint posterior density of m and s^2 is proportional to the product of the likelihood function and the prior.

(12) $$p(m, s^2 \mid \hat{m}, \hat{s}^2) \propto Gamma(\hat{s}^2 \mid s^2) \cdot N(\hat{m} \mid m, s^2) \cdot \frac{1}{s^2}$$

This posterior density could not analytically be derived. We show in Appendix A that, only when (*n*-*L*) is equal to *df*, it is possible to analytically derive the marginal posterior density of m. Because (*n*-*L*) is not equal to *df*, we numerically derived the marginal posterior distributions of m and s^2. For the numerical calculation, we used Metropolis-Hastings algorithm, one of the Markov Chain Monte Carlo (MCMC) calculation methods with Automatic Differentiation Model Builder (ADMB) software (Fournier 2000). We ran one million MCMC iterations, and sampled them at 1,000 intervals because of concern about Markov Chain autocorrelation. Also we did not use the initial 50,000 samples in the MCMC burning period.

For checking the convergence of MCMC samples, we used three indicators (Cowles and Carlin 1996; Plummer et al. 2004; Minte-Vera 2004): (1) the Raftery and Lewis statistic, (2) lag 1 autocorrelation, and (3) the ratio between the time series standard deviation (based on an estimate of the spectral density at 0) and the naïve standard deviation (ignoring autocorrelation of the chain). The ratio between the two standard deviations should be around 1 if no autocorrelation is present. Also we visually checked MCMC samples to look for obvious patterns of lack of convergence.

Decision analysis

If a population whose growth rate is worse than another population, the former is at higher risk than the latter. However when growth rate of a population is equal to another population, we have to consider variability in population sizes over time. Fig. 6 illustrates the idea.

Decision analysis of population trend is a formal tool of making a decision about population trend, considering both the growth rate of a population and the variability in population sizes over time. We used decision analysis to prioritize populations in order of at-risk.

We considered three kinds of hypotheses regarding population trend following Wade (2000).

- Hypothesis 1: population of interest is declining rapidly.
- Hypothesis 2: population of interest is declining slowly.
- Hypothesis 3: population of interest is not declining.

These hypotheses are reasonable for species listed as threatened or endangered, because they cover three possibilities: at serious extinction risk (hypothesis 1), at minor extinction risk (hypothesis 2), and at no risk (hypothesis 3).

For inference of population trend in a decision analysis, we used the posterior distribution of parameter m that reflects both the point estimate of the population growth rate and the variability in population sizes over time. A new input required for decision analysis is loss function values. A loss function value is a penalty given when a wrong hypothesis is selected out as a decision. Table 6 shows loss function values for three possible decisions regarding population trend. Note that those values in Table 6 are diagonally symmetrical, letting equal loss be assigned to over- and under- protecting a population. A detailed description of loss function values is found in Wade (2000).

As the final step, we calculated expected loss values of three possible decisions for each population of interest, and then selected a decision whose expected loss was least. The expected loss of a decision is the sum of products of the probability of each hypothesis occurring, and loss function value occurring when the corresponding hypothesis is selected. That is,

(13) Expected loss of a decision = $\sum_{h=1}^{3}\left(P_h \cdot L_h\right)$

where h = hypothesis 1, 2, and 3; P_h = probability of hypothesis h occurring ; and L_h = loss function value occurring when decision of concluding hypothesis h is selected (Table 6). For example, in case of posterior distribution of m for Catherine Creek spring/summer Chinook salmon population (Chinook code 1; Table 1) calculated with available all data and the standard uninformative prior, probabilities of three respective hypotheses are 0.409, 0.393 and 0.198 (Fig. 7). The expected loss of choosing hypothesis 1 is 0.394 (= 0.409*0 + 0.393*0.5 + 0.198*1); the expected loss of choosing hypothesis 2 is 0.304 (= 0.409*0.5 + 0.393*0 + 0.198*0.5); and the expected loss of choosing hypothesis 3 is 0.606 (= 0.409*1 + 0.393*0.5 + 0.198*0). Thus, we choose decision 2 whose expected loss is least. That is, we conclude that the population is declining slowly.

Quasi-extinction probability

It requires data of actual abundance of a population to calculate extinction probability for the population (Dennis et al. 1991). Our data for fish populations are not actual abundance but abundance indices, and thus, instead of extinction probability, we calculated the probability of a population declining by a certain proportion in future from the most recent year when data are available. We considered the probability of a population declining by 90% in 50 years to be quasi-extinction probability. Eq. 14 shows the formula for the decline probability (Dennis et al. 1991).

(14) $$\Pr(x\%\text{decline in } t_e \text{ years}) = 1 - \Phi\left[\frac{\log\left(\frac{100}{100-x}\right) + m \cdot t_e}{s \cdot \sqrt{t_e}}\right]$$

where $\Phi(y)$ denotes the cumulative probability up to y where y is the standard normal random variable (i.e., $y \sim N(0,1)$).

We built the distribution of the decline probability by parametric bootstrapping, where random values of m and s^2 sampled from the respective posterior distributions are used (Dennis et al. 1991; McClure et al. 2003). For example, to build 95% highest posterior density (HPD) region[1] of the decline probability, we sampled values of m and s^2 that lie within 95% HPD regions of the respective posterior distribution, and then used the samples in eq. 14 to calculate the decline probability.

Results

Parameters in the Diffusion Approximation model

Tables 2-5 summarize the population trend status for spring/summer Chinook salmon and steelhead populations in terms of the estimates of m and s^2, and of the marginal posterior distributions of those parameters. Figs. 8 and 9 show the marginal posterior distribution of m for spring/summer Chinook salmon and steelhead populations. There was no indication that MCMC samples for the posterior distributions of m and s^2 were lack of convergence.

Prioritization

Tables 7-10 show results of prioritization of populations based on the decision analysis results. In a row in Tables 7-10, decision with the smallest expected loss is

[1] The idea behind HPD region of a parameter is similar to confidence interval of the estimate of a parameter. Because of differences between Bayesianism and frequentism, statisticians use different terms. One of the differences is that a parameter is treated as a variable in Bayesianism but as a constant in frequentism.

shaded. Within a selected decision category, populations are in order of the mode of m (Tables 2-5).

Out of 29 Chinook salmon populations whose population trends were evaluated from the decision analysis with available all data series, we found that 15 Chinook salmon populations are declining rapidly, and 13 Chinook salmon populations are declining slowly (Table 7). Table 7 shows that one Chinook salmon population (code 27; Pahsimeroi River Chinook Salmon population) is not declining, but data on this population were not available prior to 1980 (Fig. 4). When post-1980 data series were used, three Chinook salmon populations are declining rapidly, three Chinook salmon populations are declining slowly, and 23 Chinook salmon populations are not declining (Table 8). Data for the spring/summer Chinook salmon ESU return were available for only years 1979-2003, and the ESU is not declining based on those data (Tables 7 and 8).

It is reported that Big Sheep Creek Chinook salmon population (code 6) is extinct (J. Hesse, ID). Data on the population also show that run size indices have been zero since 1996 (Fig. 4).

Out of five steelhead populations whose population trends were evaluated from the decision analysis with available all data series, we found that four steelhead populations are not declining (Table 9). Table 9 shows that one steelhead population (code 1; Tucannon River steelhead population) is declining rapidly, but data on this population were not available prior to 1980 (Fig. 5). When post-1980 data series were used, one steelhead population (code 1; Tucannon River steelhead population) is declining rapidly, one steelhead population (code 11; Upper Grande Ronde steelhead population) is declining slowly, and three populations are not declining (Table 10). Data for the steelhead ESU return were available only for years 1980-2001, and the ESU is declining slowly (Tables 9 and 10).

Quasi-extinction probability

Figs. 10 and 11 show 95% HPD region of the probability that population of interest decline by 90% in 50 years. Upper Mainstem Grande Ronde River Chinook salmon population (Chinook code 4), Tucannon River Chinook salmon population (Chinook code 8), and Tucannon River steelhead population (Steelhead code 1) are most likely to decline 90% in 50 years (Figs. 10 and 11).

Discussion

Using both pre- and post-1980 data series, we found that all spring/summer Chinook salmon populations are at risk (Table 7). These results suggest that the current viability of the fish is significantly poor, compared to that from the past healthy period.

The available data series for Snake River steelhead was limited, and therefore, we could not conclude whether the current viability was not comparable to that from the healthy time (Table 4, Fig. 5). However, even the short term data from 1980-2001 for the steelhead ESU resulted in the conclusion that the ESU is declining slowly (Tables 9 and 10). We know from the literature that Snake River steelhead were much more abundant before 1968, when the first hydropower dam (John Day dam) in the Snake River was constructed, than from 1980-2001. Therefore, it is fair to conclude that the current viability of Snake River steelhead is also very poor compared to that from the past healthy period.

Status about population extinction based on only post-1980 data series is different from that based on both pre- and post-1980 data series. Based on only post-1980 data, populations that are declining rapidly are Big Sheep Creek Chinook salmon (Chinook code 6), Upper Mainstem Grande Ronde River Chinook salmon (Chinook code 4), Tucannon River Chinook salmon (Chinook code 8), and Tucannon River steelhead (steelhead code 1) (Tables 8 and 10). Big Sheep Creek Chinook Salmon population (Chinook code 6) is already extinct; abundance indices since 1996 have been zero (Fig. 4). Again based on only post-1980 data, populations that are declining slowly are Alturas Lake Creek Chinook salmon (Chinook code 23), East Fork Salmon River spring run (Chinook code 28sp), Catherine Creek Chinook salmon (Chinook code 1), and Upper Grande Ronde steelhead (steelhead code 11) (Tables 8 and 10). 23 Chinook salmon populations and three steelhead populations are not declining (Tables 8 and 10). Data on four Chinook salmon populations and 20 steelhead populations were missing, and status of those populations could not be assessed (Table 1).

As quasi-extinction probability, we used the probability of declining by 90% in 50 years from the most recent year when data are available. 95% HPD region of the decline probability often ranges from 0 to 1, which is not informative, and also the distribution is not uni-modal (Figs. 10 and 11). Thus we present the results graphically in Figs. 10 and 11. The distribution that frequently occurs near zero means that the likelihood of the population of interest going extinct is almost zero, while the distribution that frequently occurs near one means that the population of interest almost certainly will go extinct. Those results are consistent with those from decision analysis. For example, the distribution of the quasi-extinction probability is most likely to occur near one for the following populations: Mainstem Grande Ronde River Chinook salmon (Chinook code 4), Tucannon River Chinook salmon (Chinook code 8), and Tucannon River steelhead (steelhead code 1). Because Big Sheep Creek Chinook salmon population (code 6) is extinct, we don't show the distribution of quasi-extinction probability for the population in Fig. 10.

Next work

Our analysis of risk of extinction is based on population trend, which addresses the population growth rate or productivity and the variability in population sizes over time. A complete analysis of population viability requires more data and information about actual abundance, population spatial structure, and genetic diversity.

In future analyses, we plan to proceed with other issues in population viability analysis not included in this study. The TRT has accumulated data on habitat characteristics for Columbia River Chinook salmon and steelhead populations. The data include spawning habitat size (i.e., spawning area capacity), and climate-related condition on spawning habitat. Thanks to these data, spatial interaction between populations can be addressed. It is critical to address a spatial-relationship between populations. We found a significantly high correlation in population trend between Chinook salmon populations in Mid Fork Salmon River sub-basin (Table B1). This significant high correlation enables us to consider those Chinook salmon populations to be a meta-population.

Within a meta-population, it would be possible to transfer information of populations with good quality of data to population whose data are sparse or missing.

Further we suggest to assess risk of extinction to fish populations on the level of cohort strength. Out-migration mortality of spring/summer Chinook salmon smolts from brood year 1999 is presumed to have been high during 2001 when spill amount from dams in the Columbia and Snake River were low. When we analyze spring/summer Chinook salmon return by age-class, it is found that the 1999 brood year returned poorly in 2002-2004. However, when we evaluate the fish return as a lumped run size regardless of age, the poor return of the 1999 brood year is masked by the large runs from the adjacent brood years.

Summary

Table 11 summarizes at-risk status for spring/summer Chinook salmon. Big Sheep Creek Chinook salmon (code 6) are extirpated. Using pre- and post-1980 data series, we found that 13 Chinook salmon populations are at serious risk, 12 Chinook salmon populations are at moderate risk, and status for seven Chinook salmon populations cannot be assessed due to lack of data. When we used only post-1980 data series, Snake River spring/summer Chinook salmon ESU is not at risk, two Chinook salmon populations are at serious risk, three Chinook salmon populations are at moderate risk, 22 Chinook salmon populations are not at risk, and the status for five Chinook salmon populations could not be assessed due to lack of data. Refer to Table 11 for identification of these Chinook salmon populations.

Table 12 summarizes at-risk status for steelhead. When using pre- and post-1980 data series, four steelhead populations are not at risk. Status for 21 steelhead populations could not be assessed due to lack of data. Using only post-1980 data series, steelhead ESU is at moderate risk, one steelhead population is at serious risk, one steelhead population is at moderate risk, three steelhead populations are not at risk, and status for 20 steelhead populations could not be assessed due to lack of data. Refer to Table 12 for identification for steelhead populations.

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Table 1. Snake River spring/summer chinook salmon and summer steelhead populations as defined by the Technical Review Team (TRT). Abbreviation for data index is as follows: Exp.RC = Expanded redd counts, RC = redd counts, RPKm = redds per kilometer, RPM = redds per mile, TLC = total live counts. A blank cell under data index column indicates that data of naturally produced fish are not available. Data for Valley Creek and East Fork Salmon River Chinook salmon populations (Chinook codes 24 and 28) are available by spring and summer runs, separately.

Spring/summer Chinook salmon			
Sub-basin	**ESU; Population**	**Data index**	**Code**
Snake River	ESU	TLC	-
Grande Ronde	Catherine Cr	RC	1
	Wallowa/Lostine R	RC	2
	Minam R	Exp.RC	3
	upper MS Grande Ronde R	RC	4
	Wenaha R	RC	5
Imnaha	Big Sheep Cr	RC	6
	Imnaha River mainstem	Exp.RC	7
Lower Snake trs	Tucannon R	Exp.RC	8
SF Salmon	Secesh R	RC	9
	South Fork Salmon R	RC	10
	EF SF Salmon R/Johnson Cr	Exp.RC	11
Salmon River trs	Chamberlain Cr	RPM	12
	Little Salmon R	RPM	13
MF Salmon R	Bear Valley Cr/Elk Cr	RPKm	14
	Big Cr	RPKm	15
	Camas Cr	RPKm	16
	MF Salmon R blw Indian Cr		17
	Pistol Cr		18
	Marsh Cr	RPKm	19
	Sulphur Cr	RPKm	20
	Loon Cr	RPKm	21
	MF Salmon R abv Indian Cr		22

Table 1 continued.

Spring/summer Chinook salmon			
Sub-basin	**ESU; Population**	**Data index**	**Code**
Upper Salmon R	Alturas Lake Cr	RC	23
	Valley Cr spring run	RC	24 spring
	Valley Cr summer run	RC	24 summer
	Lemhi R	RC	25
	NF Salmon R	RC	26
	Pahsimeroi R	Exp.RC	27
	East Fork Salmon R spring run	RPM	28 spring
	East Fork Salmon R summer run	RC	28 summer
	Upper MS Salmon (below Redfish Lake)	RC	29
	Upper MS Salmon (above Redfish Lake)		30
	Yankee Fork	RC	31

Summer steelhead			
Sub-basin	**ESU; Population**	**Data index**	**Code**
Snake River	ESU	TLC	-
Lower Snake	Tucannon River	Exp.RC	1
	Asotin Creek		2
Clearwater	Lower Clearwater		3
	South Fork		4
	Lolo Creek		5
	Lochsa River		6
	Selway River		7
Grande Ronde	Lower Grande Ronde		8
	Joseph Creek	Exp.RC	9
	Wallowa River	RPM	10
	Upper Grande Ronde	RPM	11
Salmon R	Little Salmon		12
	South Fork		13
	Secesh River		14
	Chamberlain Creek		15
	Big, Camas, and Loon		16
	Upper Middle Fork		17
	Panther Creek		18
	North Fork		19
	Lemhi River		20
	Pahsimeroi River		21
	East Fork		22
	Upper mainstem		23
Imnaha	Imnaha River	RPM	24
Hell's Canyon	Hell's Canyon		25

Table 2. Population trend status for spring/summer Chinook salmon based on the estimates of s^2 and m, and based on the marginal posterior distributions of those parameters where available all data series are used. The first row under the table header has results for the ESU, and the other rows are ordered by the mode of m. Population codes are shaded where the mode of m is negative. Column names are as follows: code = the population code (see Table 1); n = the length of annual time series data; y1 and y2 = the range of annual time series data; mode = the mode of marginal posterior distribution of the corresponding parameter; low = the lower bound of 95% approximate highest posterior density (HPD) region; up = the upper bound of 95% approximate HPD region.

code	n	yr1	yr2	$\hat{s}^2$	$\hat{m}$	s^2			m		
						mode	low	up	mode	low	up
ESU	25	1979	2003	0.063	0.034	0.056	0.000	0.378	0.032	-0.105	0.169
6	38	1964	2001	0.782	-0.139	0.748	0.000	2.477	-0.163	-0.515	0.189
4	42	1960	2001	0.083	-0.091	0.073	0.000	0.231	-0.102	-0.193	0.019
31	42	1960	2001	0.359	-0.073	0.315	0.000	0.999	-0.097	-0.286	0.156
25	45	1957	2001	0.179	-0.070	0.200	0.000	0.528	-0.074	-0.212	0.081
28 sp	45	1957	2001	0.179	-0.066	0.200	0.000	0.528	-0.070	-0.208	0.085
24 sp	44	1957	2001	0.442	-0.070	0.470	0.000	1.232	-0.070	-0.301	0.161
23	45	1957	2001	0.298	-0.080	0.332	0.000	0.879	-0.069	-0.279	0.100
29	46	1957	2003	0.179	-0.060	0.170	0.000	0.475	-0.067	-0.214	0.068
16	42	1960	2002	0.144	-0.051	0.126	0.000	0.401	-0.066	-0.186	0.094
28 su	46	1957	2003	0.240	-0.053	0.228	0.000	0.637	-0.061	-0.232	0.096
13	30	1972	2001	0.660	-0.055	0.705	0.000	2.633	-0.058	-0.457	0.340
11	45	1957	2001	0.085	-0.055	0.095	0.000	0.251	-0.058	-0.153	0.049
3	38	1964	2001	0.195	-0.045	0.187	0.000	0.618	-0.057	-0.233	0.119
10	45	1957	2001	0.109	-0.053	0.122	0.000	0.321	-0.056	-0.163	0.065
5	39	1963	2001	0.190	-0.042	0.162	0.000	0.602	-0.056	-0.214	0.120
14	46	1957	2002	0.162	-0.043	0.154	0.000	0.430	-0.049	-0.190	0.079
8	23	1979	2001	0.049	-0.049	0.050	0.000	0.345	-0.047	-0.198	0.085
20	46	1957	2002	0.247	-0.038	0.234	0.000	0.656	-0.046	-0.219	0.113
19	45	1958	2002	0.159	-0.054	0.177	0.000	0.469	-0.046	-0.199	0.077
2	39	1963	2001	0.133	-0.044	0.162	0.000	0.452	-0.045	-0.180	0.089
15	46	1957	2002	0.170	-0.037	0.161	0.000	0.451	-0.044	-0.187	0.088
24 su	47	1957	2003	0.197	-0.045	0.195	0.050	0.513	-0.039	-0.199	0.104
26	26	1960	2000	0.274	-0.044	0.334	0.000	1.468	-0.037	-0.340	0.222
9	44	1957	2001	0.128	-0.033	0.136	0.000	0.357	-0.033	-0.157	0.091
1	45	1957	2001	0.096	-0.039	0.107	0.000	0.283	-0.032	-0.152	0.063
21	44	1957	2002	0.168	-0.032	0.179	0.000	0.468	-0.032	-0.174	0.110
7	46	1956	2001	0.077	-0.027	0.073	0.000	0.204	-0.031	-0.128	0.057
12	20	1957	1997	0.388	-0.027	0.478	0.000	3.337	-0.029	-0.548	0.415
27	22	1980	2001	1.456	0.056	2.103	0.000	8.505	0.040	-0.654	0.821

Table 3. Population trend status for spring/summer Chinook salmon based on the estimates of s^2 and m, and based on the marginal posterior distributions of those parameters where post-1980 data series are used. The first row under the table header has results for the ESU, and the other rows are ordered by the mode of m. Population codes are shaded where the mode of m is negative. Column names are as follows: code = the population code (see Table 1); n = the length of annual time series data; y1 and y2 = the range of annual time series data; mode = the mode of marginal posterior distribution of the corresponding parameter; low = the lower bound of 95% approximate highest posterior density (HPD) region; up = the upper bound of 95% approximate HPD region.

code	n	yr1	yr2	$\hat{s}^2$	$\hat{m}$	s^2			m		
						mode	low	up	mode	low	up
ESU	24	1980	2003	0.066	0.033	0.057	0.000	0.382	0.030	-0.135	0.174
6	22	1980	2001	1.682	-0.209	2.164	0.000	9.687	-0.149	-1.054	0.642
4	22	1980	2001	0.107	-0.082	0.085	0.000	0.736	-0.094	-0.296	0.137
8	22	1980	2001	0.050	-0.056	0.040	0.000	0.344	-0.064	-0.202	0.093
23	22	1980	2001	0.437	-0.027	0.348	0.000	3.007	-0.051	-0.459	0.415
28 sp	22	1980	2001	0.318	-0.006	0.253	0.000	2.188	-0.027	-0.375	0.371
1	22	1980	2001	0.088	-0.002	0.070	0.000	0.605	-0.013	-0.196	0.196
7	22	1980	2001	0.095	0.005	0.076	0.000	0.654	-0.006	-0.197	0.211
16	22	1980	2002	0.243	0.019	0.193	0.000	1.672	0.001	-0.303	0.349
31	22	1980	2001	0.353	0.023	0.281	0.000	2.429	0.001	-0.366	0.420
25	22	1980	2001	0.343	0.024	0.273	0.000	2.360	0.002	-0.359	0.415
2	22	1980	2001	0.208	0.027	0.165	0.000	1.431	0.010	-0.271	0.332
11	22	1980	2001	0.057	0.031	0.045	0.000	0.392	0.022	-0.125	0.191
29	24	1980	2003	0.300	0.046	0.258	0.000	1.735	0.040	-0.311	0.347
27	22	1980	2001	1.456	0.056	2.103	0.000	8.505	0.040	-0.654	0.821
13	22	1980	2001	0.431	0.065	0.343	0.000	2.966	0.041	-0.364	0.504
24 su	24	1980	2003	0.314	0.050	0.270	0.000	1.816	0.044	-0.316	0.358
3	22	1980	2001	0.208	0.061	0.165	0.000	1.431	0.044	-0.237	0.366
24 sp	22	1980	2001	0.594	0.073	0.472	0.000	4.087	0.045	-0.431	0.588
5	22	1980	2001	0.204	0.070	0.162	0.000	1.404	0.053	-0.225	0.372
10	22	1980	2001	0.106	0.067	0.084	0.000	0.729	0.055	-0.146	0.285
28 su	24	1980	2003	0.435	0.068	0.375	0.000	2.515	0.061	-0.362	0.431
9	21	1980	2001	0.065	0.070	0.078	0.000	0.549	0.063	-0.109	0.235
19	23	1980	2002	0.201	0.063	0.206	0.000	1.417	0.066	-0.240	0.334
21	22	1980	2002	0.217	0.092	0.173	0.000	1.493	0.075	-0.213	0.403
20	23	1980	2002	0.247	0.081	0.253	0.000	1.741	0.085	-0.254	0.382
15	23	1980	2002	0.250	0.085	0.256	0.000	1.762	0.089	-0.252	0.387
14	23	1980	2002	0.210	0.089	0.215	0.000	1.480	0.092	-0.220	0.366
12	11	1985	1997	0.295	0.072	0.899	0.000	14.513	0.151	-1.217	1.063
26	7	1994	2000	NA	0.413	NA	NA	NA	NA	NA	NA

Table 4. Population trend status for summer steelhead based on the estimates of s^2 and m, and based on the marginal posterior distributions of those parameters where available all data series are used. The first row under the table header has results for the ESU, and the other rows are ordered by the mode of m. Population codes are shaded where the mode of m is negative. Column names are as follows: code = the population code (see Table 1); n = the length of annual time series data; y1 and y2 = the range of annual time series data; mode = the mode of marginal posterior distribution of the corresponding parameter; low = the lower bound of 95% approximate highest posterior density (HPD) region; up = the upper bound of 95% approximate HPD region.

code	n	yr1	yr2	$\hat{s}^2$	$\hat{m}$	s^2			m		
						mode	low	up	mode	low	up
ESU	22	1980	2001	0.055	-0.010	0.044	0.000	0.378	-0.019	-0.163	0.147
1	12	1987	2001	0.011	-0.123	0.088	0.000	1.552	-0.132	-0.400	0.204
11	31	1970	2002	0.163	0.022	0.207	0.000	0.601	0.019	-0.169	0.206
24	33	1970	2002	0.217	0.023	0.282	0.000	0.823	0.022	-0.182	0.226
10	33	1970	2002	0.149	0.047	0.194	0.000	0.565	0.046	-0.122	0.215
9	33	1970	2002	0.236	0.049	0.307	0.000	0.895	0.048	-0.164	0.261

Table 5. Population trend status for summer steelhead based on the estimates of s^2 and m, and based on the marginal posterior distributions of those parameters where post-1980 data series are used. The first row under the table header has results for the ESU, and the other rows are ordered by the mode of m. Population codes are shaded where the mode of m is negative. Column names are as follows: code = the population code (see Table 1); n = the length of annual time series data; y1 and y2 = the range of annual time series data; mode = the mode of marginal posterior distribution of the corresponding parameter; low = the lower bound of 95% approximate highest posterior density (HPD) region; up = the upper bound of 95% approximate HPD region.

code	n	yr1	yr2	$\hat{s}^2$	$\hat{m}$	s^2			m		
						mode	low	up	mode	low	up
ESU	22	1980	2001	0.055	-0.010	0.044	0.000	0.378	-0.019	-0.163	0.147
1	12	1987	2001	0.011	-0.123	0.088	0.000	1.552	-0.132	-0.400	0.204
11	21	1980	2002	0.124	-0.030	0.149	0.000	1.047	-0.040	-0.278	0.198
24	23	1980	2002	0.173	0.026	0.177	0.000	1.219	0.029	-0.255	0.278
9	23	1980	2002	0.240	0.050	0.245	0.000	1.692	0.054	-0.281	0.346
10	23	1980	2002	0.158	0.065	0.162	0.000	1.114	0.068	-0.203	0.305

Table 6. Loss function values used for decision analysis regarding population trend. These values are from Wade (2000).

Decisions	$m < -0.05$	$-0.05 \le m \le 0$	$m > 0$
1. Conclude hypothesis 1 that population is declining rapidly	0.0	0.5	1.0
2. Conclude hypothesis 2 that population is declining slowly	0.5	0.0	0.5
3. Conclude hypothesis 3 that population is not declining	1.0	0.5	0.0

Table 7. Prioritization of populations based on decision analysis of population trend for spring/summer Chinook salmon with available all data series and the standard uninformative prior being used. Three decisions are considered: (1) decision 1: population of interest is declining rapidly; (2) decision 2: population of interest is declining slowly; and (3) decision 3: population of interest is not declining. Decision whose expected loss value is least is selected (shaded). Within a selected decision category, populations are in order of the mode of m (Table 2). See Table 1 for population names of codes.

code	Posterior probability			Expected loss		
	m <-0.05	-0.05 ≤ m ≤ 0	m >0	Decision 1	Decision 2	Decision 3
ESU	0.097	0.183	0.720	0.812	0.408	0.188
6	0.737	0.080	0.183	0.223	0.460	0.777
4	0.800	0.161	0.039	0.119	0.419	0.881
31	0.621	0.152	0.227	0.303	0.424	0.697
25	0.614	0.241	0.145	0.266	0.379	0.734
28 sp	0.592	0.255	0.154	0.281	0.373	0.719
24 sp	0.581	0.163	0.256	0.337	0.418	0.663
23	0.638	0.195	0.167	0.265	0.403	0.735
29	0.577	0.253	0.171	0.297	0.374	0.703
16	0.534	0.257	0.209	0.338	0.372	0.662
28 su	0.527	0.244	0.228	0.351	0.378	0.649
13	0.514	0.137	0.349	0.418	0.432	0.582
11	0.541	0.344	0.115	0.287	0.328	0.713
10	0.523	0.327	0.149	0.313	0.336	0.687
8	0.508	0.316	0.176	0.334	0.342	0.666
19	0.531	0.282	0.187	0.328	0.359	0.672
3	0.494	0.246	0.260	0.383	0.377	0.617
5	0.463	0.266	0.271	0.404	0.367	0.596
14	0.481	0.288	0.231	0.375	0.356	0.625
20	0.460	0.244	0.296	0.418	0.378	0.582
2	0.477	0.296	0.227	0.375	0.352	0.625
15	0.447	0.283	0.269	0.411	0.358	0.589
24 su	0.483	0.259	0.258	0.387	0.371	0.613
26	0.484	0.172	0.344	0.430	0.414	0.570
9	0.398	0.313	0.289	0.446	0.344	0.554
1	0.409	0.393	0.198	0.394	0.304	0.606
21	0.407	0.279	0.314	0.453	0.361	0.547
7	0.313	0.437	0.251	0.469	0.282	0.531
12	0.455	0.120	0.425	0.485	0.440	0.515
27	0.365	0.076	0.559	0.597	0.462	0.403

Table 8. Prioritization of populations based on decision analysis of population trend for spring/summer Chinook salmon with post-1980 data series and the standard uninformative prior being used. Three decisions are considered: (1) decision 1: population of interest is declining rapidly; (2) decision 2: population of interest is declining slowly; and (3) decision 3: population of interest is not declining. Decision whose expected loss value is least is selected (shaded). Within a selected decision category, populations are in order of the mode of m (Table 3). See Table 1 for population names of codes.

code	Posterior probability			Expected loss		
	$m < -0.05$	$-0.05 \le m \le 0$	$m > 0$	Decision 1	Decision 2	Decision 3
ESU	0.119	0.186	0.695	0.788	0.407	0.212
6	0.694	0.053	0.254	0.280	0.474	0.720
4	0.673	0.179	0.148	0.238	0.411	0.762
8	0.561	0.289	0.149	0.294	0.355	0.706
23	0.454	0.123	0.423	0.485	0.438	0.515
28 sp	0.380	0.145	0.475	0.547	0.427	0.453
1	0.265	0.259	0.476	0.605	0.371	0.395
7	0.245	0.237	0.518	0.636	0.382	0.364
16	0.293	0.156	0.552	0.629	0.422	0.371
31	0.318	0.129	0.553	0.617	0.435	0.383
25	0.315	0.129	0.556	0.621	0.435	0.379
2	0.252	0.164	0.584	0.666	0.418	0.334
11	0.113	0.195	0.693	0.790	0.403	0.210
29	0.252	0.121	0.627	0.688	0.439	0.312
27	0.365	0.076	0.559	0.597	0.462	0.403
13	0.248	0.097	0.655	0.703	0.452	0.297
24 su	0.251	0.112	0.638	0.694	0.444	0.306
3	0.178	0.127	0.695	0.758	0.436	0.242
24 sp	0.268	0.084	0.647	0.689	0.458	0.311
5	0.163	0.109	0.727	0.782	0.445	0.218
10	0.106	0.108	0.785	0.839	0.446	0.161
28 su	0.251	0.092	0.658	0.704	0.454	0.296
9	0.072	0.083	0.845	0.887	0.458	0.113
19	0.166	0.132	0.702	0.768	0.434	0.232
21	0.136	0.086	0.778	0.821	0.457	0.179
20	0.157	0.117	0.726	0.785	0.442	0.215
15	0.155	0.112	0.734	0.789	0.444	0.211
14	0.132	0.103	0.765	0.817	0.448	0.183
12	0.320	0.068	0.612	0.646	0.466	0.354
26	0.454	0.006	0.540	0.543	0.497	0.457

Table 9. Prioritization of populations based on decision analysis of population trend for summer steelhead with available all data series and the standard uninformative prior being used. Three decisions are considered: (1) decision 1: population of interest is declining rapidly; (2) decision 2: population of interest is declining slowly; and (3) decision 3: population of interest is not declining. Decision whose expected loss value is least is selected (shaded). Within a selected decision category, populations are in order of the mode of m (Table 4). See Table 1 for population names of codes.

code	Posterior probability			Expected loss		
	m <-0.05	-0.05 ≤ m ≤ 0	m >0	Decision 1	Decision 2	Decision 3
ESU	0.252	0.325	0.423	0.586	0.337	0.414
1	0.886	0.051	0.063	0.088	0.475	0.912
11	0.194	0.208	0.598	0.702	0.396	0.298
24	0.223	0.176	0.601	0.689	0.412	0.311
10	0.119	0.159	0.722	0.802	0.421	0.198
9	0.161	0.149	0.689	0.764	0.425	0.236

Table 10. Prioritization of populations based on decision analysis of population trend for summer steelhead with post-1980 data series and the standard uninformative prior being used. Three decisions are considered: (1) decision 1: population of interest is declining rapidly; (2) decision 2: population of interest is declining slowly; and (3) decision 3: population of interest is not declining. Decision whose expected loss value is least is selected (shaded). Within a selected decision category, populations are in order of the mode of m (Table 5). See Table 1 for population names of codes.

code	Posterior probability			Expected loss		
	m <-0.05	-0.05 ≤ m ≤ 0	m >0	Decision 1	Decision 2	Decision 3
ESU	0.252	0.325	0.423	0.586	0.337	0.414
1	0.886	0.051	0.063	0.088	0.475	0.912
11	0.425	0.213	0.362	0.468	0.394	0.532
24	0.253	0.163	0.584	0.666	0.418	0.334
9	0.216	0.138	0.646	0.715	0.431	0.285
10	0.142	0.131	0.727	0.793	0.435	0.207

Table 11. Summary of at-risk status for spring/summer Chinook salmon populations. S risk = at serious risk; M risk = at moderate risk; No = at no risk. 'NA' indicates that enough data are not available. See Tables 7 and 8 for order of populations at severity of risk. Big Sheep Creek Chinook salmon population (code 6) is extinct.

Sub-basin	ESU; population	Code	Pre- and Post-1980 data			Post-1980 data		
			S risk	M risk	No	S risk	M risk	No
Snake R	ESU	-	NA	NA	NA			X
Grande Ronde	Catherine Cr	1		X			X	
	Wallowa/Lostine R	2		X				X
	Minam R	3		X				X
	upper MS Grande Ronde R	4	X			X		
	Wenaha R	5		X				X
Imnaha	Big Sheep Cr	6	Extinct	Extinct	Extinct	Extinct	Extinct	Extinct
	Imnaha River mainstem	7		X				X
Lower Snake trs	Tucannon R	8	NA	NA	NA	X		
SF Salmon	Secesh R	9		X				X
	South Fork Salmon R	10	X					X
	EF SF Salmon R/Johnson Cr	11	X					X
Salmon River trs	Chamberlain Cr	12	NA	NA	NA	NA	NA	NA
	Little Salmon R	13	X					X
MF Salmon R	Bear Valley Cr/Elk Cr	14		X				X
	Big Cr	15		X				X
	Camas Cr	16	X					X
	MF Salmon R blw Indian Cr	17	NA	NA	NA	NA	NA	NA
	Pistol Cr	18	NA	NA	NA	NA	NA	NA
	Marsh Cr	19	X					X
	Sulphur Cr	20		X				X
	Loon Cr	21		X				X
	MF Salmon R abv Indian Cr	22	NA	NA	NA	NA	NA	NA

Table 11 continued.

Sub-basin	ESU; population	Code	Pre- and Post-1980 data			Post-1980 data		
			S risk	M risk	No	S risk	M risk	No
Upper Salmon R	Alturas Lake Cr	23	X				X	
	Valley Cr spring	24 sp	X					X
	Valley Cr summer	24 su		X				X
	Lemhi R	25	X					X
	NF Salmon R	26		X				X
	Pahsimeroi R	27	NA	NA	NA			X
	East Fork Salmon R spring	28 sp	X				X	
	East Fork Salmon R summer	28 su	X					X
	Upper MS Salmon (below Redfish Lake)	29	X					X
	Upper MS Salmon (above Redfish Lake)	30	NA	NA	NA	NA	NA	NA
	Yankee Fork	31	X					X

Table 12. Summary of at-risk status for summer steelhead populations. S risk = at serious risk; M risk = at moderate risk; No = at no risk. 'NA' indicates that enough data are not available. See Tables 9 and 10 for order of populations at severity of risk.

Sub-basin	ESU; population	code	Pre- and Post-1980 data			Post-1980 data		
			S risk	M risk	No	S risk	M risk	No
Snake R	ESU	-	NA	NA	NA		X	
Lower Snake	Tucannon River	1	NA	NA	NA	X		
	Asotin Creek	2	NA	NA	NA	NA	NA	NA
Clearwater	Lower Clearwater	3	NA	NA	NA	NA	NA	NA
	South Fork	4	NA	NA	NA	NA	NA	NA
	Lolo Creek	5	NA	NA	NA	NA	NA	NA
	Lochsa River	6	NA	NA	NA	NA	NA	NA
	Selway River	7	NA	NA	NA	NA	NA	NA
Grande Ronde	Lower Grande Ronde	8	NA	NA	NA	NA	NA	NA
	Joseph Creek	9			X			X
	Wallowa River	10			X			X
	Upper Grande Ronde	11			X		X	
Salmon R	Little Salmon	12	NA	NA	NA	NA	NA	NA
	South Fork	13	NA	NA	NA	NA	NA	NA
	Secesh River	14	NA	NA	NA	NA	NA	NA
	Chamberlain Creek	15	NA	NA	NA	NA	NA	NA
	Big, Camas, and Loon	16	NA	NA	NA	NA	NA	NA
	Upper Middle Fork	17	NA	NA	NA	NA	NA	NA
	Panther Creek	18	NA	NA	NA	NA	NA	NA
	North Fork	19	NA	NA	NA	NA	NA	NA
	Lemhi River	20	NA	NA	NA	NA	NA	NA
	Pahsimeroi River	21	NA	NA	NA	NA	NA	NA
	East Fork	22	NA	NA	NA	NA	NA	NA
	Upper mainstem	23	NA	NA	NA	NA	NA	NA
Imnaha	Imnaha River	24			X			X
Hell's Canyon	Hell's Canyon	25	NA	NA	NA	NA	NA	NA

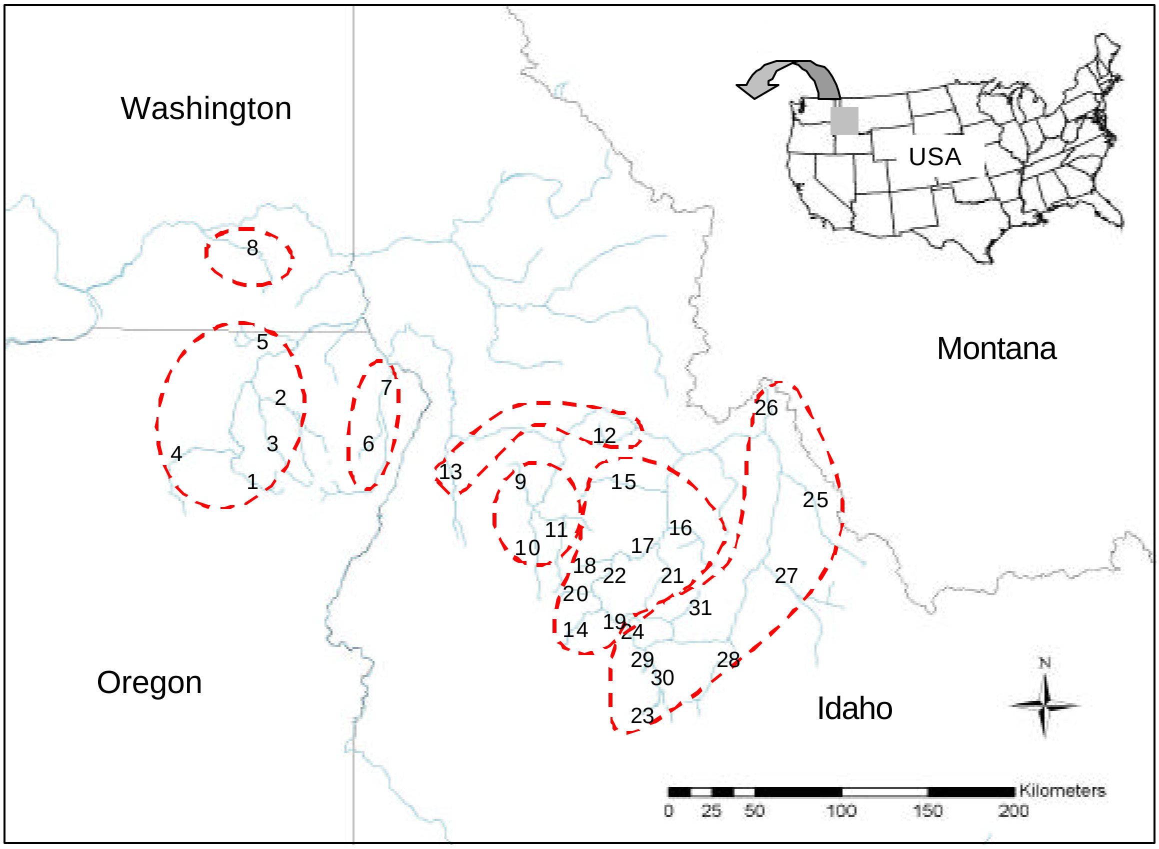

Fig. 1. Spawning areas of Snake River spring/summer Chinook salmon populations. Each number indicates Chinook salmon population code (Table 1). Populations within a dotted boundary belong to the same sub-basin.

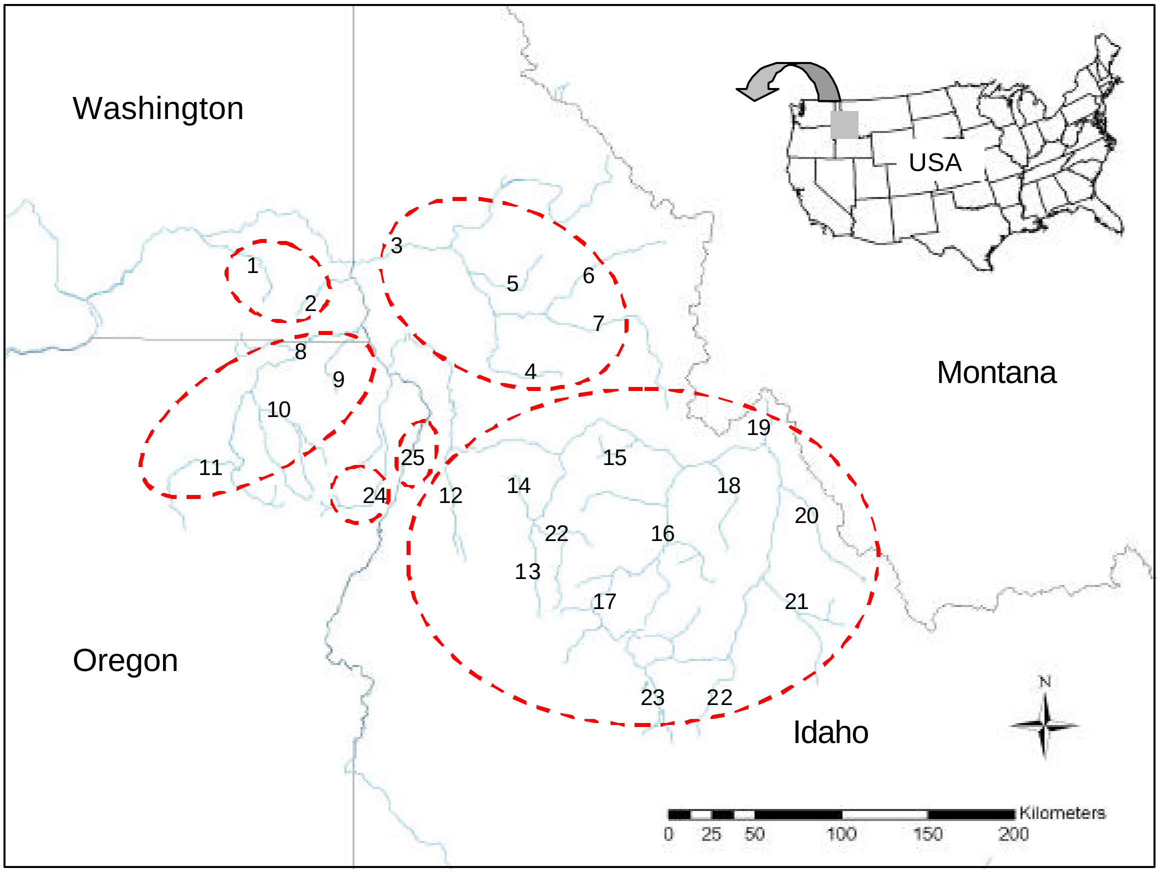

Fig. 2. Spawning areas of Snake Rive summer steelhead populations. Each number indicates steelhead population code (Table 1). Populations within a dotted boundary belong to the same sub-basin.

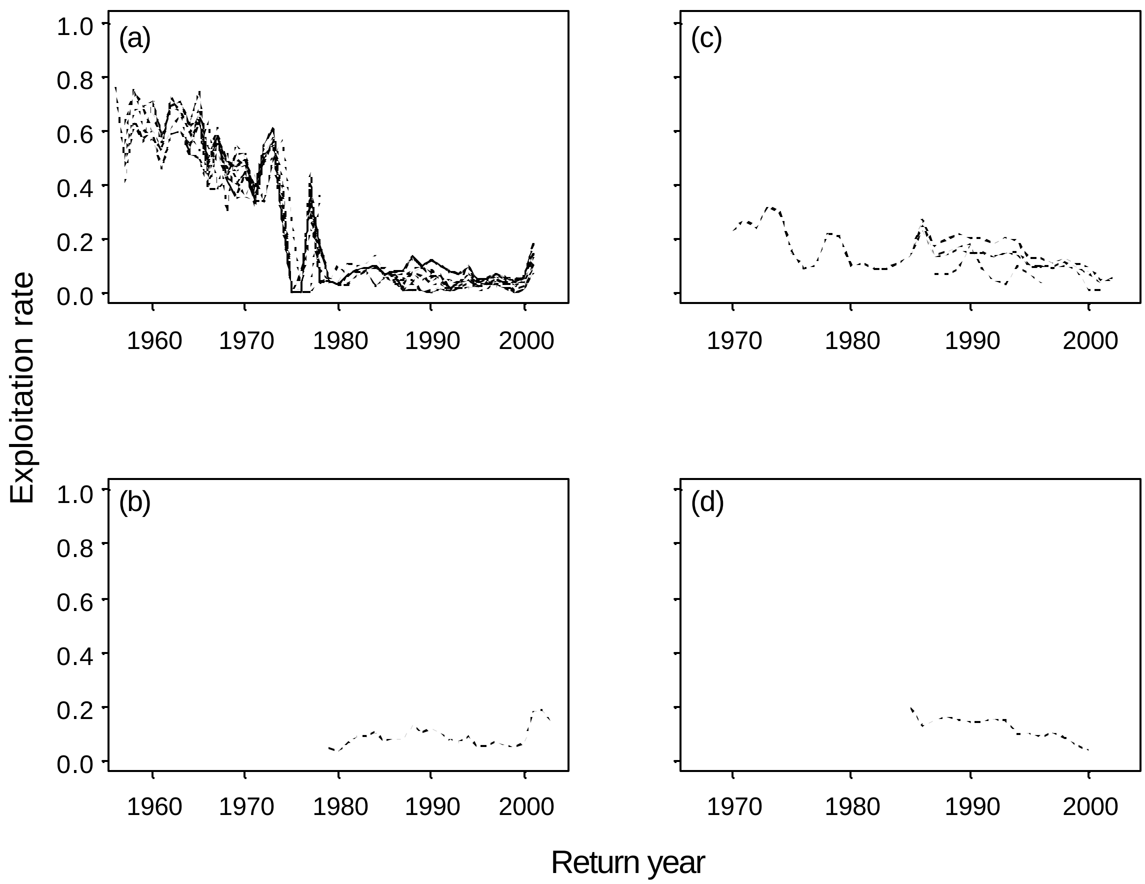

Fig. 3. (a) Annual exploitation rate from the TRT dataset for most Snake River spring/summer Chinook salmon populations except for Secesh River and South Fork Salmon River Chinook populations (Chinook codes 9 and 10). (b) Annual exploitation rate from the TAC dataset for Snake River spring/summer Chinook salmon ESU. (c) Annual exploitation rates from the TRT dataset for five Snake River A-run steelhead populations. (d) Annual exploitation rate from the TAC dataset for Snake River A-run steelhead.

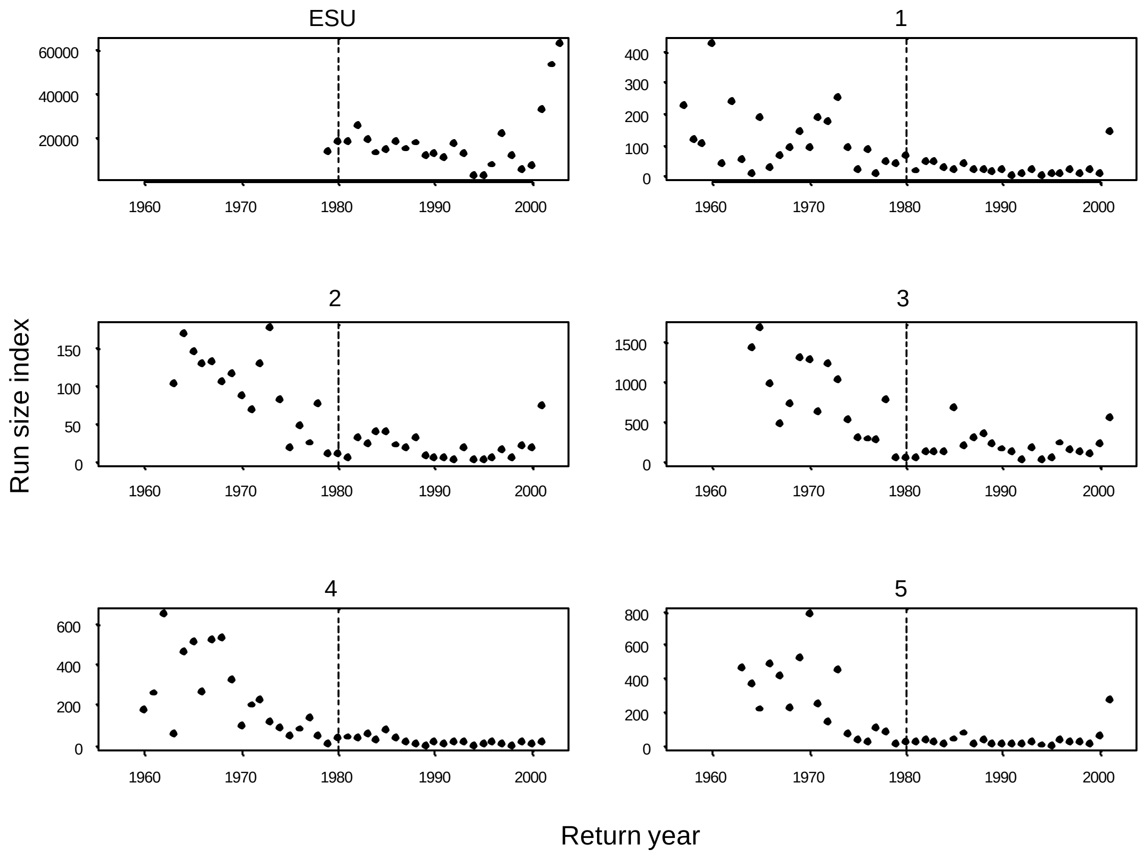

Fig. 4. Abundance index over time of spring/summer Chinook salmon populations. The number above each plot is Chinook population code (Table 1). Abundance index unit is shown in Table 1. The dotted vertical line is added on year 1980. Data of spring and summer runs are separately available for Valley Creek and East Fork Salmon River Chinook salmon populations (Chinook codes 24 and 28) where the left and right sides of y-axis indicates spring and summer runs respectively.

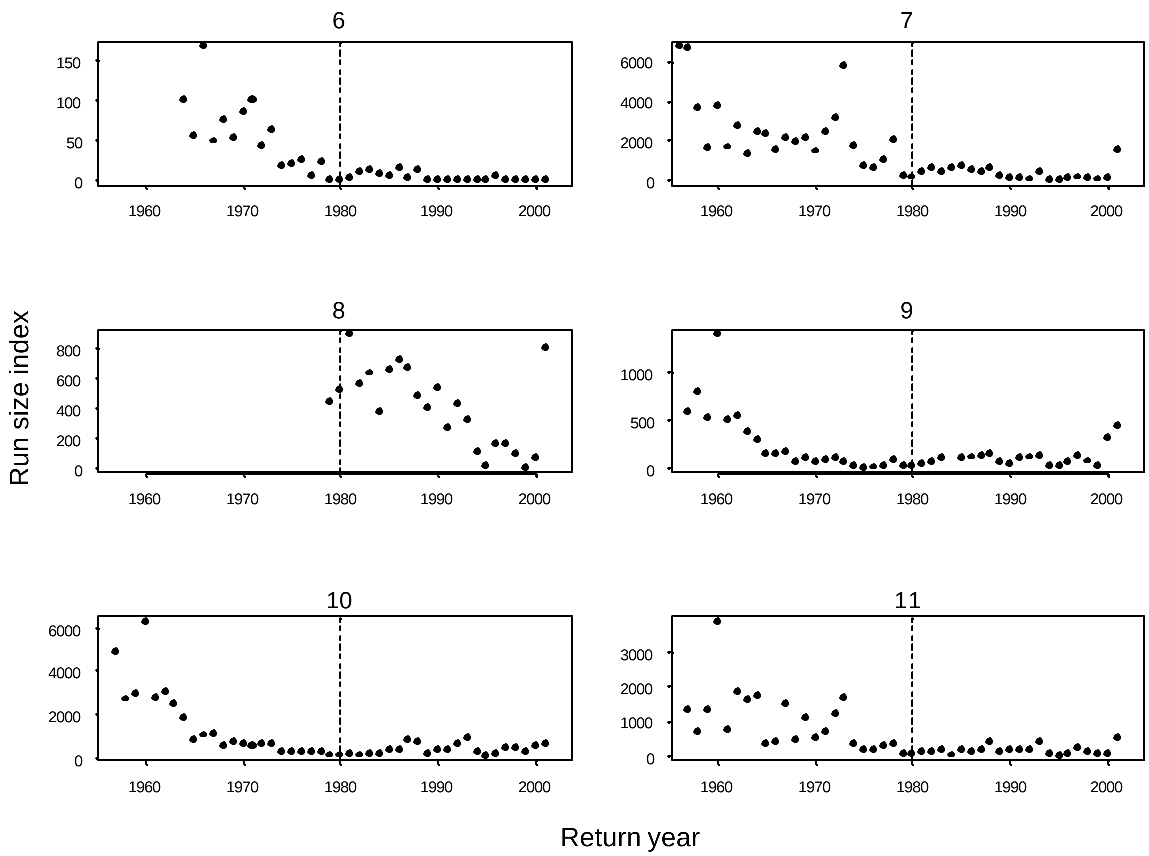

Fig. 4 continued.

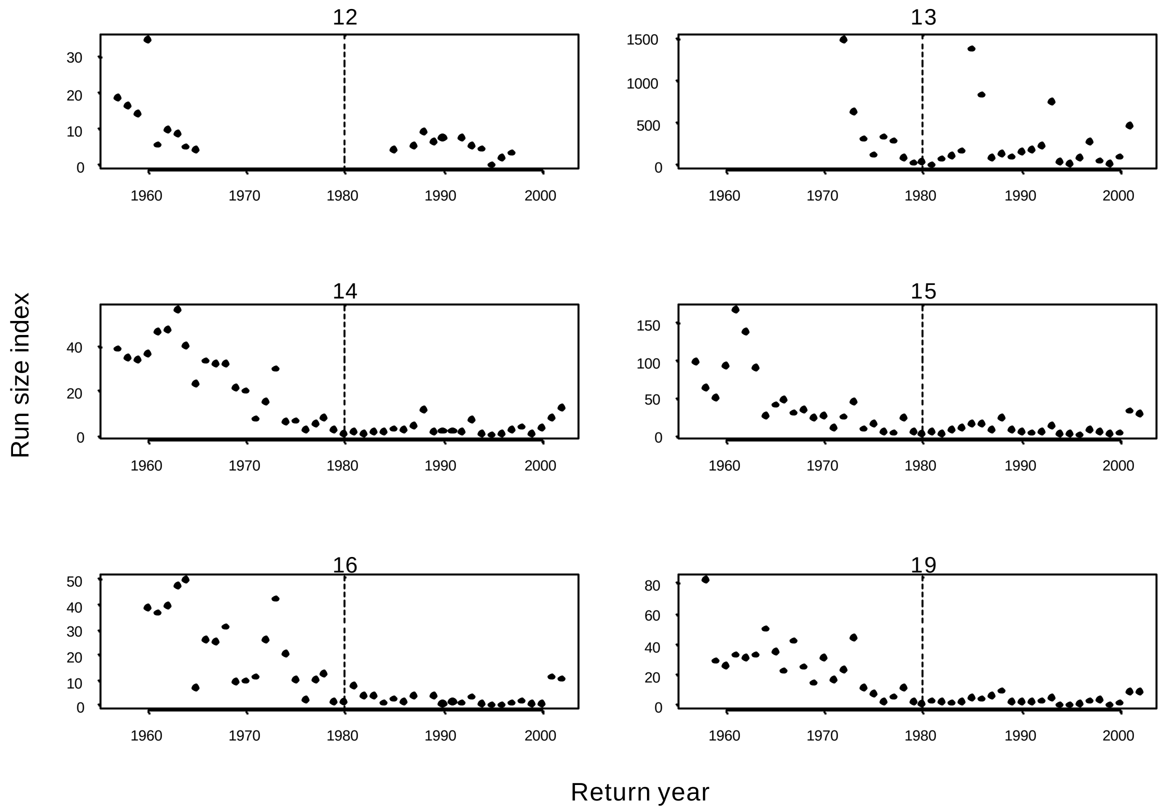

Fig. 4 continued.

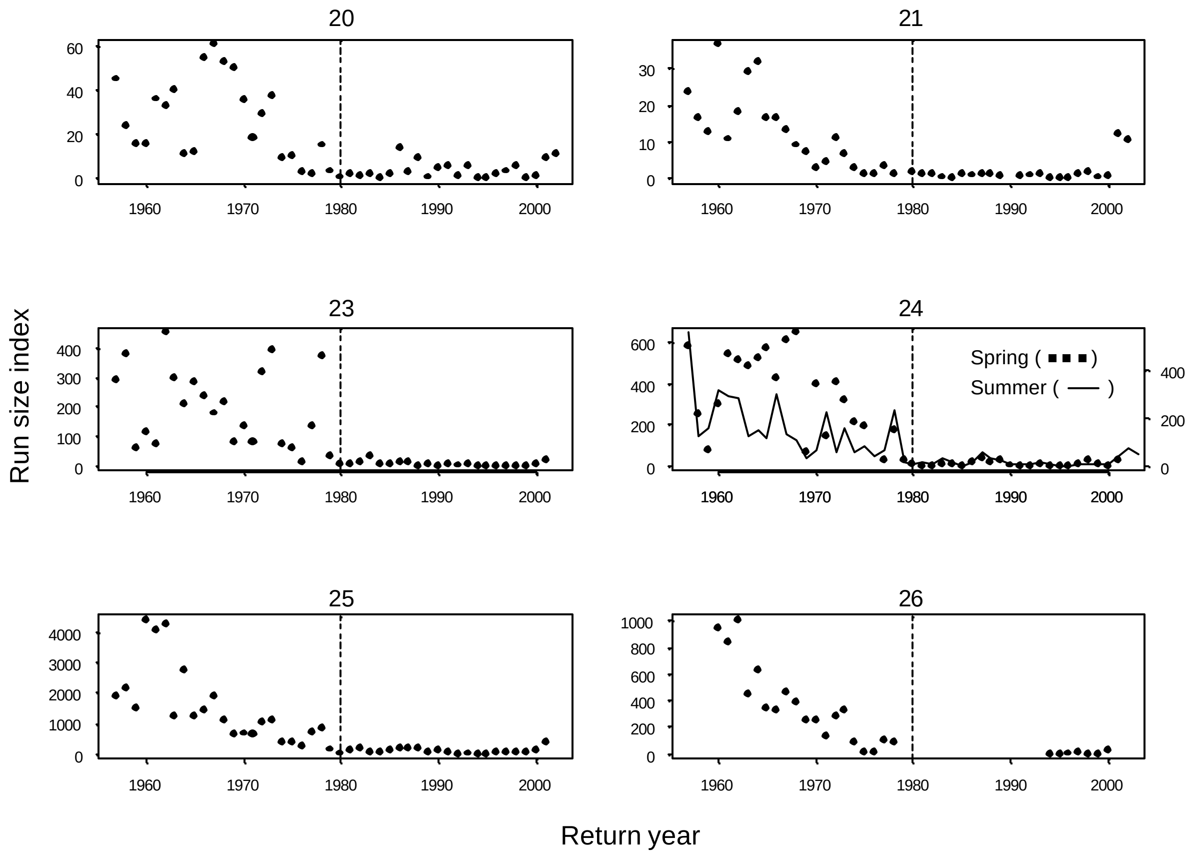

Fig. 4 continued.

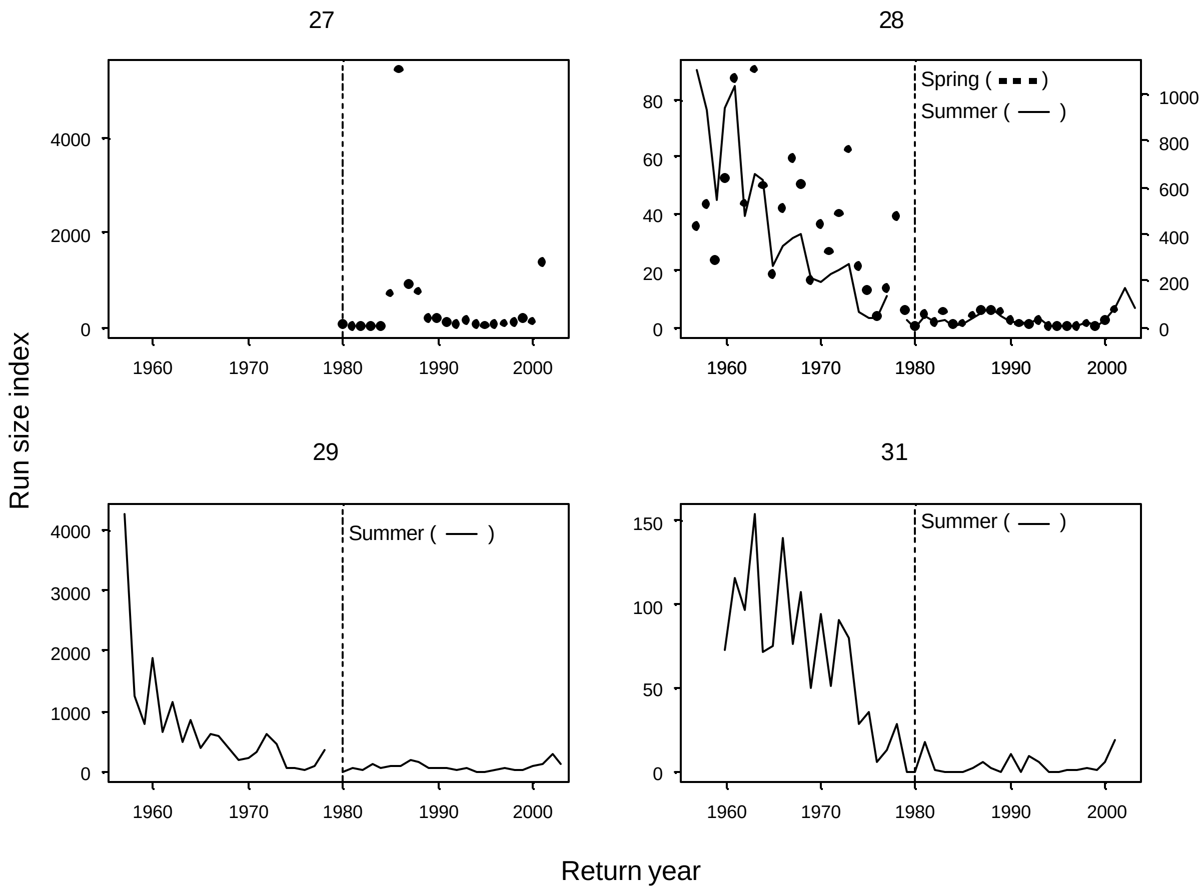

Fig. 4 continued.

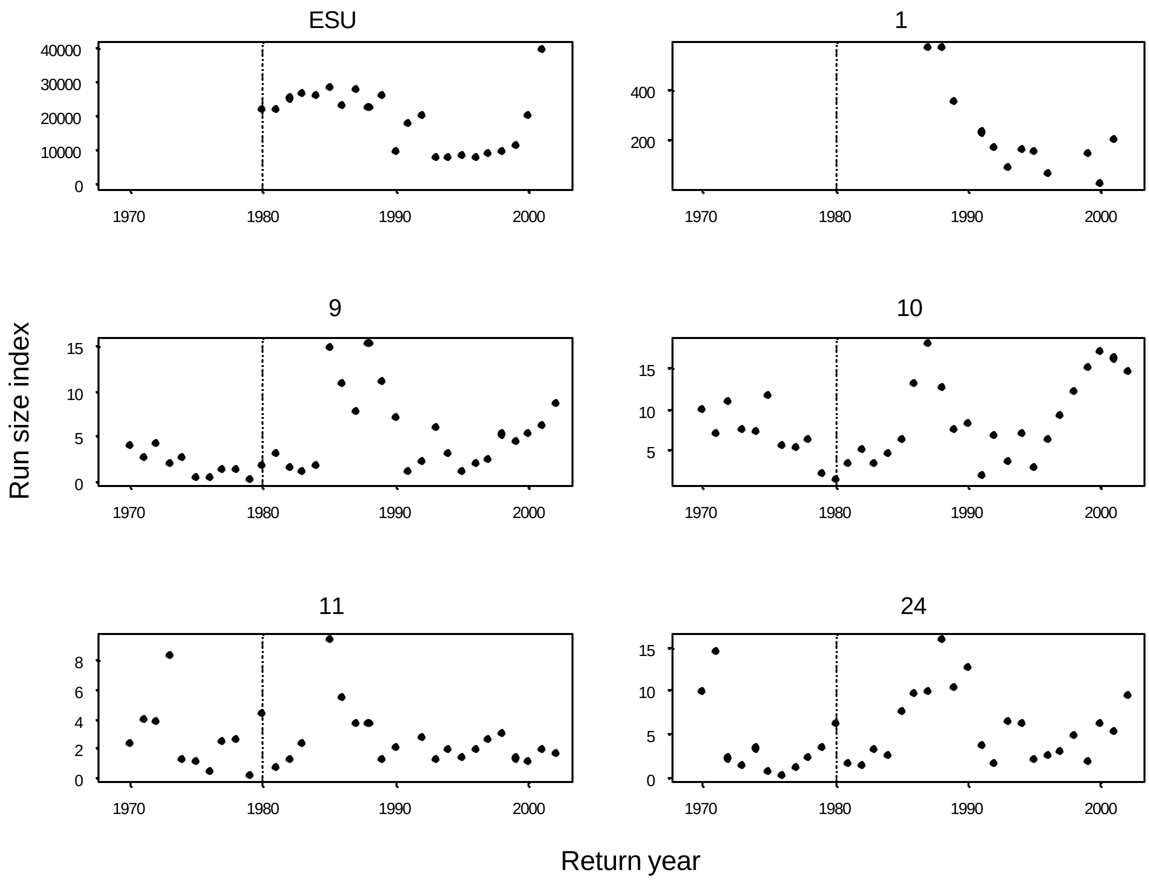

Fig. 5. Abundance index over time of summer steelhead populations. The number above each plot is population code (Table 1). Abundance index unit is shown in Table 1. The dotted vertical line is added on year 1980.

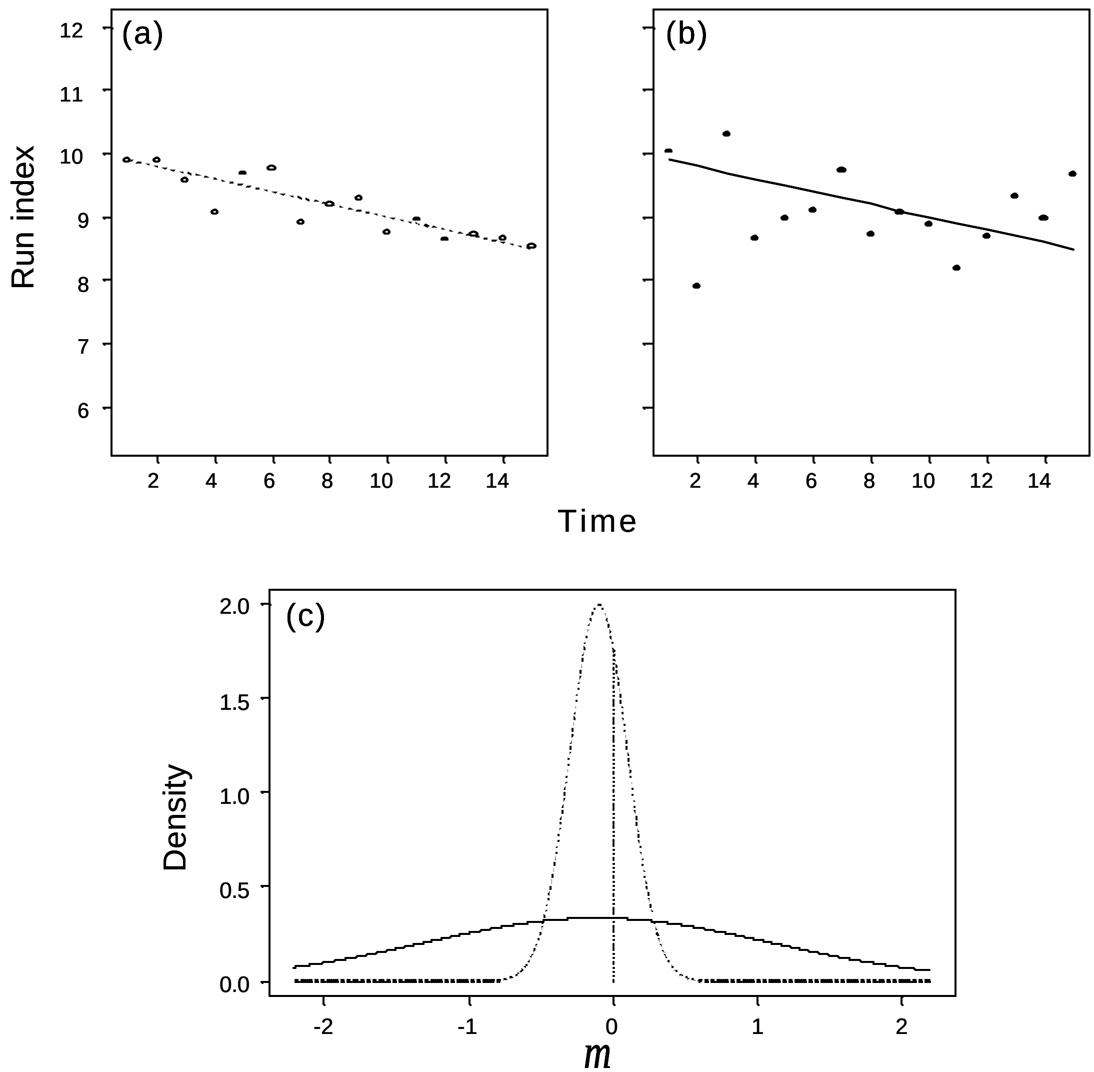

Fig. 6. (a) Trend of population A; (b) Trend of population B; and (c) Comparison of two populations in the posterior distribution of population growth rate m, where the dotted curve indicates the distribution of m for population A, and the solid curve is that for population B. Estimates of m for two populations A, and B are equal to each other: $\hat{m}_A = \hat{m}_B = -0.1$. But the variability in population sizes over time is different between those populations: the estimate of $Var(m_A) = 0.2^2$ and that of $Var(m_B) = 1.2^2$. We add the vertical line of '$m = 0$' to help to compare areas under these two density curves that indicate $\Pr(m < 0)$. Because $\Pr(m_A < 0) = 0.691$ and $\Pr(m_B < 0) = 0.533$, population A is at higher risk than population B.

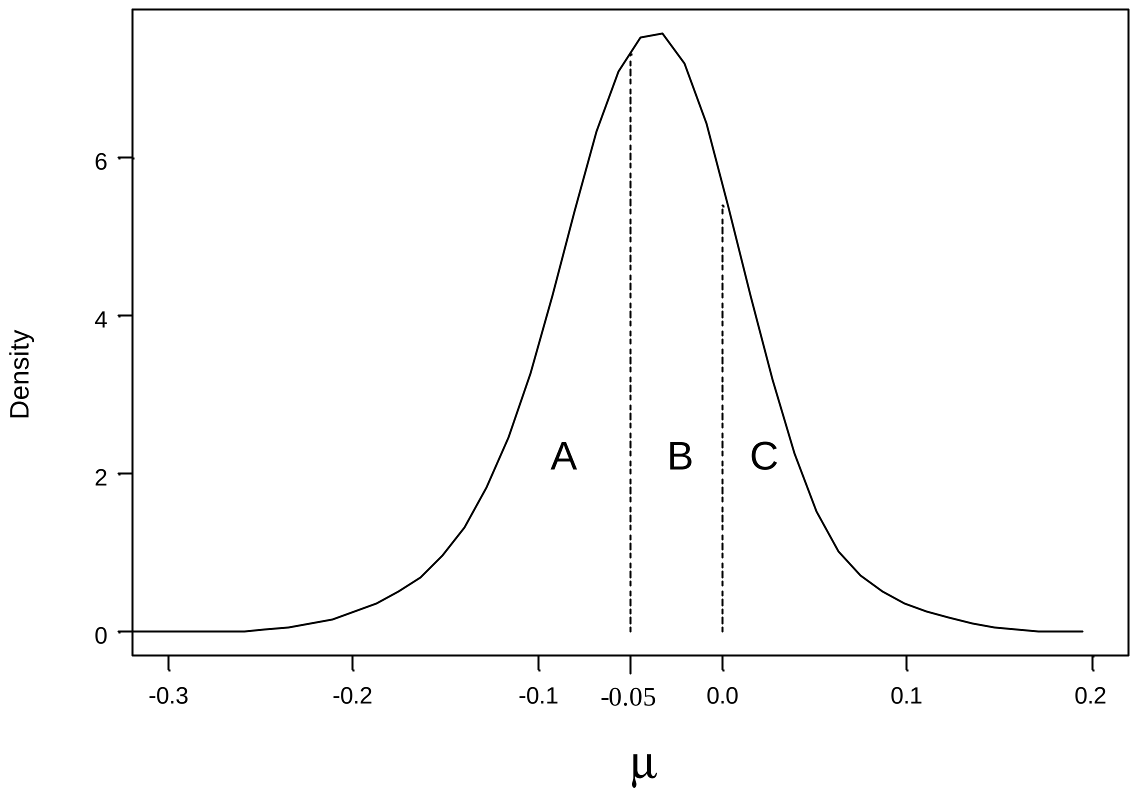

Fig. 7. Posterior probabilities for three ranges of parameter m : (1) $m < -0.05$; (2) $-0.05 \leq m \leq 0$; (3) $m > 0$. Pr($m < -0.05$) = area A; Pr($-0.05 \leq m \leq 0$) = area B; Pr($m > 0$) = area C. As an example, this shape is the posterior distribution of m for Catherine Creek spring/summer Chinook salmon population (Chinook code 1; Table 1) with available all data series and the standard uninformative prior being used. In this example, area A = 0.409; area B = 0.393; and area C = 0.198.

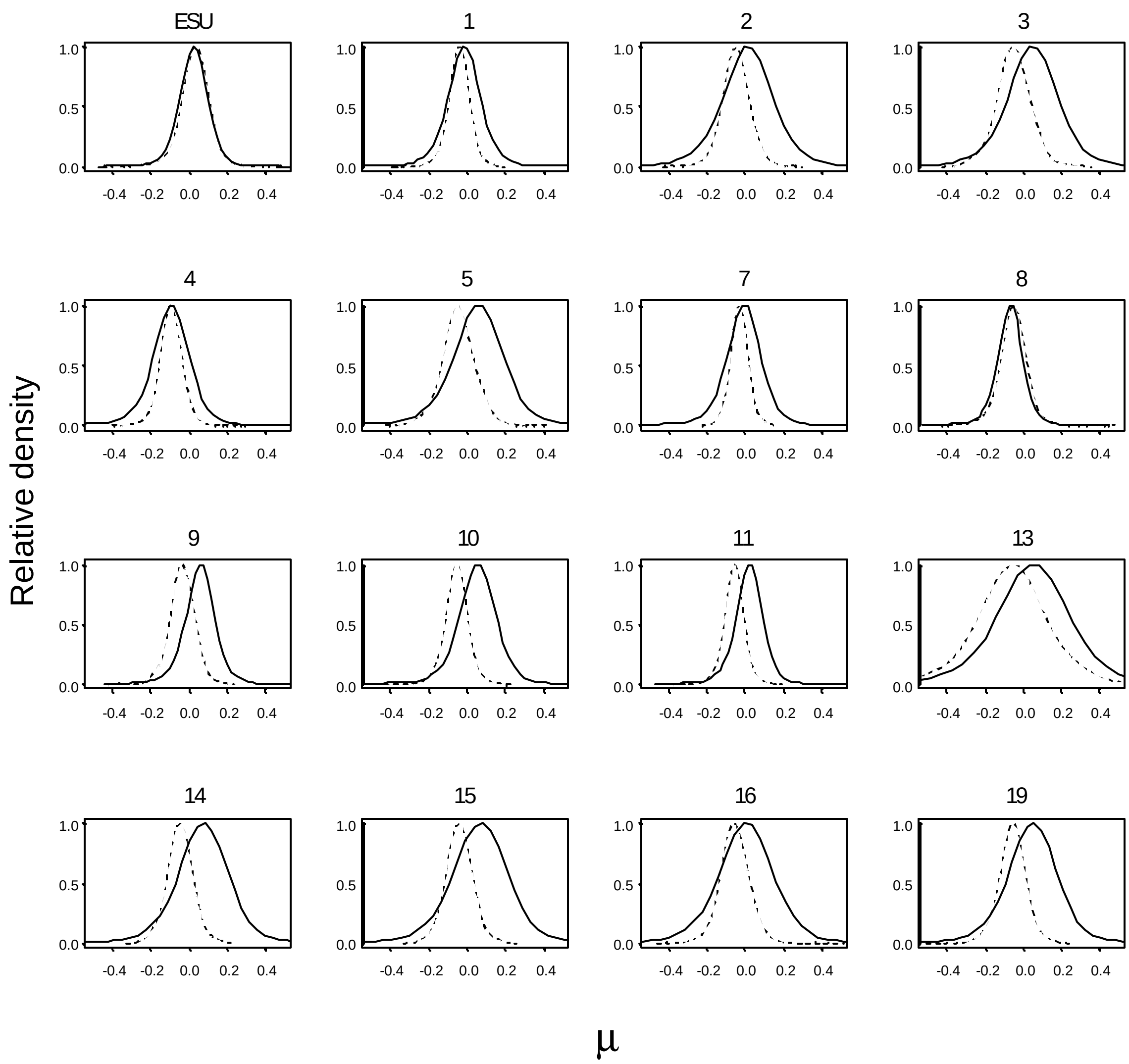

Fig. 8. Posterior distribution of *m* for spring/summer Chinook salmon. The number above each plot is population code (Table 1). Dotted line is based on available all data series, whereas solid line is based on post-1980 data series. Big Sheep Creek Chinook salmon population (code 6) is extinct, data for Chamberlain Creek Chinook salmon population (code 12) are not enough, and data are not available for Mid-Fork Salmon River Chinook salmon populations below and above Indian Creek (codes 17, 22), for Pistol Creek Chinook salmon population (code 18), and for Upper Mainstem Salmon River Chinook salmon population above Redfish Lake (code 30).

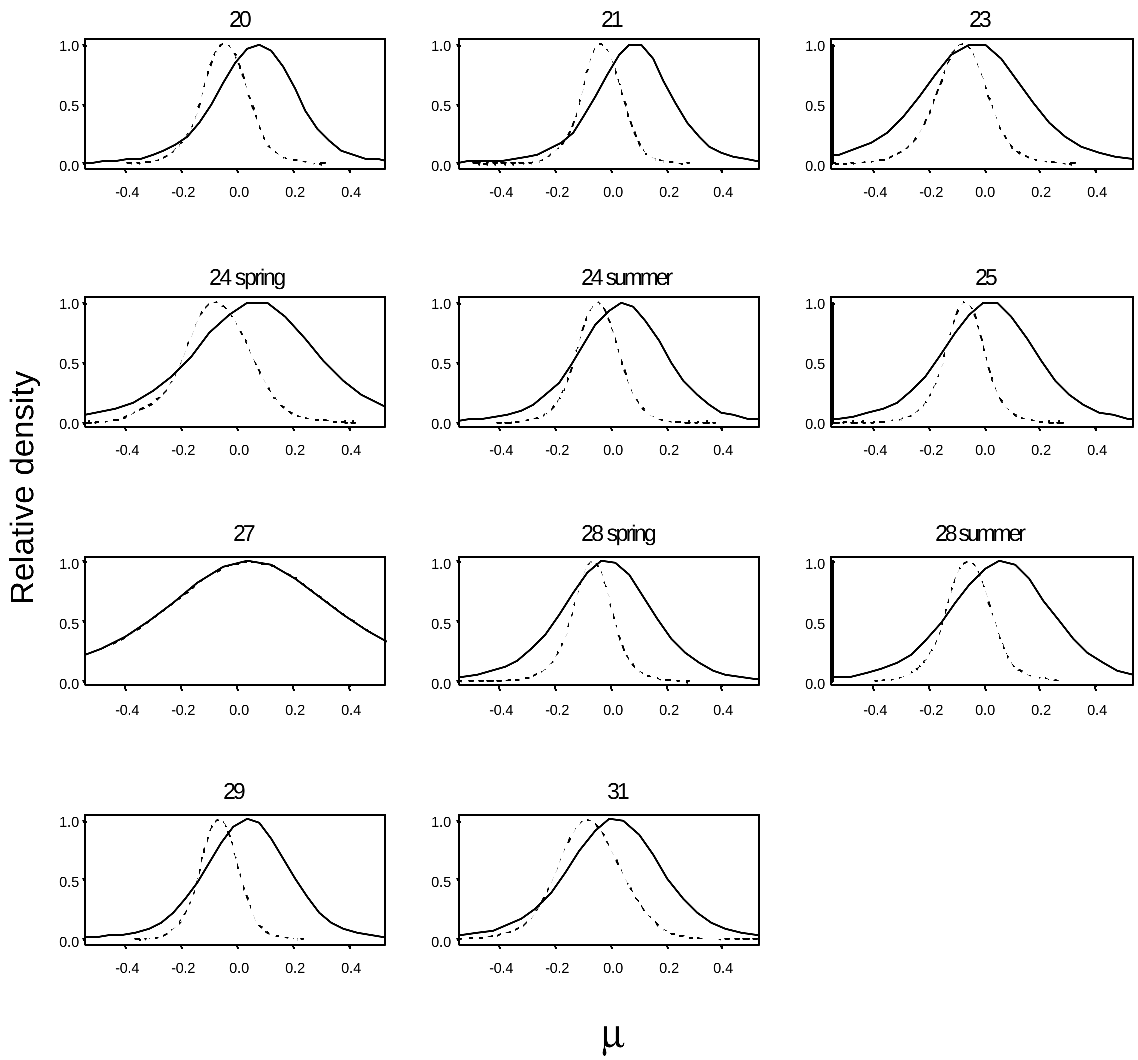

Fig. 8 continued.

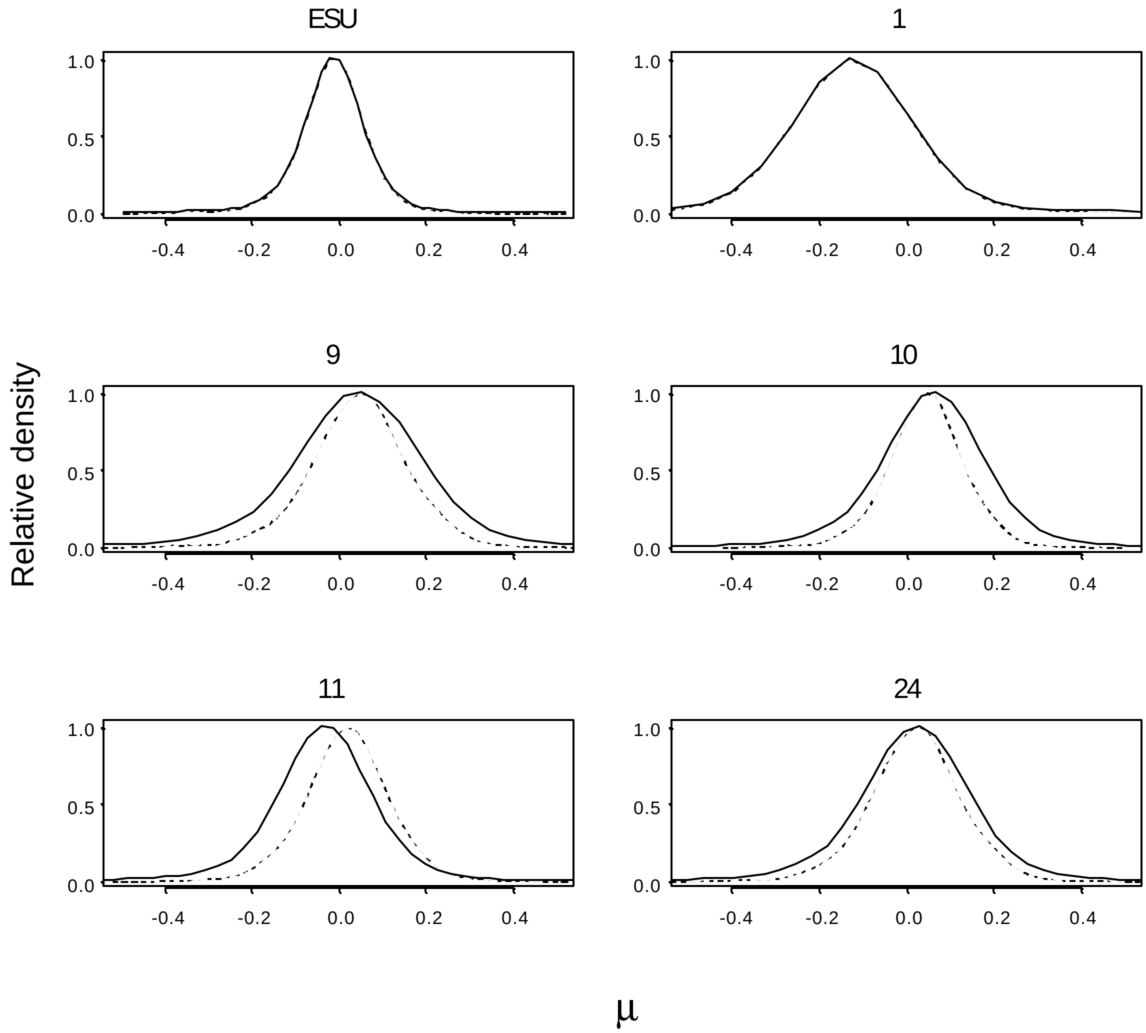

Fig. 9. Posterior distribution of *m* for summer steelhead. The number above each plot is population code (Table 1). Dotted line is based on available all data series, whereas solid line is based on post-1980 data series. Missing populations are due to lack of data.

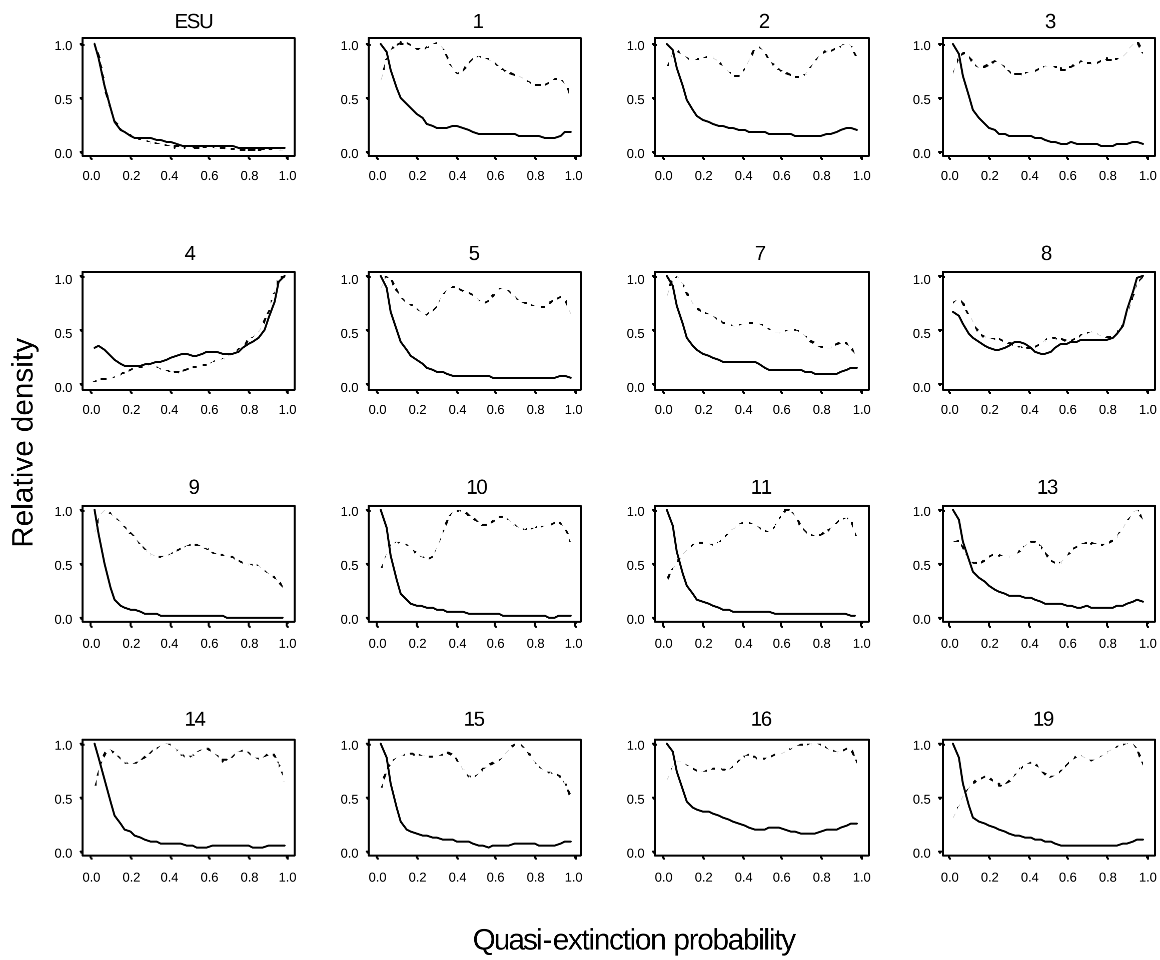

Fig. 10. Distribution of quasi-extinction probability for spring/summer Chinook salmon: 95% HPD region of the probability that population of interest declining by 90% in 50 years. The number above each plot is Chinook salmon population code (Table 1). Dotted line is based on available all data series and solid line is based on post-1980 data series. Big Sheep Creek Chinook salmon population (code 6) is extinct, data for Chamberlain Creek Chinook salmon population (code 12) are not enough, and data are not available for Mid-Fork Salmon River Chinook salmon populations below and above Indian Creek (codes 17, 22), for Pistol Creek Chinook salmon population (code 18), and for Upper Mainstem Salmon River Chinook salmon population above Redfish Lake (code 30).

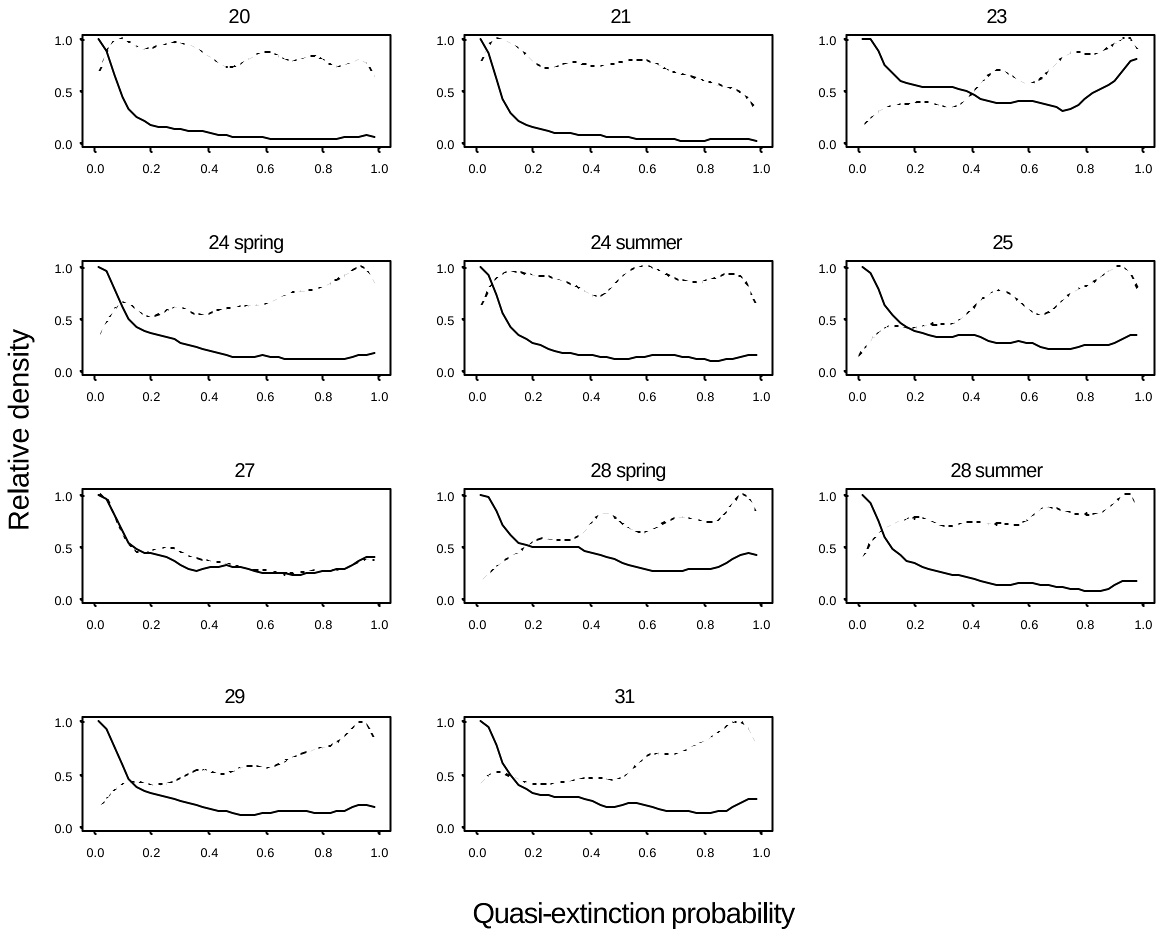

Fig. 10 continued.

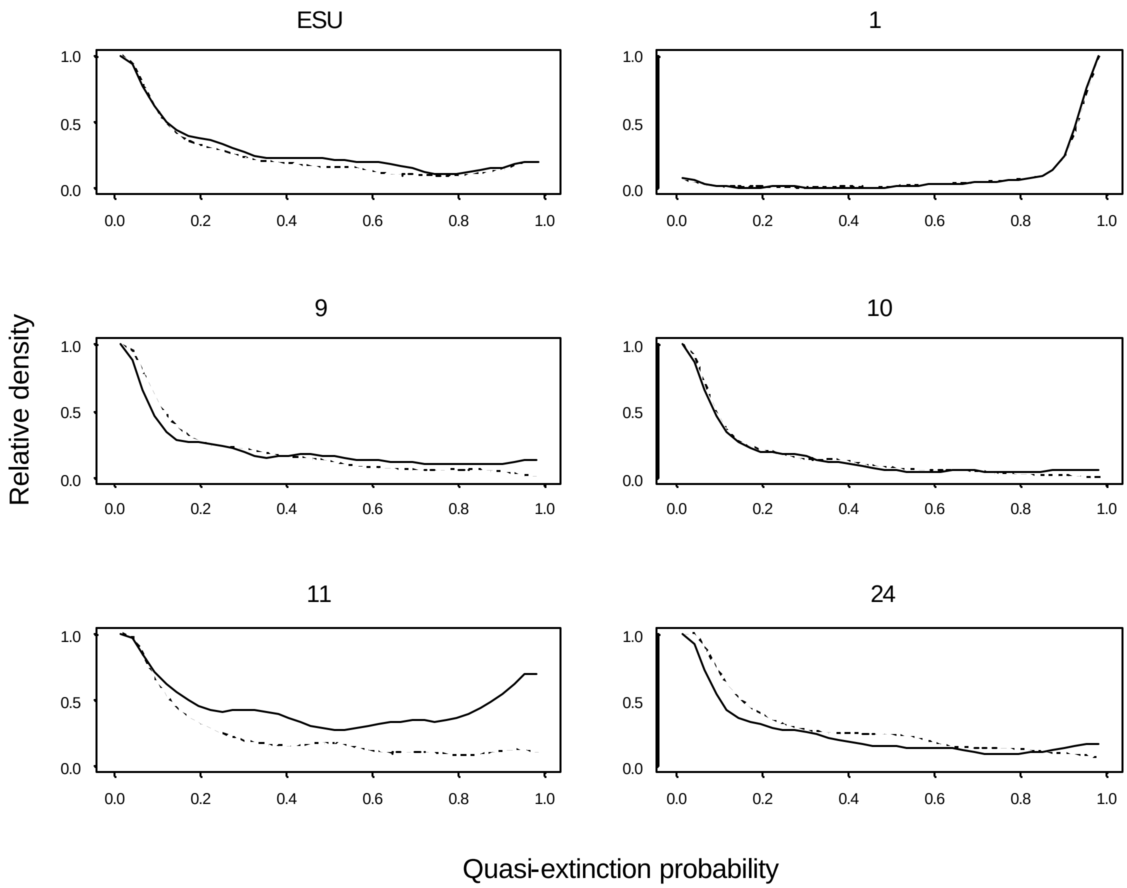

Fig. 11. Distribution of quasi-extinction probability for summer steelhead: 95% HPD region of the probability that population of interest declining by 90% in 50 years. The number above each plot is steelhead population code (Table 1). Dotted line is based on available all data series and solid line is based on post-1980 data series. Missing populations are due to lack of data.

Appendix A. Mathematical expression of Bayesian framework

We show mathematical notations of the likelihood function and the prior and posterior densities of the DA parameters m and s^2. Also we show it is not possible to analytically derive the marginal density of m unless (n - L) is equal to (df+1), where $df \approx 0.333 + 0.212n - 0.387L$; n = the length of annual data series; and L = 4 (eqs. 5-9).

Likelihood, prior, and posterior

The following is the joint likelihood function of m and s^2 (eq. 10).

(A1) $L(m, s^2 \mid \hat{m}, \hat{s}^2) = p(\hat{s}^2 \mid s^2) \cdot p(\hat{m} \mid m, s^2)$.

$p(\hat{s}^2 \mid s^2)$ is Gamma density based on eq. 7. That is,

(A2) $$p(\hat{s}^2 \mid s^2) = \frac{1}{\Gamma(df/2) \cdot (2s^2/df)^{(df/2)}} \cdot \left(\hat{s}^2\right)^{[(df/2)-1]} \cdot \exp\left[-\frac{\hat{s}^2}{(2s^2/df)}\right]$$

$p(\hat{m} \mid m, s^2)$ is normal density based on eq. 8. That is,

(A3) $$p(\hat{m} \mid m, s^2) = \frac{1}{\sqrt{2p\left[s^2/(n-L)\right]}} \cdot \exp\left(-\frac{(\hat{m}-m)^2}{2\left[s^2/(n-L)\right]}\right)$$

For the location (m) and scale (s^2) parameters, we used the standard uninformative prior (Gelman et al. 1995).

(A4) $$p(m, s^2) \propto \frac{1}{s^2}$$

Thus, the joint posterior density of m and s^2 is eq. A5, where constants with respect to m and s^2 are ignored.

(A5) $$\begin{aligned} p(m, s^2 \mid \hat{m}, \hat{s}^2) &\propto (s^2)^{-(df/2)-(1/2)} \cdot \exp\left[-\frac{\hat{s}^2}{(2s^2/df)} - \frac{(\hat{m}-m)^2}{2\left[s^2/(n-L)\right]}\right] \cdot \frac{1}{s^2} \\ &= (s^2)^{-(df+1)/2} \cdot \exp\left[-\frac{1}{2s^2}\left(df \cdot \hat{s}^2 + (n-L) \cdot (\hat{m}-m)^2\right)\right] \cdot \frac{1}{s^2} \\ &= (s^2)^{-(df+3)/2} \cdot \exp\left[-\frac{1}{2s^2}\left(df \cdot \hat{s}^2 + (n-L) \cdot (\hat{m}-m)^2\right)\right] \end{aligned}$$

Marginal posterior density

The marginal posterior density of s^2 is calculated by integrating the joint posterior density of m and s^2 (eq. A5) over m. That is,

(A6) $$p(s^2) = \int_{-\infty}^{\infty} p(m, s^2 \mid \hat{m}, \hat{s}^2)\, dm$$

$$= (s^2)^{-(df+3)/2} \cdot \exp\left[-\frac{df \cdot \hat{s}^2}{2s^2}\right] \cdot \int_{-\infty}^{\infty} \exp\left[-\frac{(n-L)\cdot(\hat{m}-m)^2}{2s^2}\right] dm$$

$$= (s^2)^{-(df+3)/2} \cdot \exp\left[-\frac{df \cdot \hat{s}^2}{2s^2}\right] \cdot \sqrt{\frac{2ps^2}{n-L}} \cdot \int_{-\infty}^{\infty} \frac{1}{\sqrt{2ps^2/(n-L)}} \exp\left[-\frac{(n-L)\cdot(\hat{m}-m)^2}{2s^2}\right] dm$$

The form inside the integral notation of the last part is the kernel of a normal density, so the integral of the normal density over the entire domain $(-\infty, +\infty)$ is one.

$$= (s^2)^{-(df+3)/2} \cdot \exp\left[-\frac{df \cdot \hat{s}^2}{2s^2}\right] \cdot \sqrt{\frac{2ps^2}{n-L}}$$

$$\propto (s^2)^{-(df+2)/2} \cdot \exp\left[-\frac{df \cdot \hat{s}^2}{2s^2}\right] \qquad (\because \text{ ignoring constants with respect to } s^2)$$

$$= \left(s^{-2}\right)^{(df+2)/2} \cdot \exp\left[-\frac{s^{-2}}{2/\left(df \cdot \hat{s}^2\right)}\right]$$

$$= \left(s^{-2}\right)^{[(df+3)/2]-1} \cdot \exp\left[-\frac{s^{-2}}{2/\left(df \cdot \hat{s}^2\right)}\right]$$

This above form is a gamma density whose random variable is $1/s^2$.

(A7) $$\frac{1}{s^2} \sim \text{Gamma}\left(\text{shape} = \frac{(df+3)}{2}, \text{scale} = \frac{2}{df \cdot \hat{s}^2}\right)$$

That is, the marginal posterior density of s^2 is from an inverse Gamma (eq. A7).

The marginal posterior density of m is calculated by integrating the joint posterior density of m and s^2 (eq. A5) over s^2. That is,

(A8) $$p(m) = \int_0^{\infty} p(m, s^2 \mid \hat{m}, \hat{s}^2)\, ds^2$$

$$= \int_0^{\infty} (s^2)^{-(df+3)/2} \cdot \exp\left[-\frac{1}{2s^2} \left(df \cdot \hat{s}^2 + (n-L) \cdot (\hat{m} - m)^2 \right) \right] ds^2$$

Letting $z = \dfrac{A}{2 \cdot s^2}$, where $A = \left(df \cdot \hat{s}^2 + (n-L) \cdot (\hat{m} - m)^2 \right)$

$$= \int_0^{\infty} \left(\frac{A}{2z} \right)^{-(df+3)/2} \cdot \exp(-z)\, ds^2$$

$$= \int_0^{\infty} \left(\frac{A}{2z} \right)^{-(df+3)/2} \cdot \exp(-z) \cdot \left(-\frac{A}{2 \cdot z^2} \right) dz$$

$$\propto A^{-(df+1)/2} \int_0^{\infty} z^{(df+1)/2-1} \cdot \exp(-z)\; dz \qquad (\because \text{ ignoring constants})$$

The form inside the integral notation of the last part is the kernel of a gamma density, so the integral of the gamma density over the entire domain $(0, +\infty)$ is one.

$$= \left(df \cdot \hat{s}^2 + (n-L) \cdot (\hat{m} - m)^2 \right)^{-(df+1)/2} \qquad (\because \text{ replacing } A \text{ with the original notation})$$

$$= \left(1 + \frac{(n-L) \cdot (\hat{m} - m)^2}{df \cdot \hat{s}^2} \right)^{-(df+1)/2}$$

This above form can be the kernel of t density only when $(n\text{-}L) = (df+1)$. Because the equality of $(n\text{-}L) = (df+1)$ cannot be held, it is impossible to analytically derive the marginal posterior density of m. We used Metropolis-Hastings algorithm, one of the MCMC numerical methods to build the marginal posterior distributions of m and s^2.

Appendix B. Correlation in population trend between populations

Table B1. Correlation matrix in post-1980 population trend between Snake River Chinook salmon populations by sub-basin. 'cd number' denotes population code shown in Table 1. cd24.1 and cd24.2 represent Valley Creek spring and summer runs, and cd28.1 and cd28.2 are East Folk Salmon River spring and summer runs. Shaded are correlation coefficients that are larger than or equal to 0.6.

Grande Ronde River sub-basin

	cd1	cd2	cd3	cd4	cd5
cd1	1.000				
cd2	0.781	1.000			
cd3	0.418	0.692	1.000		
cd4	0.280	0.357	0.358	1.000	
cd5	0.855	0.773	0.574	0.071	1.000

Imnaha River sub-basin

	cd6	cd7
cd6	1.000	
cd7	0.352	1.000

South Fork Salmon River sub-basin

	cd9	cd10	cd11
cd9	1.000		
cd10	0.540	1.000	
cd11	0.654	0.734	1.000

Salmon River tributaries sub-basin

	cd12	cd13
cd12	1.000	
cd13	-0.023	1.000

Mid Fork Salmon River sub-basin

	cd14	cd15	cd16	cd19	cd20	cd21
cd14	1.000					
cd15	0.827	1.000				
cd16	0.742	0.789	1.000			
cd19	0.900	0.904	0.775	1.000		
cd20	0.658	0.709	0.478	0.708	1.000	
cd21	0.821	0.874	0.861	0.801	0.598	1.000

Table B1 continued.

Upper Salmon River sub-basin										
	cd23	cd24.1	cd24.2	cd25	cd26	cd27	cd28.1	cd28.2	cd29	cd31
cd23	1.000									
cd24.1	-0.200	1.000								
cd24.2	-0.282	0.498	1.000							
cd25	0.798	0.155	0.054	1.000						
cd26	0.861	-0.130	0.020	0.912	1.000					
cd27	0.270	0.146	-0.038	0.458	0.151	1.000				
cd28.1	0.856	0.324	0.039	0.820	0.756	0.290	1.000			
cd28.2	0.844	0.337	0.058	0.810	0.752	0.263	0.999	1.000		
cd29	0.817	0.053	0.097	0.975	0.961	0.342	0.804	0.801	1.000	
cd31	0.940	0.125	-0.083	0.911	0.882	0.321	0.962	0.954	0.901	1.000

Table B2. Correlation matrix in post-1980 population trend between Snake River steelhead populations by sub-basin. 'cd number' denotes population code shown in Table 1.

Grande Ronde River sub-basin			
	cd9	cd10	cd11
cd9	1.000		
cd10	0.414	1.000	
cd11	0.557	0.016	1.000